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**STUDY AND DEVELOPMENT
OF A LASER BASED ALIGNMENT SYSTEM
FOR THE COMPACT LINEAR COLLIDER**

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presented by

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Abstract

The first objective of the PhD thesis is to develop a new type of positioning sensor to align components at micrometre level over 200 m with respect to a laser beam as straight line reference. The second objective is to estimate the measurement accuracy of the total alignment system over 200 m. The context of the PhD thesis is the Compact Linear Collider project, which is a study for a future particle accelerator.

The proposed positioning sensor is made of a camera and an open/close shutter. The sensor can measure the position of the laser beam with respect to its own coordinate system. To do a measurement, the shutter closes, a laser spot appears on it, the camera captures a picture of the laser spot and the coordinates of the laser spot centre are reconstructed in the sensor coordinate system with image processing. Such a measurement requires reference targets on the positioning sensor.

To reach the first objective of the PhD thesis, we used laser theory and camera model to define an accurate image processing and we performed experiments to validate a prototype of a positioning sensor. For the second objective, we could not obtain results regarding measurement accuracy because we could not develop a full alignment system under vacuum over 200 m. However, we could estimate laser pointing stability over 200 m by extrapolating results obtained over 12 m.

As a result, we present in this report a sensor design, a calibration protocol and estimations regarding measurement uncertainty. In case of a separate calibration with theodolites, we estimated the measurement uncertainty of the positioning sensor to be $4\text{ }\mu\text{m}$ for all coordinates. In case of a full auto-calibration, we estimated the measurement uncertainty of the positioning sensor to be $10\text{ }\mu\text{m}$ for the radial and the vertical coordinates and $20\text{ }\mu\text{m}$ for the depth coordinate. Concerning the extrapolation over long distance, we estimated laser pointing stability to be $10\text{ }\mu\text{m}$ for a laser beam propagation distance of 200 m.

Our work does not provide a complete laser beam alignment system at micrometre level over 200 m but it is the first necessary step towards it.

Résumé

Le premier objectif de la thèse est de développer un nouveau type de capteur de positionnement afin d'aligner des composants au micromètre sur une distance de 200 m par rapport à un faisceau laser comme ligne droite de référence. Le second objectif est d'estimer l'exactitude de mesure du système total sur 200 m. Le contexte de la thèse est le projet du Compact Linear Collider, qui est une étude pour un futur accélérateur de particules.

Le capteur de positionnement proposé est composé d'une caméra et d'un obturateur qui peut s'ouvrir et se fermer. Le capteur peut mesurer la position du faisceau laser par rapport à son propre système de coordonnées. Pour faire une mesure, l'obturateur se ferme, un spot laser se forme à sa surface, la caméra prend une photo du spot laser et les coordonnées du spot laser sont reconstruites dans le système de coordonnées du capteur par du traitement d'image. Une telle mesure nécessite des cibles de référence sur le capteur de positionnement.

Pour atteindre le premier objectif de la thèse, nous avons utilisé la théorie du laser et de la caméra en vue de définir un traitement d'image approprié et nous avons effectué des expériences pour valider un prototype de capteur de positionnement. Pour le second objectif, nous n'avons pas obtenu de résultats concernant l'exactitude de mesure parce que nous n'avons pas pu développer un système d'alignement sous vide sur une distance de 200 m. Toutefois, nous avons pu estimer la stabilité de pointage pour une distance de propagation de 200 m en extrapolant nos résultats obtenus sur 12 m.

Nous présentons dans ce rapport un design pour le capteur, un protocole de calibration et des estimations d'incertitude de mesures. Dans le cas d'une calibration séparée avec des théodolites, nous avons estimé l'incertitude de mesure du capteur de repositionnement à 4 μm pour toutes les coordonnées. Dans le cas d'une auto-calibration complète, nous avons estimé l'incertitude de mesure du capteur de repositionnement à 10 μm pour les coordonnées radiale et verticale, et 20 μm pour la coordonnée en profondeur. En ce qui concerne l'extrapolation sur longue distance, nous avons estimé la stabilité de pointage à 10 μm pour une distance de propagation de 200 m.

Notre travail ne fournit pas un système complet d'alignement au micromètre sur 200 m mais il constitue le premier pas nécessaire dans cette direction.

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Chapter 1

Introduction

1.1 Introduction

The Compact Linear Collider (CLIC) is an international project for a future linear collider to be built by the year 2030 [CLIC, 2015]. It aims at making electrons and positrons collide up to several TeV so that physicists gain a new insight into high energy physics. In particular, it will allow physicists to further analyse what was discovered by the Large Hadron Collider (LHC).

CLIC is highly demanding in terms of alignment accuracy over long distance. Indeed, the Conceptual Design Report (CDR) of CLIC requires beam-related components to be aligned along 20 km of linear accelerators (linacs) with an accuracy of 10 μm at 1 σ over 200 m [Aicheler et al., 2012].

Alignment techniques based on a stretched wire or water level have been studied and developed over the past decades in the survey section of CERN (European Organisation for Nuclear Research) [Quesnel et al., 2008a, Quesnel et al., 2008b, Coosemans, 1990]. These techniques could be envisaged for CLIC because their accuracies are close to the requirements. However, their cost and their difficult implementation are drawbacks that leave space for alternatives. A laser beam is a natural candidate for alignment over long distance, since it propagates along a straight line in vacuum. In addition, it is based on a different physical principle than a stretched wire or water level, which is interesting in order to do inter-comparisons between different alignment systems.

One of the main challenges of a laser-based alignment system is the link between the laser beam and the components to be aligned. In other words, how can we measure the position of a component to be aligned with respect to the position of the laser beam? To answer this question, particle accelerator centres like SLAC (Stanford Linear Accelerator Centre) or KEK (Japanese High Energy Accelerator Research Organisation) have developed laser-based alignment systems with open/close targets [Ruland and Fischer, 1990, Suwada et al., 2013]. However, these systems do not meet the CLIC requirements.

At CERN, the study of a laser-based alignment system began in the late

2010's. The idea consists of (1) interrupting the laser beam at different distances of propagation with shutters, (2) capturing pictures of the laser spots as well as reference targets with cameras and (3) processing pictures to determine the positions of the components to be aligned with respect to the laser spots centres. In a first iteration, the shutters were transparent windows but it had two drawbacks: each transparent window did not only modify the straightness of the beam but it also weakened the laser beam intensity [Lackner and Al Yahyaei, 2010]. In a second iteration, the transparent windows were replaced by open/close shutters. This idea was described in a technical proposal of 2010 as the LAMBDA project, which stands for Laser Alignment Multipoint Based - Design Approach [Lackner et al., 2010]. Soon, the LAMBDA project gave birth to the present PhD thesis.

In the present chapter, we will first present the state of the art in sub-millimetre alignment over hundreds of metres (see Section 1.2). Such a study will allow us to better understand the alignment needs. It will show us the advantages and the drawbacks of existing systems, which will help us during the development of the LAMBDA system. In addition, it will indicate in which range we can expect the accuracy and the precision of the LAMBDA system to be.

Second, we will focus on the problem statement of the LAMBDA project (see Section 1.3). In particular, we will describe in more details the CLIC project, the proposed alignment system, the sensor requirements and the possible sources of uncertainty in the measurement process. It will result in the objectives of the PhD thesis and the strategy to reach them.

Evaluation criteria In order to do a consistent study throughout the whole report, evaluation criteria have to be defined from the beginning. We will take following definitions from the JCGM (Joint Committee for Guides in Metrology) [JCGM, 2008a, JCGM, 2008b]:

- Measurement trueness: closeness of agreement between the average of an infinite number of replicate measured quantity values and a reference quantity value
- Measurement precision: closeness of agreement between indications or measured quantity values obtained by replicate measurements on the same or similar objects under specified conditions
- Measurement accuracy: closeness of agreement between a measured quantity value and a true quantity value of a measurand
- Measurement uncertainty: non-negative parameter characterising the dispersion of the quantity values being attributed to a measurand, based on the information used

Measurement precision will be used very often in the present report. It will be characterised numerically by a standard deviation (at 1σ) or a tolerance (at 3σ).

Measurement accuracy is related to measurement trueness and measurement precision at the same time. It will be used less frequently than measurement precision in the PhD report, since it requires reference values. Such reference values could be obtained by inter-comparison with another alignment system based on a different principle like stretched wire or water level but this has not been done in the frame of the PhD thesis. Another way of having reference values is to make the assumption that, when doing a least-squares adjustment, the vector of real observations is a random vector which has a known symmetric distribution centred on the vector of true observations. In this case, the standard deviation of the residuals (at 1σ) or the tolerance (at 3σ) characterises numerically the measurement accuracy (see Figure 1.1 and Section 3.5).

Measurement uncertainty is another term that will be used very often in the PhD report to characterise numerically the measurement precision and/or measurement accuracy. It includes components coming from systematic effects, thus it is more general than standard deviation or tolerance.

Concept of alignment In the whole PhD report, we will use very often the term *alignment*. Before entering into details, we want to explain what we mean with it. Let us define a 3D coordinate system with the origin point O and three axes x , y and z . In addition, let us define N points $(x_i, y_i, z_i)_{i \in [1:N]}$. Let us compute the fitting line of these points with the least-squares method and define the residuals $r_{i,i \in [1:N]}$ as the distances from the N points to the fitting line (see Figure 1.1). The N points are aligned with an accuracy a if, and only if, the standard deviation of the residuals is smaller than a .

In practice, the radial and the vertical coordinates are treated separately but the same reasoning holds for each coordinate. The N points are aligned in radial (respectively vertical) direction with accuracy a if, and only if, the standard deviation of the residuals in radial (respectively vertical) direction is smaller than a .

1.2 State of the art in sub-millimetre alignment over hundreds of metres

1.2.1 Introduction

The origin of the PhD project is the alignment at micrometre level over 200 m. The solution proposed in the PhD report combines laser beam as straight line reference and camera/shutter assemblies as positioning sensors.

Before entering into details of the solution, we want to understand the motivation of the project. Why is micrometre or more generally sub-millimetre alignment needed over long distance? What are existing alignment systems, their accuracies and their limitations? Why study a system combining laser beam and camera/shutter assemblies? Answering these questions is the goal of the present section.

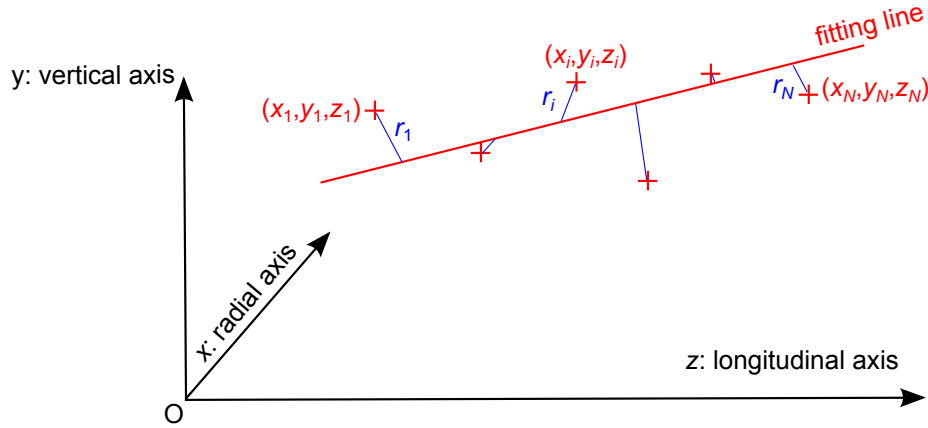


Figure 1.1: N points are aligned with accuracy a if the standard deviation of their residuals with respect to their fitting line is smaller than a .

In the end, the state of the art will not only describe existing systems but will also give us hints in which directions to go or which directions to avoid for future research.

1.2.2 Alignment need

Introduction

In the field of circular colliders like LHC, particles travel million times along the accelerating components before the collision in order to store energy. The fact that multiple travels are possible implies that magnets do not need to be positioned on a perfect circle, only neighbouring magnets have to be aligned accurately [Schwarz, 1990].

In the field of linear colliders, particles travel only once along the accelerating structures. To transfer energy to the particles, multiple travels are not possible, so other solutions have to be found. Preserving ultra-low emittance of the particle beam is a possible solution. It requires accelerator components to be aligned accurately [Schulte, 2009, Mainaud Durand et al., 2013]. This is the reason why projects of linear colliders have triggered research and development in the field of alignment at sub-millimetre level over hundreds of metres.

For example, in the 1960's at SLAC, the alignment tolerance for components of the linear accelerator was 0.5 mm over 3000 m [Herrmannsfeldt, 1965]. In the late 1980's always at SLAC, the tolerance for the components of the FFTB (Final Focus Test Beam) was 10 μm over 300 m [Ruland and Fischer, 1990]. At about the same time at CERN, physicists started to discuss the CLIC project (Compact Linear Collider) [Johnsen et al., 1986] that would finally lead to a required alignment accuracy for beam-related components of 10 μm over 200 m [Aicheler et al., 2012].

In the recent years, several projects of linear accelerators were born next to FTTB and CLIC. The present section describes these projects, starting from the oldest ones (FFTB and CLIC) to the most recent ones (XFEL and ILC). In particular, it gives their alignment tolerances.

Initial need coming from two linac projects

Final Focus Test Beam In the early 90's, the linear collider at SLAC was able to provide collisions between positrons and electrons at an energy of 50 GeV [Tenenbaum, 1995]. In order to reach energies up to 1500 GeV, a new collider was required, which triggered studies for the Next Linear Collider (NLC). In terms of luminosity, the NLC goal was $10^{34} \text{ cm}^{-2}\text{s}^{-1}$, which implies a collision area of about 300 nm (radial) by 3 nm (vertical). To meet such requirements, the alignment of the final focus system had to be improved.

The Final Focus Test Beam (FFTB) was a prototype for the final focus system of a linear collider. It was built at SLAC in 1993 and was made of quadrupoles focusing the beam and sextupoles correcting the focusing. Its goal was to focus down the particle beam to a size of 60 nm in vertical.

Over a distance of 300 m, the tolerances for the absolute alignment (initial alignment) were 100 μm (radial) and 30 μm (vertical), whereas the tolerances for the relative alignment (on-line monitoring) were 15 μm (radial) and 5 μm (vertical) [Ruland and Fischer, 1990]. Theodolites, laser trackers, portable water hydrostatic levels and the Fresnel laser reference system (see Subsection 1.2.3) were used for the absolute alignment, stretched wires for the relative alignment.

The alignment system of the FFTB reduces the time to focus the particle beam. In addition, it permanently controls the positions of the magnets. Thus, it improves the focusing during runs and it reduces the time of repositioning magnets between runs.

Compact Linear Collider At CERN, at about the same time as the Final Focus Test Beam, an advisory panel was created in order to investigate on electron/positron colliders in the TeV range [Johnsen et al., 1986]. First ideas led to start a study on a CERN linear collider called CLIC with a centre of mass of about 2 TeV and a luminosity up to $10^{34} \text{ cm}^{-2}\text{s}^{-1}$. In addition, the advisory panel suggested a two-beam setup with a main linac and a medium energy drive linac.

Since the existing alignment systems were not accurate enough to meet the required luminosity, new alignment methods were studied at CERN in the early 1990's [Coosemans, 1990]. At that time, alignment tolerances had not been clearly defined because surveyors were looking for the best possibilities of a method and were not responding to a precise requirement.

Twenty years later, the conceptual design report (CDR) of CLIC was published [Aicheler et al., 2012]. The report focuses on a linear collider with a centre of mass of 3 TeV and a luminosity of $2 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$. The length of each linac is around 20 km

The report also gives requirements regarding active pre-alignment. The alignment should be done for overlapping sections of 200 m. The error budget allocated to the absolute positioning of the components of the main beam is $14\text{ }\mu\text{m}$ for the RF structures and $17\text{ }\mu\text{m}$ for the main beam quadrupoles. The error budget for the components of the beam delivery system is $10\text{ }\mu\text{m}$. The pre-alignment is called *active* because it consists of two steps: first, sensors measure the position of the components; second, actuators re-adjust misaligned components remotely. An active pre-alignment is necessary because of the tight tolerances. Indeed, perturbing phenomena like seismic ground movements, cultural noise, human and industrial activity or temperature variations are not negligible with respect to these tolerances and components need to be permanently readjusted [Becker et al., 2003].

The technical solution considered in the CDR for the pre-alignment includes stretched wires and Wire Positioning Sensors (WPS) [Mainaud Durand et al., 2010]. The solution based on laser beam as straight line reference is mentioned to be at the stage of research and development.

The future of CLIC is not known yet and depends on LHC results. If these results show that it would be interesting to have particle collisions up to 3 TeV, CLIC might be built.

Increasingly growing demand thanks to new projects

TESLA TESLA (TeV-Energy Superconducting Linear Accelerator) was a project for a future electron positron collider, which is now abandoned [Edwards et al., 1995, Romaniuk, 2013]. The idea was to have a centre of mass of 500 GeV and a luminosity above $10^{33}\text{ cm}^{-2}\text{s}^{-1}$. The TESLA project differed from other projects regarding superconducting accelerating structures and low frequency (1.3 GHz).

The alignment tolerances were 0.1 mm for quadrupoles and 0.5 mm for cavities over a total length of 33 km.

XFEL There are different XFEL (X-Ray Free-Electron Laser) projects around the world and in Europe in particular (e.g. in Germany, in Switzerland, in Sweden, in the Netherlands or in Turkey). In the present section, we are going to give a quick overview of the European XFEL which is an international collaboration coordinated by DESY in Germany [Altarelli et al., 2007].

It actually derives from the TESLA project because it uses similar technology. The goal of XFEL is to generate extremely brilliant ultra-short pulses of spatially coherent x-rays with wavelengths down to 0.1 nm in order to make experiments in various fields like physics, chemistry, material science and biology.

Alignment also plays a major role for the European XFEL. The required accuracy for the alignment of the main linac is 0.3 mm over 150 m and for the connection between monochromators and undulators 0.5 mm over 1000 m [Schlösser and Prenting, 2006]. The envisaged solution is based on a laser beam as straight line reference (with Poisson pattern or direct observation of the laser spot, see Subsection 1.2.3).

ILC Similar to CLIC, ILC (International Linear Collider) is a project for a future linear electron-positron collider [Behnke et al., 2013]. Its centre of mass energy (0.2 to 0.5 TeV) should be smaller than for CLIC (3 TeV). ILC derives from the TESLA collaboration and is based on 1.3 GHz superconducting accelerating structures.

Alignment tolerances for ILC depend on the considered areas [Adolphsen et al., 2013, Mainaud Durand et al., 2013]. In the beam delivery system and final focus areas, the error budget is 30 μm . In the main linac, the error of fiducialisation is 0.1 mm and the error of misalignment of the fiducials is 0.2 mm over 600 m. Here, the length of the sliding window is particularly challenging.

Conclusion

Alignment at sub-millimetre level over hundreds of metres is closely related to the history of linear accelerators. In the late 80's and early 90's, the projects of the Final Focus Test Beam at SLAC and the Compact Linear Collider at CERN pushed research and development in this field. More recently, different projects (e.g. XFEL, ILC) increased the trend.

The goal of the LAMBDA project (accuracy of 10 μm over 200 m) has the tightest alignment requirements as it is an absolute alignment.

1.2.3 Existing systems

Introduction

As presented in Subsection 1.2.2, linear accelerators require sub-millimetre alignment over long distance (> 100 m). This issue has already been studied by many research centres in the past decades. In most of the cases, alignment systems have been developed. In order to learn lessons from past studies, we will have a closer look at them. In particular, the present section aims at describing existing alignment systems, giving their accuracies as well as their advantages and their drawbacks.

The main feature of an alignment system is its straight line reference (SLR) [Griffith, 1989]. Thus, Ruland proposes a classification of alignment systems according to their straight line reference: (1) optical reference line, (2) mechanical reference line and (3) gravity as reference [Ruland, 1995]. For the first category, he distinguishes three different techniques: optical axis reference using traditional alignment instruments, laser beam reference and diffraction optics reference. For the second category, he points out stretched wires combined with Wire Positioning Sensors (WPS). For the third category, he mentions in particular water surface combined with Hydrostatic Levelling Systems (HLS).

Ruland's classification will structure our section about existing alignment systems.

Systems based on optical axis

Systems based on optical axis comprise traditional alignment instruments like electronic theodolites, electronic distance metres or laser trackers [Ruland, 1995]. These instruments are well suited for an alignment over relatively short distance (< 100 m) but they do not work for an alignment over few hundreds of metres [Suwada et al., 2013]. For example, it is possible to align components of the SLAC accelerator with a telescope aiming at targets with an angular tolerance of 10^{-5} rad over approximately 10 m [Herrmannsfeldt, 1965]. But extending this method to the entire 3 km long accelerator would require the telescope to be held stable with an angular tolerance of 10^{-7} rad. This is not attainable because of vibrations, especially from traffic on the nearby highway.

Systems based on laser beam

A laser beam as straight line reference can also be used for the alignment in combination with Position Sensitive Detectors (PSD), Quadrant Detectors (QD) or Charge-Coupled Devices (CCD) as beam positioning sensors [Ruland, 1995]. The instability due to the laser beam production can be compensated by adding a beam splitter and reference sensor at the beginning of the propagation. The instability due to laser beam propagation can be minimised by working under vacuum. For example, when the temperature gradient is 1 K m^{-1} , the bending of the laser beam results in a laser spot displacement of 4.5 mm after 300 m [Griffith, 1989]. Using a vacuum pipe with pressure below 0.001 mbar limits the impact of the temperature gradient on laser spot displacement below 25 μm over 300 m.

Several institutes studied laser-based alignment systems. In the following, the examples of KEK in Japan and JINR in Russia are going to be tackled.

KEK A laser-based alignment system has been installed since 1982 at the Japanese High Energy Accelerator Research Organization (KEK) [Suwada et al., 2013]. It was originally used for KEK B injector linac, where magnets have to be aligned over 500 m with an accuracy of 0.1 mm.

The straight line reference of the alignment system is the laser beam under vacuum (0.03 mbar). To measure the position of the laser beam with respect to the components to be aligned, open/close quadrant photo-detectors are attached to the components. When they are open, the laser beam propagates. When one of them is closed, the laser beam is interrupted. The closed quadrant photo-detector measures the spatial distribution of the laser spot intensity, which gives the position of the attached component.

The alignment system is equipped with a feedback loop that controls the incident angle of the laser beam. This feedback loop makes the laser beam stable over time. Laser pointing stability was computed to be around 40 μm at a distance of 500 m from the laser source.

The authors point out the advantages of their alignment system. It meets the desired relative accuracy (0.1 mm over 500 m). It can be used to align

neighbouring linac components over long distance (> 100 m) and also to monitor the alignment during the operation.

Drawbacks of this alignment system have to be mentioned. First of all, it is not radiation-hard, which makes the KEK surveyors consider replacing their alignment system by a Fresnel lens system (see Subsection 1.2.3). In addition, the repeatability of the open/close mechanism of the quadrant photo-detectors is not studied in the paper [Suwada et al., 2013].

JINR Researchers from the Joint Institute for Nuclear Research (JINR) performed an experiment of laser pointing stability in order to develop a laser-based alignment system [Batusov et al., 2010a]. The position of the laser beam is measured with a dual photoreceiver. The measurement precision was computed for four configurations: laser beam propagating over 10 m (1) in air, (2) in a tube with both ends open, (3) in a tube with one end open, the other end closed and (4) in a tube with both ends closed. The measurement precision was $7.5\text{ }\mu\text{m}$, $2.3\text{ }\mu\text{m}$, $1.6\text{ }\mu\text{m}$ and $0.2\text{ }\mu\text{m}$, respectively.

This experiment shows how important it is to protect the laser beam from atmospheric disturbance. However, even though laser pointing stability has improved, the experiment does not guarantee the straightness of the beam. Indeed, the tube is not a vacuum pipe and temperature gradients may bend the laser beam.

A complementary experiment over longer distance (up to 70 m) confirmed that the measurement precision is about 100 times more stable within a tube than without [Batusov et al., 2010b]. It also showed that measurement precision linearly increases with the distance (around $0.2\text{ }\mu\text{m}$ every 10 m).

Systems based on diffraction optics

Observing diffraction patterns of objects positioned across a laser beam is another way of aligning components. Many institutes have studied this option, in particular SLAC (Fresnel pattern), DESY (Poisson pattern), Spring 8 (Airy pattern) and NIKHEF (other patterns).

Observation of Fresnel pattern The Stanford Linear Accelerator Centre (SLAC) has developed an alignment system with a HeNe laser source, targets and a detector [Herrmannsfeldt, 1965]. Targets are rectangular Fresnel lenses that are attached to the components to be aligned. They can be mechanically switched across the laser beam. When all the targets are up, the laser beam propagates to the detector without interruption. When one target is down, the laser beam is modified and a diffraction pattern appears on the detector. Depending on the spatial distribution of the signal on the detector, radial and vertical misalignments of the components can be detected. In addition, levels are used to detect azimuthal misalignments.

Without beam expander, the laser beam diameter measures 0.15 mm at the laser source and 100 cm at 100 m from the laser source. Such differences in diameter imply significant differences of illumination. In order to have a similar

illumination for all targets, a diverging lens is added to the laser source. A vacuum pipe provides 0.013 mbar pressure in order to guarantee the straightness of the laser beam.

In the Final Focus Test Beam (FFTB, see Subsection 1.2.2), the centres of the targets were determined with $100\text{ }\mu\text{m}$ accuracy with respect to fiducials outside of the vacuum pipe and the centres of the diffraction patterns were detected with $25\text{ }\mu\text{m}$ accuracy [Bressler et al., 1992].

Two advantages of the Fresnel alignment system can be pointed out: it is radiation hard and it enables the alignment of a large number of components. Two drawbacks can also be mentioned: targets are huge (50 cm) and their open/close mechanism brings uncertainty [LeCocq et al., 2008].

Observation of Poisson pattern Poisson and Fresnel alignment systems are based on the same principle: observing the diffraction pattern of a target. The only difference is the target positioned across the laser beam. In case of Fresnel, it is a Fresnel lens. In case of Poisson, it is a sphere.

The Poisson line is the light line generated by diffraction behind a sphere illuminated by a plane wave [Griffith, 1989, Feier et al., 1998]. It can be used as straight line reference over a long distance. For example, using a sphere with 2.5 cm diameter, the diameter of the Poisson line is around 8 mm at 300 m. In atmospheric conditions, the temperature gradient bends the laser beam more than the pressure gradient. For example, a temperature gradient of 1 K m^{-1} makes the laser beam deviate by 4.5 mm over 300 m. To limit the effect of a temperature gradient, pressure has to be smaller than 0.001 mbar.

Two methods are considered for the alignment of components. The first one consists of using an open/close mechanism to check the position of one component at a time. The second one consists of using a laser beam with large diameter and placing all spheres across the laser beam.

The second method was chosen at Lawrence Livermore National Laboratory (LLNL), where 60 spheres are positioned within a large diameter laser beam (around 46 cm). Targets are detected with $25\text{ }\mu\text{m}$ accuracy. A feedback loop maintains laser beam pointing stability within $5\text{ }\mu\text{m}$ at 300 m.

The Poisson line alignment system has three advantages. First, it is radiation hard. Second, it uses simple and fixed targets. Third, the Poisson spot remains smaller than 1 cm over 300 m, which is not feasible with a diverging Gaussian beam. The alignment system also has three drawbacks. It can only support a limited number of targets. Measurement uncertainty gets larger when the distance between the target and the detector increases. When two targets are close to each other, the targets (and the wires supporting them) slightly modify their diffraction patterns, which brings measurement uncertainty.

The Poisson alignment system is also used at DESY for the XFEL beam (see Subsection 1.2.2). The desired alignment accuracy is about 0.3 mm over 150 m [Kaemtner and Prenting, 2006].

Observation of Airy pattern An Airy pattern appears when a laser beam is diffracted by an iris [Zhang and Matsui, 2012]. This principle is under study at Spring8 in Japan in order to perform alignment over short distance (about 10 m).

A HeNe laser source is positioned at one end of the system, a CCD camera at the other end. In between, 4 diaphragms are attached to components to be aligned. When all diaphragms are wide open, the laser propagates without being diffracted. When one diaphragm is almost closed, it forms an iris of diameter 1 mm and an Airy pattern appears on the camera. Image processing gives the coordinates of the centre of the pattern. Thus, a displacement of the Airy pattern indicates a displacement of the components to be aligned.

Measurement precision is around $8\text{ }\mu\text{m}$ (at 2σ) over 8 m. Measurement accuracy is expected to be $10\text{ }\mu\text{m}$ (at 2σ).

This alignment concept has three advantages. First, it is radiation hard. Second, it can theoretically comprise a large number of diaphragms. Third, diaphragms can be opened and closed remotely, which allows a complete check of the alignment within 30 s. But it also has two drawbacks. First, it has only been tested on short distance so far. The application on longer distance (up to 200 m) may complicate the system since irises and/or detectors would have to be enlarged. Second, the open/close mechanism of the diaphragms brings uncertainty into the measurement of the pattern centre.

Observation of other diffraction patterns The Dutch National Institute for Nuclear Physics and High Energy Physics (NIKHEF) developed alignment systems based on diffraction optics for CLIC [Deelen, 2015]. A first version of the alignment system (Rasnik) was based on a LED light source, a lens and a four-quadrant detector or a CCD detector. Since this system was impractical and expensive over long distance, a second version of the alignment system (Rasdif) was implemented and based on a laser source, a diffraction plate and a CCD detector.

In any case, the alignment concept was based on three points. In order to measure more points, it was necessary to use several Rasnik and/or Rasdif alignment systems, and to make them overlap. Rasnik and Rasdif were compared to Wire Positioning Sensors experimentally. Their measurement repeatability was estimated to be between $10\text{ }\mu\text{m}$ and $20\text{ }\mu\text{m}$ over 140 m [Deelen, 2015].

Rasnik and Rasdif alignment systems have the advantage of being static, which reduces the measurement uncertainty. The Rasdif has also the advantage of working over long distance ($> 100\text{ m}$). However, both systems deal with only three points, which is a drawback in terms of propagation of measurement uncertainty.

Stretched wires and Wire Positioning Sensors

A stretched wire can be used as straight line reference for the alignment of accelerator components. This is the case at CERN, where stretched wires have

been developed and used since the 60's [Quesnel et al., 2008b, Mainaud Durand et al., 2010].

The sensors measuring the position of the wire with respect to the components to be aligned are called Wire Positioning Sensors (WPS). Two types of WPS exist. Capacitive WPS (cWPS) are equipped with electrodes measuring the capacitance between them and the wire. This operation requires a conductive wire. Optical WPS (oWPS) are equipped with two cameras capturing pictures of the wire. The position of the wire is computed with image processing.

The wire-based alignment system was tested over 140 m in an old tunnel at CERN (TT1). The measurement precision of the WPS was computed over 33 days to be around 2 μm and the measurement accuracy to be 11 μm in vertical and 17 μm in radial.

The wire-based alignment system has two advantages. It is stable in time, contrary to a laser beam that needs a feedback loop. Its accuracy is close to 5 μm , which is the goal for the CLIC project [Mainaud Durand et al., 2012]. But the wire-based alignment system also has drawbacks. First, it is very expensive. Second, the wire sag has to be taken into account (around 49 cm for a 500 m long wire [Quesnel et al., 2008b]). Third, in case the wire breaks, it takes time to reinstall it. Finally, capacitive WPS are radiation hard but require a conductive wire, which is an additional constraint. Optical WPS are cheaper and do not require a conductive wire, but they are not radiation hard.

Hydrostatic levelling systems

Gravity as reference is the third idea suggested for an alignment over long distance [Ruland, 1995]. It is based on the principle of communicating vessels. The water surface defines the alignment reference. The height of the water level is measured at different locations by Hydrostatic Levelling Systems (HLS). When HLS are positioned on components to be aligned, they give information about the vertical positions of the components.

HLS have been used at CERN for LEP and for LHC [Tecker et al., 1997, Mainaud Durand et al., 2004] but also at other institutes like ESRF [Roux, 1989], DESY [Schlösser and Herty, 2002] or Fermilab [Seryi et al., 2001]. Components can be aligned vertically over 70 m with 5 μm accuracy with HLS [Quesnel et al., 2008a].

Contrary to laser- or wire- based alignment systems, HLS do not need a straight line-of-sight. This can be a great advantage in obstructed environments.

Yet, HLS have two drawbacks. First, they only perform vertical measurements: according to their configuration, they can provide one translation (vertical displacement) and two rotations (pitch and roll). Second, they measure with respect to the water surface, which follows the equipotential surface of gravity. This surface has to be determined accurately before measurements if one needs to perform an alignment with respect to a straight line [Guillaume et al., 2011].

Conclusion

Conventional alignment tools like theodolites or distance metres are not suitable for alignment at micrometre level over hundreds of metres because of their measurement uncertainties and propagation of errors.

This is why many institutes throughout the world developed alignment systems based on different principles. These systems can be distinguished with their straight line references: optical, mechanical or gravity.

Among them, systems based on a laser beam (direct observation or diffraction), a stretched wire or a water level gave interesting results in terms of accuracy, approaching $10\text{ }\mu\text{m}$ over 200 m. However, each of them has its drawbacks. Laser-based systems need a vacuum pipe and an open/close mechanism with a good repositioning of targets. In addition, these are often not radiation hard, except the Fresnel lens system. Wire-based systems are also not practical to implement (wire can break, sag has to be taken into account) and are very expensive. Finally, HLS give only information about three degrees of freedom. In addition, the equipotential of gravity needs to be determined accurately before the measurements if we need to refer the measurements with respect to a straight line.

1.2.4 Research gap

Introduction

Even though the idea of combining a laser beam with camera/shutter assemblies is simple, the concrete study of such a system is recent.

In 2008, first tests were performed at CERN involving a laser beam and transparent windows as targets [Lackner and Al Yahyaei, 2010]. However, this setup had a major drawback: each window modifies the laser beam propagation and the straight line reference is lost.

In 2010, a new proposal was written, where the idea of open/close shutters appeared [Lackner, 2010]. The LAMBDA project was launched.

The present section explains why such a concept was finally born. The first reason is the need for an alignment at $10\text{ }\mu\text{m}$ level over 200 m and the lack of existing systems able to meet this requirement. The second reason is technical progress that made such a project feasible.

Current systems not fully satisfying

The most challenging accuracy required by CLIC for the alignment of some components is $10\text{ }\mu\text{m}$ over 200 m. Based on the state of the art, none of the existing systems guarantees such a value. This is a first motivation to work on a new concept for an alignment system.

Wire-based alignment systems are close to the accuracy requirement. Indeed, a first prototype built at CERN showed an accuracy of $14\text{ }\mu\text{m}$ [Aicheler et al., 2012]. However, in order to be fully validated, they should be compared with

a system based on a different physical principle. A laser beam as straight line reference is a candidate for such a comparison.

Hydrostatic Levelling Systems are also close to the accuracy requirement. However, they are only able to provide information about three degrees of freedom and not about transverse positions. A laser beam coupled with camera/shutter assemblies delivers radial and vertical positions.

An important difference between the KEK laser-based alignment system and the LAMBDA project lies in the way of measuring the laser spot. At KEK, this is done by means of quadrant photo-detectors. This method has a drawback: if there is any irregularity in the laser spot shape, the centre coordinates might be determined with a significant error. On the contrary, in the LAMBDA project, the laser spot is processed by 2D Gaussian fitting, which is more robust in case of irregularities in the laser spot shape.

Alignment systems based on diffraction optics with fixed targets have the drawback that they can only measure a limited number of targets because of the diameter of the laser beam. The LAMBDA alignment system does not have such a limitation.

To sum up, no current system imposes itself as unique solution to perform alignment at 10 μm level over 200 m. This research gap allows us to look for an alternative.

Technical progress opening up new perspectives

The alignment idea of the LAMBDA project is a laser beam as straight line reference and camera/shutter assemblies as laser beam positioning sensors. This could have been studied in the past but it was not. Probably the most important reason why it was not studied was that the technique was not ready for such a development.

As mentioned in the state of the art, many existing alignment systems are based on quadrant photo-detectors. Such detectors limit the accuracy of detecting the laser spot coordinates. With the development of CCD cameras, new algorithms enabled sub-pixel accuracy ($< 1 \mu\text{m}$) [Kaemtner and Prenting, 2006]. In addition, the miniaturisation of cameras made possible the compactness of the sensor.

Another point is related to the automation of the alignment system. Having an automatised system is not only convenient, it is also necessary for aligning at the micrometre level over hundreds of metres. Indeed, for such accuracies, ground motion is not negligible ($1 \mu\text{m min}^{-1}$) [Ruland and Fischer, 1990], neither is laser pointing stability. Current hardware and software make it possible to synchronise 200 open/close shutters with 200 cameras within few seconds, limiting the uncertainty due to ground motion or laser pointing stability.

1.2.5 Conclusion

The world of linear accelerators has been mainly asking for an alignment at the sub-millimetre level over hundreds of metres, in particular through the FFTB

and the CLIC projects. In the recent years, several projects have been started in this area of research (e.g. XFEL, ILC) and are still under development.

Aligning accelerator components with respect to a laser beam had already been studied in the past by many institutes throughout the world (e.g. SLAC, CERN, DESY, KEK). However, an accuracy of 10 μm over 200 m has never been reached so far, mainly due to lacking technologies.

The LAMBDA project was born in 2010, on one hand because other projects did not meet the alignment requirements and on the other hand because technique has become mature enough.

Aligning components at the 10 μm level over 200 m is not feasible yet, which leaves space for an alternative alignment system. A laser beam as straight line reference is common and has been used in the past. Combining camera and open/close shutters has not been developed yet but technical progress made it possible in the recent years.

1.3 Problem statement of the PhD thesis

1.3.1 Introduction

The state of the art showed that no current alignment system meets the CLIC requirements, namely the 10 μm micrometre level over 200 m. We propose to fill the research gap with a system based on a laser beam as straight line reference and camera/shutter assemblies as positioning sensors.

The goal of the present section is to explain what we want to achieve with the PhD thesis. We will first describe the CLIC project, which is the context of the PhD thesis. Then, we will detail the alignment solution envisaged with the LAMBDA project. Finally, we will state the concrete objective of the PhD thesis as well as the research strategy.

1.3.2 CLIC project

Physics on particle interactions requires a collider in the TeV energy range in order to complete results obtained by the LHC (Large Hadron Collider) [Aicheler et al., 2012]. The CLIC (Compact Linear Collider) study proposes a solution with the design of a linear collider with a centre-of-mass collision energy of 3 TeV and a luminosity of $2 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$.

The CLIC acceleration concept is presented in Figure 1.2. The particle beams are generated in the injectors. Their emittance is reduced in the damping rings (DR). Then they are transported to both ends of the accelerators through common linacs. After having passed the turnarounds (TA), the particle beams are accelerated with a gradient of 100 MVm^{-1} . Finally, they are brought to the beam delivery systems (BDS) and collide at the interaction point (IP). The innovation lies in the use of drive beams instead of klystrons to accelerate the main beams. Compressing and reconverting the drive beams into RF power close

to the main beams results in decelerating the drive beams and accelerating the main beams.

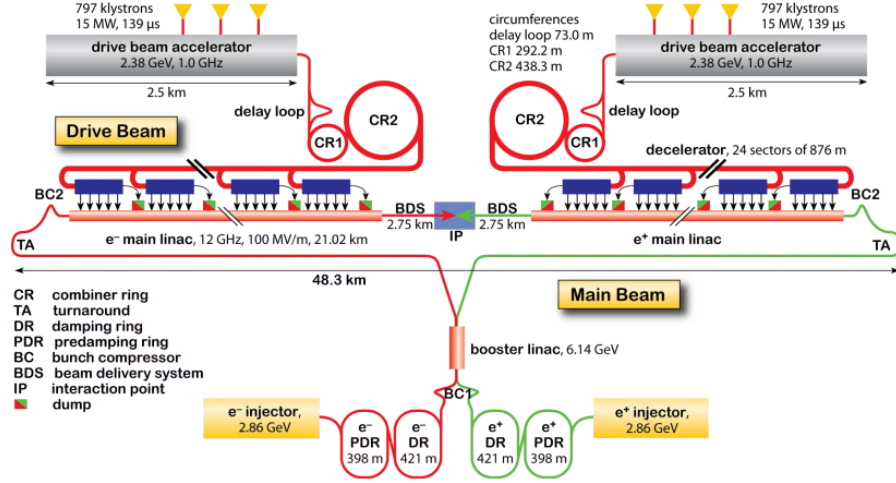


Figure 1.2: Compact Linear Collider layout (taken from [Aicheler et al., 2012])

CLIC alignment Accelerating a particle beam into the TeV energy range requires preserving ultra-low emittance of the beam during the acceleration, which in turn requires accelerator components to be aligned and stabilised with tight tolerances.

The complete alignment process of CLIC actually comprises seven steps [Mainaud Durand et al., 2013]. The first three steps comprise the determination of the surface geodetic network, the transfer of the reference into the tunnel and the determination of the tunnel geodetic network. The next two steps deal with the absolute and relative alignment of the components. Since CLIC tolerances are one order of magnitude tighter than for the LHC, these steps are challenging and will be replaced by an active pre-alignment step. The system is called *active* because it does not only check whether the components are aligned or not, but it also re-adjusts misaligned components by means of actuators.

More precisely, two metrological networks are foreseen to perform the alignment of components: a primary network called Metrological Reference Network (MRN) enabling the propagation of the alignment along the 20 km of the linac within a few micrometres by means of overlapping windows of 200 m, and a secondary network called Support Proximity Network (SPN), allowing an alignment accuracy of a few microns over 10 m [Touzé, 2010].

The MRN proposed in the CLIC CDR consists of overlapping stretched wires, metrological plates with Wire Positioning Sensors (WPS) and Hydrostatic Levelling Systems (HLS). The overlap between wires requires to have 2 WPS per metrological plate (see Figure 1.3). In addition, there is an inclinometer

per metrological plate in order to measure the roll of the components. Relative measurements of CLIC components are performed by means of a Support Pre-alignment Network (SPN). The SPN proposed in the CLIC CDR is based on stretched wires and WPS [Mainaud Durand et al., 2010, Touzé, 2010].

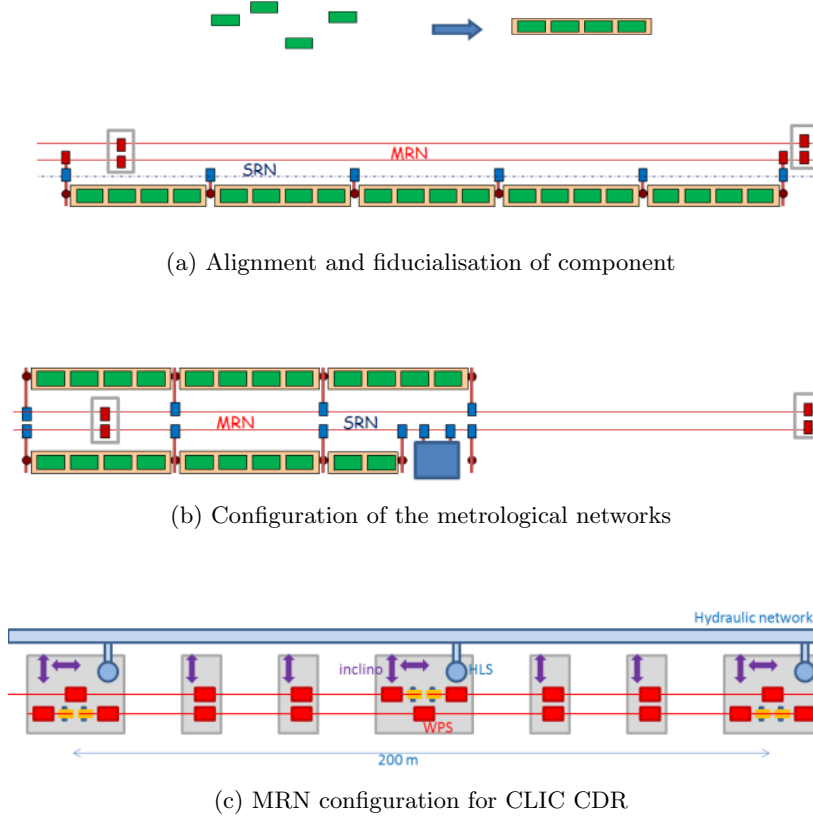


Figure 1.3: Metrological Reference Network (MRN) and Support Pre-alignment Network (SPN) (taken from [Mainaud Durand et al., 2010]). The LAMBDA alignment system could be used for both networks.

The goal of the LAMBDA project is to propose a valid system for an MRN and an SPN, thus it deals with the first part regarding the checking of the alignment of components. Other studies tackle the second part regarding re-adjustment (for instance [Kempinen et al., 2012]).

In any case, since the total length of CLIC is approximately 40 km, the total number of positioning sensors (like WPS and/or HLS) to be manufactured is a real challenge. For the SPN, one sensor is needed every 2 m for the main beam and one sensor is needed every 2 m for the drive beam, which means 40,000 sensors. Also for the SPN, two sensors are needed for 4000 quadrupoles, which means 8000 sensors. Furthermore, for the MRN, three sensors are needed every

100 m on the metrological plates and four intermediate sensors are needed every 100 m as well, which means 700 additional sensors. In total, approximately 50,000 sensors are necessary for the whole CLIC.

Last but not least, another important step within the CLIC alignment challenge is the fiducialisation process of the components (see top of Figure 1.3). This is a calibration step, necessary to link the reference axes of the components with external alignment targets. It is carried out before the installation of the components in the tunnel, as once the components are in place, the reference axes are not accessible anymore. The components are then aligned using the external alignment targets.

Error budget For the CLIC project, the error budget in terms of alignment tolerances is $14\text{ }\mu\text{m}$ for the electrical zero of the beam positioning monitors (BPM), $17\text{ }\mu\text{m}$ for the quadrupole magnetic axes, $14\text{ }\mu\text{m}$ for the mechanical axes of the accelerating cavities and $10\text{ }\mu\text{m}$ for all components of the Beam Delivery System (BDS) [Mainaud Durand et al., 2013]. For the wire-based system, five components enter into the calculation of the total error budget [Mainaud Durand et al., 2011].

First, the components to be aligned need to be fiducialised with respect to their reference axes. This operation is estimated to be done at $5\text{ }\mu\text{m}$ uncertainty for RF structures and $5\text{ }\mu\text{m}$ uncertainty for Main Beam Quadrupoles (MB quad). It does not involve the wire-based or the laser-based alignment system.

Second, the link between component fiducials and sensor interfaces need to be determined. This operation can be done by CMM (Coordinate Measuring Machine) measurements. Its uncertainty depends on the CMM uncertainty.

Third, the link between the kinematic mounts and the zeros of the sensors need to be determined. For the WPS, a calibration process is necessary and a dedicated calibration bench has been developed [Touzé et al., 2009]. The goal is a $5\text{ }\mu\text{m}$ uncertainty.

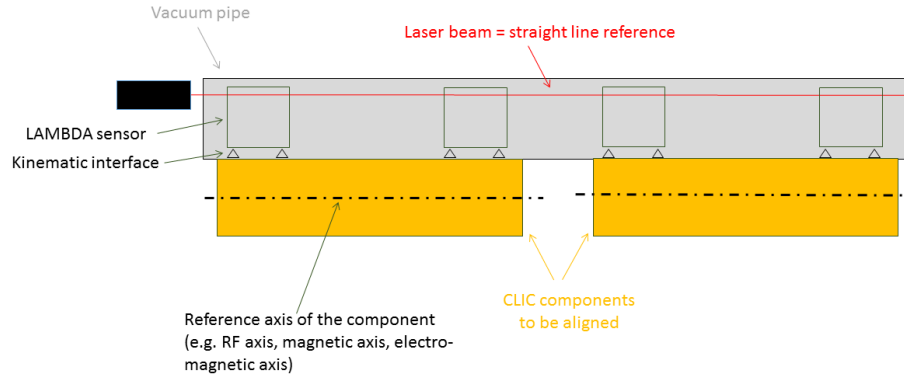
Fourth, the measurements of the sensors need to be related to the straight line. For WPS, this operation is done through capacitive measurements and its accuracy is estimated to be $5\text{ }\mu\text{m}$.

Fifth, the stability and the straightness of the alignment reference are the last aspects of the error budget. For the stretched wires, they were estimated to be $10\text{ }\mu\text{m}$.

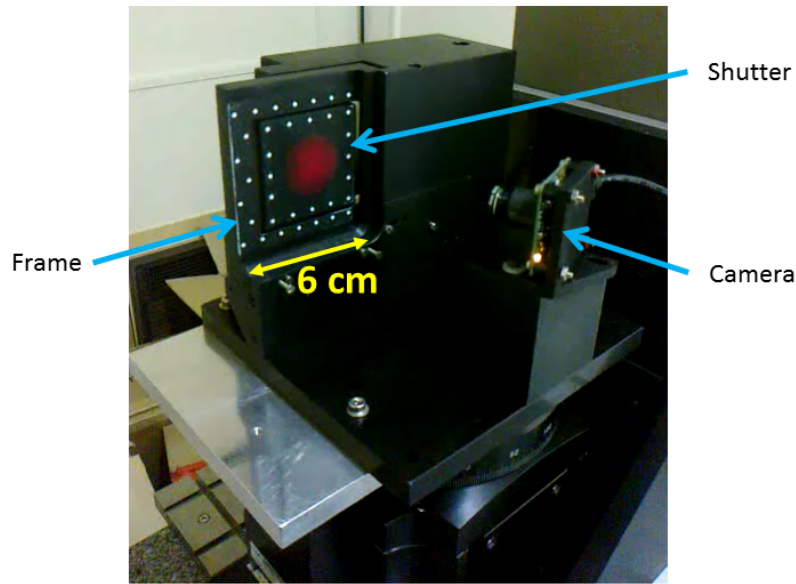
To sum up, for the wire based alignment system, the total error budget was $14\text{ }\mu\text{m}$ for RF structures and $17\text{ }\mu\text{m}$ for MB quad.

1.3.3 LAMBDA project

An alignment system comprises three parts: (1) elements to be aligned, (2) a straight line reference and (3) sensors determining the positions of the elements to be aligned with respect to the straight line reference. In the LAMBDA project, these three parts are CLIC components, a laser beam under vacuum and LAMBDA sensors with their kinematic interfaces, respectively (see top of Figure 1.4).



(a) Schematic overview of the LAMBDA alignment system. The LAMBDA sensors measure the positions of the laser beam with respect to their local coordinate systems. Thanks to calibration and fiducialisation, the positions are transformed from the sensor coordinate systems to the coordinate systems of the CLIC components.



(b) Example of a prototype of LAMBDA sensor. The frame (U shape) and the shutter (square shape) have white targets on their surfaces. A red laser spot appears in the middle of the shutter.

Figure 1.4: Principle of LAMBDA alignment system (top) and LAMBDA sensor (bottom).

A LAMBDA sensor is made of a camera, an open/close shutter and a frame around the open/close shutter (see bottom of Figure 1.4). Shutter and frame are equipped with targets in order to have references and to define coordinate systems. When the shutter is closed, it interrupts the laser beam and a laser spot appears on the shutter. The coordinates of the laser spot centre are determined by image processing in the frame coordinate system, which is also the LAMBDA sensor coordinate system. Subsequently, the LAMBDA sensor can provide the radial and vertical offset of the laser beam centre in its local coordinate system.

LAMBDA sensors are connected by means of kinematic interfaces to each linac component or to each articulation point between linac components. A calibration step provides the parameters of the transformation between LAMBDA sensors and their kinematic interfaces (see Section 4.3). The fiducialisation process provides the parameters of the transformation between kinematic interfaces and the CLIC components to be aligned. The coordinate systems of the CLIC components are based on reference axes, for example the magnetic axes of quadrupoles, the RF axes of accelerating structures and the electrical zeros of Beam Positioning Monitors (BPM). The coordinate systems of the kinematic interfaces are based on their three balls.

Checking the alignment of linac components requires to measure their positions with respect to the laser beam. Since using one LAMBDA sensor prevents the laser beam from propagating until the next ones, not all measurements cannot be done simultaneously. Thus, each LAMBDA sensor is used one after the other. Two reference LAMBDA sensors can be added at both ends of the alignment system that are not attached to CLIC components in order to have reference values and to detect possible laser beam fluctuations.

The LAMBDA sensor has to meet following requirements. First, its measurement accuracy has to be below $5\mu\text{m}$ and its measurement precision below $1\mu\text{m}$. This comes from the error budget of CLIC (see Subsection 1.3.2). Second, its measurement range has to be within $\pm 3\text{mm}$. This corresponds to the range of the actuators moving the components. Third, it has to be compact (maximum $100\text{mm} \times 100\text{mm} \times 100\text{mm}$). This limit was set in order to have the same size as the optical WPS. Fourth, it has to check the alignment within 1 s, which means performing 200 measurements every second.

1.3.4 Objective

The PhD thesis aims at estimating the measurement accuracy of the LAMBDA alignment system over 200 m and proposing a prototype for a LAMBDA sensor. It is challenging because sources of uncertainty exist in all parts of the alignment system.

First of all, the laser source is not perfectly stable in time and needs to be characterised. Then, the laser beam straightness has to be guaranteed over 200 m. This is not easy because it requires a vacuum pipe, which brings additional constraints in terms of implementing the whole alignment system and designing the LAMBDA sensor.

Concerning the LAMBDA sensors, they have to determine accurately the

positions of the CLIC components with respect to the laser beam. This implies to study the interaction between laser beam and shutter, which is a complex field. It also requires to study the links between LAMBDA sensors and CLIC components. In particular, the fact that the shutters open and close brings additional uncertainty into the measurement process. Appropriate material has to be selected for the LAMBDA sensors so that their requirements are met (see Subsection 1.3.3). A software has to be implemented to process pictures captured by the camera in order to reconstruct the laser spot position in the sensor coordinate system and to estimate the measurement uncertainty. Experiments have to be performed in different configurations (over long distance, in vacuum) to validate the LAMBDA sensors. Necessary calibration steps have to be defined for the manufacturing of future LAMBDA sensors.

1.3.5 Strategy

In order to reach the objective of the PhD thesis, several steps are needed.

First, we will study the different parts of the alignment system from a theoretical point of view (see Chapter 2). This will consist of describing mathematically the laser beam propagation and interaction with the shutter, the camera model and the image processing. As a result, it will provide a method to calculate the coordinates of the laser spot centre in the frame coordinate system and to estimate their uncertainties.

Second, we will present the main experiments done within the PhD thesis (see Chapter 3). This part will be organised in a chronological way. It will show step-by-step the improvements in the sensor design and validation. Experiments over short distance will focus on sensor performance whereas experiments over long distance will result in estimating the accuracy of the whole LAMBDA alignment system. In addition, experiments regarding measurement accuracy and repositioning will lay the foundations of the calibration protocol.

Third, we will summarise our recommendations in terms of sensor design and fabrication process in Chapter 4. We will also give a calibration protocol required for future LAMBDA sensors and we will discuss their uncertainties.

Finally, we will conclude by summarising the main contribution of the PhD thesis in Chapter 5. Since the work has been rather focused on the LAMBDA sensor itself and not on the whole system over 200 m, we will show how to integrate the LAMBDA sensor into the whole LAMBDA alignment system and we will present future possible experiments.

1.3.6 Conclusion

The present section has been dedicated to the problem statement of the PhD thesis. First, we described the general context which is the CLIC project, its alignment and its tight tolerances. We pointed out that the PhD project deals with checking the alignment of components and not repositioning them. Second, we proposed a solution to this challenge with the LAMBDA alignment system. In particular, we presented the different parts of the system, we showed how they

are connected with each other and we gave the requirements for the LAMBDA sensor. Finally, we defined the concrete objective of the PhD thesis and we prepared a strategy to reach it. At the same time, the strategy delivers the outline for the coming chapters.

1.4 Conclusion

In this introduction chapter, we presented the context of the PhD thesis which is the CLIC project and its tight alignment requirements (10 μm over a sliding window of 200 m). We established the state-of-the-art in sub-millimetre alignment over hundreds of metres and we concluded that no current alignment system would meet the CLIC requirements. To fill this research gap, we proposed a new system based on laser-beam under vacuum as straight line reference and camera/shutter assemblies combined with image processing as positioning sensors. We defined the objective of the PhD thesis which is the estimation of the measurement uncertainty of the whole alignment system over 200 m as well as the development and the validation of a sensor prototype, and we stated our strategy to reach the objective.

Chapter 2

Theoretical background

2.1 Introduction

The LAMBDA alignment system comprises a laser beam under vacuum that propagates until a shutter. The laser spot that appears on the shutter is captured by a camera before being sent to image processing. In order to implement image processing, we need to have accurate models for laser and camera. These models can be provided by theory.

On one hand, we are going to deal with the theoretical aspects of a laser. This includes laser beam production, propagation, interaction with shutter and speckle. In particular, we will give mathematical formulas of the laser beam/spot at different stages. On the other hand, we are going to present the camera model and the image processing used within the PhD thesis. This comprises the transformation between frame and shutter, the transformation between shutter and camera as well as the distortion study. At the end of the chapter, we will have the mathematical form of the laser spot in the sensor coordinate system.

2.2 Laser

2.2.1 Introduction

A laser beam is a light beam of high intensity and generally a narrow frequency band. LASER is an acronym that means Light Amplification by Stimulated Emission of Radiation [Silfvast, 2004]. Einstein postulated the concept of stimulated emission at the beginning of the 20th century but laser systems were developed only in the second half of the century. In 1960, Maiman observed the laser effect for the first time with a ruby crystal (wavelength $\lambda = 694.3$ nm). In 1961, Javan, Bennet and Herriot obtained laser effects with helium-neon gas ($\lambda = 1150$ nm).

2.2.2 Laser beam production

A laser beam requires three elements to be produced: a pumping system, an amplifying medium and an optical resonator (see Figure 2.1) [Balembois, 2012]. The pumping system can be optical (e.g. sun, lamp, other laser), electrical or chemical. The amplifying system can be solid (e.g. ruby crystal) or gas (e.g. helium-neon). The optical resonator is generally made of two mirrors, one fully reflecting and the other one partially transmitting.

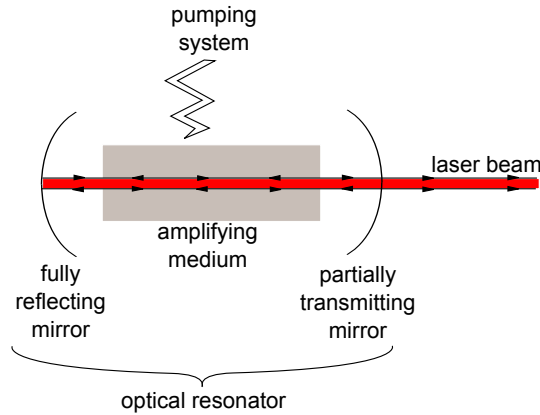


Figure 2.1: Schematic view of the production of a laser beam

The laser beam production works as follows. The pumping system transfers energy to the amplifying medium in order to create a population inversion. A population inversion occurs in the amplifying medium when more electrons are in a higher energy level than in a lower one. In such a situation, photons can be created by spontaneous emission or stimulated emission. In case of spontaneous emission, an electron drops from a high energy level to a low energy level. As a result, a photon appears with random direction. In case of stimulated emission, a photon interacts with an electron in a high energy level. As a result, the electron drops from the high energy level to the low energy level and a second photon is created with the same phase, frequency and direction as the incident photon. If the direction of propagation of both photons is perpendicular to the mirrors, they will bounce within the amplifying medium and create more photons with the same phase, frequency and direction. Repeating this process leads to the formation of the laser beam.

2.2.3 Laser beam propagation

Let us define the laser coordinate system with the z axis coinciding with the propagation axis and with the origin point where the beam size is minimal. The laser beam produced is a light beam that can be modelled by a Gaussian beam. Derived from Maxwell's equation, the complex amplitude of the electric field of

the Gaussian beam yields [Yariv and Yeh, 2007]:

$$E(x_L, y_L, z_L) = E_0 \left(\frac{\omega_0}{\omega(z_L)} \right) e^{- \left[i \left(kz_L - \tan^{-1} \left(\frac{z_L}{z_0} \right) \right) + r^2 \left(\frac{1}{\omega(z_L)^2} + \frac{ik}{2R(z_L)} \right) \right]} \quad (2.1)$$

with (x_L, y_L, z_L) any point in the laser coordinate system, E_0 the amplitude at the origin point $(x_L, y_L, z_L) = (0, 0, 0)$, ω_0 the beam size at distance $z_L = 0$ which is also the minimum spot size, $\omega(z_L)$ the beam size at distance z_L , z_0 the Rayleigh length, $r = \sqrt{x_L^2 + y_L^2}$ the distance from the propagation axis, k the wave number and $R(z_L)$ the radius of curvature of the Gaussian beam. If we take the squared modulus of the field amplitude $I = |E|^2$, we find the signal intensity of the Gaussian beam:

$$I(x_L, y_L, z_L) = I_0 \left(\frac{\omega_0}{\omega(z_L)} \right)^2 e^{- \left[\frac{2r^2}{\omega(z_L)^2} \right]} \quad (2.2)$$

with I_0 the intensity at the origin point $(x_L, y_L, z_L) = (0, 0, 0)$. This is a key formula for the PhD thesis. Indeed, for any perpendicular plan to the propagation axis, the intensity pattern of a laser beam propagating in a homogeneous medium is a two dimensional Gaussian curve and its maximum is obtained for $(x_L, y_L) = (0, 0)$, which is located on the propagation axis (z_L axis). In other words, if we capture a picture of a laser spot and we estimate the position of its centre, then we have a reference point located on a straight line.

In practice, a perfectly homogeneous medium does not exist. For example in air, if the laser beam propagates across air molecules or a temperature gradient, it will be bent. This phenomenon is called beam refraction. It can be minimised by using a vacuum pipe, which we confirmed experimentally (see Section 3.4).

Besides the intensity formula, laser theory provides us the definition of the spot size $\omega(z_L)$ at distance z_L :

$$\omega(z_L) = \omega_0 \sqrt{1 + \frac{z_L^2}{z_0^2}} \quad (2.3)$$

On one hand, we can notice that the spot size $\omega(z_L)$ corresponds to the distance r where the field amplitude is down by a factor $1/e$ compared to its value on the propagation axis. On the other hand, we can see that the laser beam diverges when the distance of propagation increases.

The beam divergence may be problematic for the LAMBDA alignment system. Indeed, if the laser spot size gets too wide and too flat, it will exceed the dimension of the LAMBDA sensor, which will compromise an accurate measurement of the laser spot centre. Nevertheless, another result from laser theory is

the formula for the angle of divergence:

$$\theta_{\text{divergence}} = \tan^{-1} \left(\frac{\lambda}{\pi \omega_0 n} \right) \quad (2.4)$$

with λ the laser wavelength and n the index of refraction of the medium. We can notice that if we increase the initial spot size ω_0 , we decrease the angle of divergence. Increasing the initial spot size can be done with a beam expander. We confirmed by experiments that adding a beam expander to the setup allows us to have a beam size within 4 cm over 200 m (see Section 3.4).

2.2.4 Laser spot on shutter

In the previous section, we presented the mathematical model for the propagation of the laser beam. We found that the intensity profile is a Gaussian beam centred around the axis of propagation of the laser beam.

In our application, the laser beam is projected onto a shutter, which is modelled as a flat surface. Thus, a laser spot appears on the shutter surface. Depending on the position and the orientation of the shutter, the shape of the laser spot on the shutter surface changes. The present section aims at giving the mathematical form of the signal intensity on the shutter. This involves the transformation from laser coordinate system to shutter coordinate system.

We did calculations for a given LAMBDA sensor, which means for a given distance of propagation (see Appendix B for mathematical details). Our preliminary result was that, for a given LAMBDA sensor, we can consider the laser beam size constant.

Then, we distinguished two cases: shutter orientation completely random or shutter plane almost perpendicular to the propagation axis of the laser beam. We found that, in case the shutter orientation is completely random, the signal intensity on the shutter is an elliptic two-dimensional Gaussian curve with the following formula:

$$I(x_s, y_s) = a \cdot e^{- \left[\left(\frac{x_s - x_{\text{cent}}}{s_x} \right)^2 + \left(\frac{y_s - y_{\text{cent}}}{s_y} \right)^2 + \frac{2s_{xy}}{s_x s_y} \left(\frac{x_s - x_{\text{cent}}}{s_x} \right) \left(\frac{y_s - y_{\text{cent}}}{s_y} \right) \right]} \quad (2.5)$$

with (x_s, y_s) any point on the shutter surface in the shutter coordinate system, a the maximal signal intensity, $(x_{\text{cent}}, y_{\text{cent}})$ coordinates of the laser spot centre, (s_x, s_y) the parameters characterising the spread of the elliptic Gaussian curve in radial and vertical directions and s_{xy} the parameter characterising the orientation of the elliptic Gaussian curve (see Figure 2.2). The parameters s_x , s_y , s_{xy} , x_{cent} , y_{cent} and a depend on ω_0 and z_0 , as well as on the rotation matrix and the translation vector between laser coordinate system and shutter coordinate system.

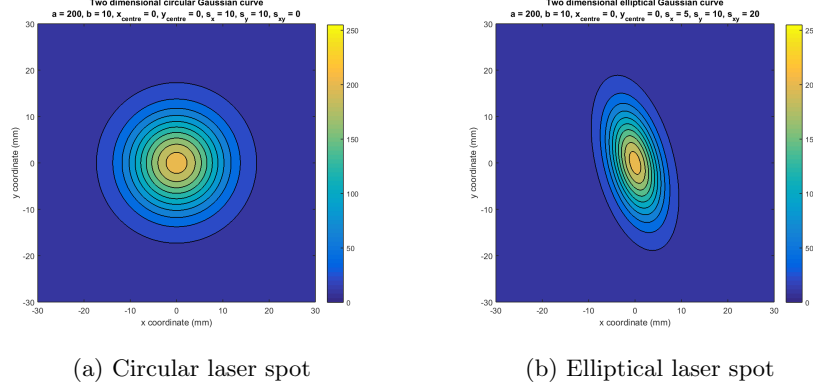


Figure 2.2: Examples of 2D Gaussian curves. For both graphs, the amplitude ($a = 150$), the background level ($b = 0$), the coordinates of the spot centre ($(x_{\text{cent}}, y_{\text{cent}}) = (0 \text{ mm}, 0 \text{ mm})$) are the same. On the contrary, the parameters characterising how the laser spot is spread in x and y directions (s_x, s_y) as well as the parameter characterising the orientation (s_{xy}) are different.

However, in the LAMBDA alignment system, the shutter is assumed to be almost perpendicular to the propagation axis of the laser beam (e.g. the rotation angles between shutter coordinate system and laser coordinate system are smaller than 0.01 rad). Thus we could apply small angle approximation and found that the signal intensity is a circular two-dimensional Gaussian curve with the following formula:

$$I(x_s, y_s) = I_0 \left(\frac{\omega_0}{\omega} \right)^2 e^{-\left[\frac{2((x_s + t_1)^2 + (y_s + t_2)^2)}{\omega^2} \right]} \quad (2.6)$$

with ω the beam size for a given LAMBDA sensor and (t_1, t_2) the radial and the vertical coordinates of the translation vector between laser coordinate system and shutter coordinate system.

In our application, the beam size ω remains smaller than 4 cm . Since the shutter size is up to 10 cm , the coordinates (t_1, t_2) are both contained in $[-5 \text{ cm}, 5 \text{ cm}]$.

2.2.5 Laser speckle

In the previous section, we dealt with the interaction between laser beam and shutter from a geometry point of view. However, such a calculation does not fully describe the laser spot on the shutter because of the speckle phenomenon.

Speckle is a type of granularity that appears when a rough surface is illuminated with a coherent light like a laser [Goodman, 2010]. The speckle intensity of a laser light on a surface like paper or ceramic is characterised by a negative

exponential probability density function. Thus, for any point of the observation plane, where the light intensity average is $\bar{I}$, the probability p_s of observing an intensity I_s is:

$$p_s(I_s) = \frac{I_s}{\bar{I}^2} e^{-\left[\frac{I_s}{\bar{I}}\right]} \quad (2.7)$$

This relationship corresponds to a gamma noise with shape factor 2 and scale factor $\bar{I}$. Figure 2.3 shows an example of the simulated speckle.

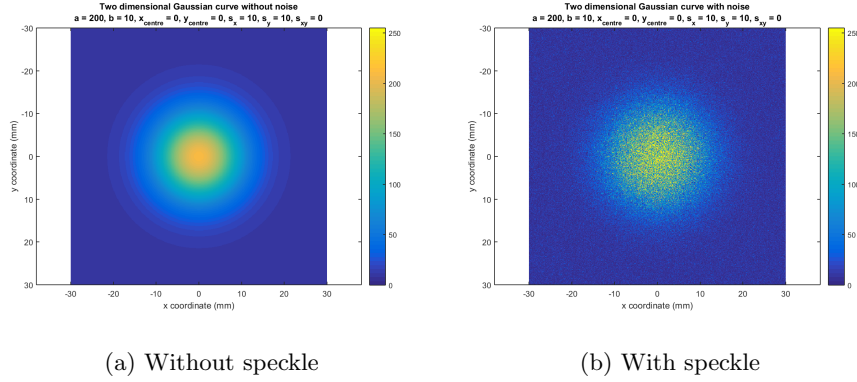


Figure 2.3: Simulation of two dimensional Gaussian curve. In the first case (without speckle), no noise was added. In the second case (with speckle), gamma noise with (shape = 2) and (scale = light intensity average $\bar{I}$) was added.

Since speckle adds gamma noise to the laser spot, determining the centre of the laser spot will not be straightforward. On the contrary, we will need to perform an adjustment between the pixel observations and the theoretical model of the laser spot (see Section 2.4).

2.2.6 Conclusion

To sum up, in case the shutter is almost perpendicular to the propagation axis of the laser beam (small angle approximation, e.g. angles smaller than 0.01 rad), laser theory shows that for a given LAMBDA sensor, the mathematical form of the laser spot on the shutter is a two-dimensional circular Gaussian curve corrupted by gamma noise. To extract the coordinates of the laser spot centre, an adjustment will be needed.

2.3 Camera model

2.3.1 Introduction

So far, we have described mathematically the laser beam propagation and its interaction with the shutter. Since the next step consists of capturing a picture of the laser spot, we need to present the camera model. The camera model contains mainly two parts: (1) the transformation from any point in the scene to a corresponding point on the camera chip and (2) the distortion model.

During the PhD thesis, we used two methods to transform points from scene to camera, namely projective geometry and perspective projection. We started with projective geometry because it was easy to implement. However, this method turned out not to be the most appropriate for our application, in particular when we had to compute the parameters of transformation between shutter coordinate system and camera coordinate system (see Section 3.5). On the contrary, perspective projection is a more accurate model for a camera [Horn, 1999].

In the following, we are going to present the mathematical formulas of both methods. Then we will briefly describe the distortion model used in the PhD thesis. In order to avoid confusion, we define different variables for the coordinates of the laser spot centre in Table 2.1. These definitions will be valid for the current section as well as for Section 2.4. A drawing showing all coordinate systems is given in Figure 2.4.

Variables	Coord. System	Origin	Distortion	Unit
(x_F, y_F, z_F)	frame	on frame		mm
(x_S, y_S, z_S)	shutter	on shutter		mm
(x_C, y_C)	camera	principal point	without	pixel
(x_I, y_I)	image	centre of top left pixel	with	pixel

Table 2.1: Variables used to represent the coordinates of the laser spot centre in different coordinate systems

2.3.2 Projective geometry

Projective geometry deals with the mapping of points from a plane to another plane. Let (x_S, y_S) be the coordinates of a point on the shutter plane and (x_C, y_C) the coordinates of the corresponding point on the camera plane. The transformation from the shutter plane to the camera plane can be described by the following equations:

$$x_C = \frac{h_{11}x_S + h_{12}y_S + h_{13}}{h_{31}x_S + h_{32}y_S + 1} \quad (2.8)$$

$$y_C = \frac{h_{21}x_S + h_{22}y_S + h_{23}}{h_{31}x_S + h_{32}y_S + 1} \quad (2.9)$$

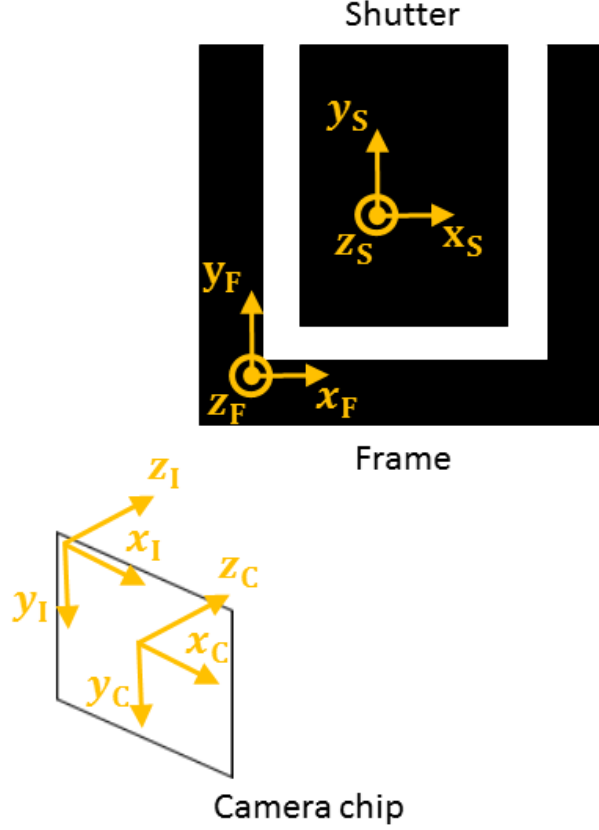


Figure 2.4: Coordinate systems related to image (I), camera (C), shutter (S) and frame (F)

with h_{ij} denoting the 8 parameters of the transformation. Determining the 8 parameters of projective geometry can be done for example with reference targets on the shutter and a least-squares adjustment.

Besides the direct transformation of projective geometry (from shutter to camera), we can also present the inverse transformation (from camera to shutter). The inverse transformation can be useful for example for reconstructing reference targets or a laser spot centre. A small calculation shows that the inverse transformation is also a projective geometry transformation with 8 parameters $h_{\text{inv } ij}$:

$$x_S = \frac{h_{\text{inv } 11}x_C + h_{\text{inv } 12}y_C + h_{\text{inv } 13}}{h_{\text{inv } 31}x_C + h_{\text{inv } 32}y_C + 1} \quad (2.10)$$

$$y_S = \frac{h_{\text{inv } 21}x_C + h_{\text{inv } 22}y_C + h_{\text{inv } 23}}{h_{\text{inv } 31}x_C + h_{\text{inv } 32}y_C + 1} \quad (2.11)$$

In addition, the parameters of the direct transformation (h_{ij}) and the inverse transformation ($h_{\text{inv } ij}$) are linked as follows:

$$\begin{pmatrix} h_{\text{inv } 11} \\ h_{\text{inv } 12} \\ h_{\text{inv } 13} \\ h_{\text{inv } 21} \\ h_{\text{inv } 22} \\ h_{\text{inv } 23} \\ h_{\text{inv } 31} \\ h_{\text{inv } 32} \end{pmatrix} = \frac{1}{h_{11}h_{22} - h_{12}h_{21}} \begin{pmatrix} h_{22} & - & h_{23}h_{32} \\ h_{32}h_{13} & - & h_{12} \\ h_{12}h_{23} & - & h_{22}h_{13} \\ h_{31}h_{23} & - & h_{21} \\ h_{11} & - & h_{13}h_{31} \\ h_{21}h_{13} & - & h_{11}h_{23} \\ h_{21}h_{32} & - & h_{22}h_{31} \\ h_{12}h_{31} & - & h_{11}h_{32} \end{pmatrix} \quad (2.12)$$

With projective geometry, the position and the orientation of the camera coordinate system can be recovered only approximately with respect to the shutter coordinate system [Horn, 1999]. For example, in our application we found errors up to 30 cm for the translation vector and up to 13 mrad for the rotation angles. Thus, projective geometry cannot be used for the final least-squares adjustment but it can be kept as a good first approximation for the rotation angles.

2.3.3 Perspective projection

Compared to projective geometry that has 8 parameters, the model with perspective projection has only 6 parameters (3 parameters for translation and 3 parameters for rotation), which is more appropriate for a camera [Horn, 1999]. The model based on perspective projection maps any 3D point related to the shutter coordinate system to a 2D point related to the camera coordinate system. It works in two steps: first rigid body transformation to pass from shutter coordinate system to camera coordinate system, and then the actual perspective projection to transform 3D shutter points into 2D camera points. It can be summarised with the following equations:

$$x_C = z_P \frac{r_{\text{SC } 11}x_S + r_{\text{SC } 12}y_S + r_{\text{SC } 13}z_S + t_{\text{SC } 1}}{r_{\text{SC } 31}x_S + r_{\text{SC } 32}y_S + r_{\text{SC } 33}z_S + t_{\text{SC } 3}} \quad (2.13)$$

$$y_C = z_P \frac{r_{\text{SC } 21}x_S + r_{\text{SC } 22}y_S + r_{\text{SC } 23}z_S + t_{\text{SC } 2}}{r_{\text{SC } 31}x_S + r_{\text{SC } 32}y_S + r_{\text{SC } 33}z_S + t_{\text{SC } 3}} \quad (2.14)$$

with (x_S, y_S, z_S) any 3D point in the shutter coordinate system, (x_C, y_C) the corresponding 2D point in the camera coordinate system, z_P the principal distance of the camera, R_{SC} the rotation matrix from shutter to camera with elements $r_{\text{SC } ij}$ and T_{SC} the translation vector from shutter to camera with elements $t_{\text{SC } i}$.

The principal distance as well as the rotation matrix and the translation vector need to be determined by calibration.

Besides the direct transformation of the perspective projection (from shutter to camera), we can also compute the inverse transformation (from camera to

shutter). If we rearrange Equations 2.13 and 2.14, we find:

$$\begin{aligned} (r_{\text{SC } 31}x_C - r_{\text{SC } 11}z_P)x_S + (r_{\text{SC } 32}x_C - r_{\text{SC } 12}z_P)y_S \\ = (r_{\text{SC } 13}z_P - r_{\text{SC } 33}x_C)z_S + t_{\text{SC } 1}z_P - t_{\text{SC } 3}x_C \end{aligned} \quad (2.15)$$

$$\begin{aligned} (r_{\text{SC } 31}y_C - r_{\text{SC } 21}z_P)x_S + (r_{\text{SC } 32}y_C - r_{\text{SC } 22}z_P)y_S \\ = (r_{\text{SC } 23}z_P - r_{\text{SC } 33}y_C)z_S + t_{\text{SC } 2}z_P - t_{\text{SC } 3}y_C \end{aligned} \quad (2.16)$$

If we assume that we know z_S , we have a system of two equations (2.15 and 2.16) and two unknowns (x_S and y_S). Solving the system provides us the laser spot coordinates in the shutter coordinate system (x_S, y_S, z_S).

2.3.4 Distortion model

Errors due to camera lens distortion are not negligible for our application and need to be corrected. The distortion model used during the PhD thesis is based on 10 parameters [Luhmann et al., 2006]. The first two parameters are the coordinates of the principal point (x_P, y_P). The third parameter is the radius around the principal point, where there is no distortion by definition (R_0). The last seven parameters characterise radial distortion (A_1, A_2, A_3), tangential distortion (B_1, B_2) and affinity and shear (C_1, C_2). These 10 parameters are determined by a calibration step (see Appendix D for more details).

Let us define (x_i, y_i) the coordinates of a point with distortion and (x_C, y_C) the coordinates of the corresponding point without distortion. (x_i, y_i) are in the image coordinate system, thus they are related in our application to the centre of the top left pixel. (x_C, y_C) are in the camera coordinate system, thus they are related to the principal point. Let us call $r_C = \sqrt{x_C^2 + y_C^2}$ the distance between the distortion-free point and the principal point. The equations used for radial distortion, tangential distortion, affinity and shear are:

$$\Delta_{\text{rad } x} = x_C(A_1(r_C^2 - R_0^2) + A_2(r_C^4 - R_0^4) + A_3(r_C^6 - R_0^6)) \quad (2.17)$$

$$\Delta_{\text{rad } y} = y_C(A_1(r_C^2 - R_0^2) + A_2(r_C^4 - R_0^4) + A_3(r_C^6 - R_0^6)) \quad (2.18)$$

$$\Delta_{\text{tan } x} = B_1(r_C^2 + 2x_C^2) + 2B_2x_Cy_C \quad (2.19)$$

$$\Delta_{\text{tan } y} = B_2(r_C^2 + 2y_C^2) + 2B_1x_Cy_C \quad (2.20)$$

$$\Delta_{\text{aff } x} = C_1x_C + C_2y_C \quad (2.21)$$

$$\Delta_{\text{aff } y} = 0 \quad (2.22)$$

Based on these definitions, distortion can be added as follows:

$$x_i = x_C + x_P + (\Delta_{\text{rad } x} + \Delta_{\text{tan } x} + \Delta_{\text{aff } x}) \quad (2.23)$$

$$y_i = y_C + y_P + (\Delta_{\text{rad } y} + \Delta_{\text{tan } y} + \Delta_{\text{aff } y}) \quad (2.24)$$

and corrected as follows:

$$x_C = x_I - x_P - (\Delta_{\text{rad } x} + \Delta_{\text{tan } x} + \Delta_{\text{aff } x}) \quad (2.25)$$

$$y_C = y_I - y_P - (\Delta_{\text{rad } y} + \Delta_{\text{tan } y} + \Delta_{\text{aff } y}) \quad (2.26)$$

Since corrections are computed from corrected values, an iterative process is needed (see code in Appendix D for more details).

As an example, distortion was computed and corrected for 20 targets, based on Equations 2.25 and 2.26. The differences between initial positions and corrected positions are shown in Figure 2.5.

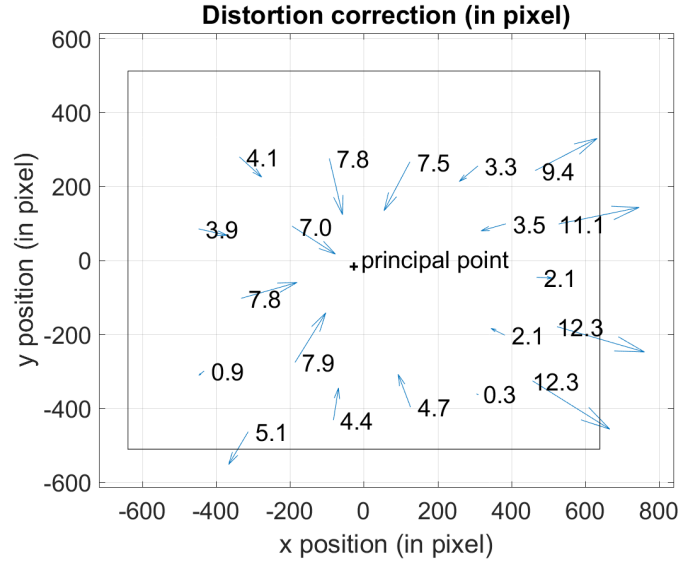


Figure 2.5: Distortion correction of 20 target positions. The black rectangle represents the camera chip.

We can see that the targets close to the principal point were corrected towards the inside, whereas targets close to the edges of the picture were corrected towards the outside. In this example, the maximal correction is 15.5 pixel, which corresponds approximately to 56 μm on the camera chip.

2.3.5 Conclusion

Theory provides two alternatives for the camera model: projective geometry and perspective projection. For both models, we presented the mathematical formulas of the direct transformation as well as the inverse transformation. Since the first one is easy to implement and the second one is more accurate, we will use projective geometry as a first approximation and perspective projection for the final adjustment. Theory also provides the distortion model used for

the PhD thesis. Again, we have the direct transformation (add distortion) and the inverse transformation (correct distortion). The direct transformations will be necessary for camera auto-calibration and the inverse transformations for reconstruction of the laser spot centre from camera to shutter (see Section 2.4).

Concerning the laser spot, we saw in the previous section that it can mathematically be described by a two-dimensional circular Gaussian curve corrupted by noise. In our application, since the camera axis exhibits an angle with respect to the normal to the shutter (generally between 20° and 30°), we will assume that the laser spot is described by a two-dimensional elliptical Gaussian curve corrupted by noise (see Subsections 2.2.4 and 2.2.5 for the mathematical formulas).

2.4 Image processing

2.4.1 Introduction

A LAMBDA sensor is made of a camera, a fixed frame and an open/close shutter. During a series of measurements, the camera captures pictures of the frame and the shutter with the laser spot and targets (see top of Figure 2.6). We saw in the section about problem statement (see Section 1.3) that the LAMBDA sensor has to deliver the coordinates of the laser spot centre in the frame coordinate system. This can be done by image processing.

The input of image processing is an image, which is a matrix containing values between 0 and 255. The output of image processing are coordinates of the laser spot centre (in mm) in the frame coordinate system. Several steps are needed to pass from the input to the output. The present section first gives an overview of the whole image processing and then describes each step in details.

2.4.2 Overview of the whole image processing

The goal of the image processing is to reconstruct the coordinates of the laser spot centre in the frame coordinate system. To reach this goal, we could think of two methods. On one hand, we can reconstruct pixel by pixel the signal intensity from camera chip to shutter plane and then adjust the outcome with a two-dimensional circular Gaussian curve. On the other hand, we can directly adjust the signal intensity of the picture with a two-dimensional elliptical Gaussian curve and then reconstruct its centre from camera chip to shutter plane. We chose the second option during the PhD thesis because it was easier to implement than the first option. However, with the second option, we had to assume that the signal intensity on the camera chip is a two-dimensional elliptical Gaussian curve corrupted by Gaussian noise.

Figure 2.6 shows the whole image processing.

First, the coordinates of the laser spot centre are extracted from the image by two-dimensional elliptical Gaussian fitting. These coordinates are in pixel. Then they are translated to the principal point coordinate system and distortion

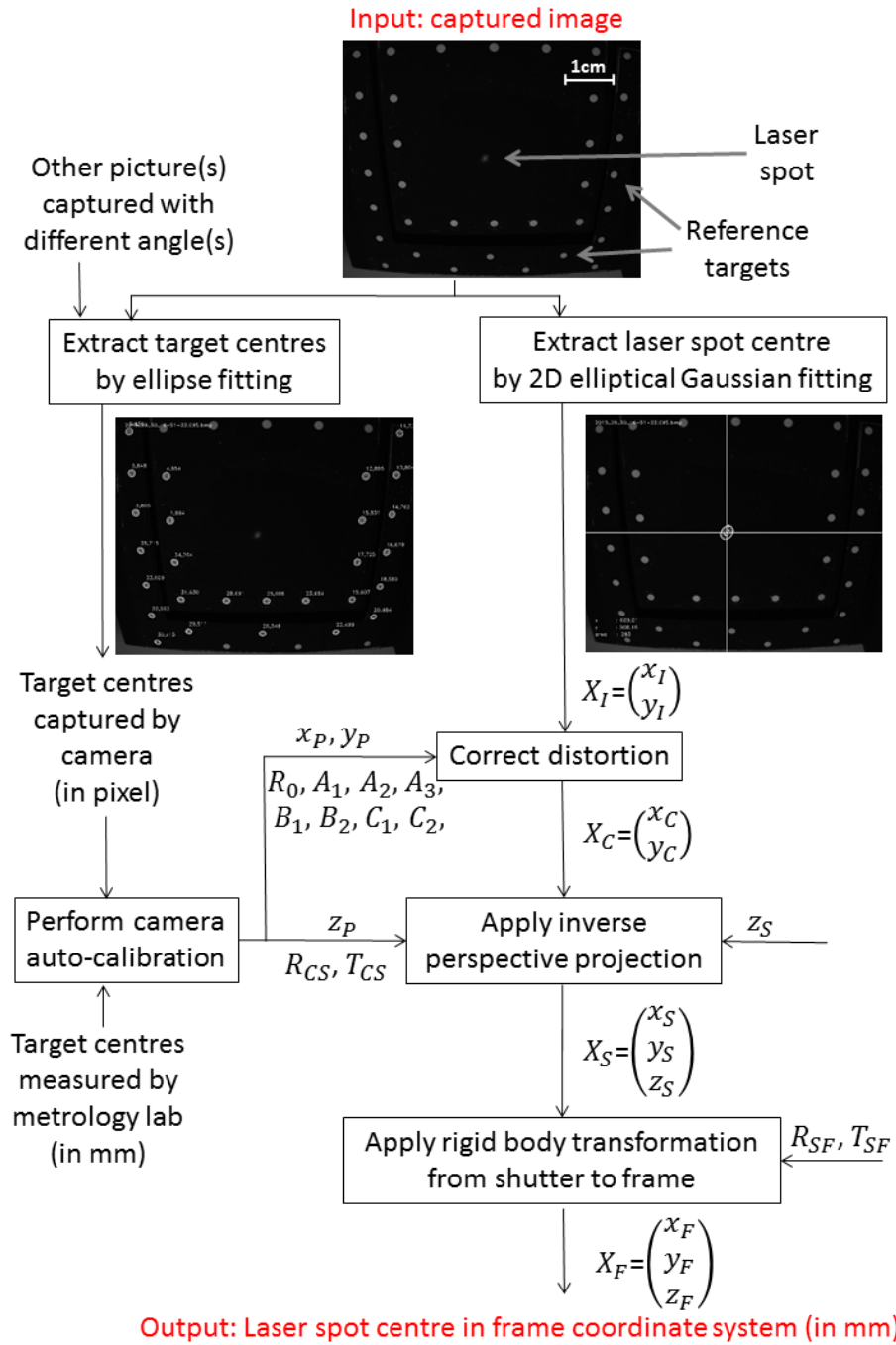


Figure 2.6: Overview of the image processing

is corrected. This requires to know the parameters of interior orientation, in particular the coordinates of the principal point and the distortion parameters. After these steps, the coordinates of the laser spot centre are still referred to the camera chip in pixel. To pass from the camera chip to the shutter plane, the inverse transformation of perspective projection is applied. It requires to know the focal distance of the camera. Finally, to pass from the camera coordinate system to the shutter coordinate system, and then from the shutter coordinate system to the frame coordinate system, two rigid body transformations are used, one after the other. Each of them is described by 6 parameters, 3 parameters for the rotation and 3 parameters for the translation.

All parameters mentioned above are provided by the calibration step (see Section 4.3). The reference targets present on the shutter and on the frame around the laser spot will be useful during this calibration step.

In practice, during the PhD thesis, we performed the extraction of the laser spot centre and the target centres with Sébastien Guillaume's program called *Targets Extraction* [Guillaume, 2011b]. The rest of the image processing was developed in MATLAB.

2.4.3 Extract laser spot centre by 2D elliptical Gaussian fitting

Extracting the laser spot centre takes as input an image and delivers as output the coordinates of the laser spot centre in pixels in the camera coordinate system.

As mentioned in Section 2.2, we assume that the shape of the laser spot on the camera chip is a two-dimensional elliptical Gaussian curve corrupted by noise. Because of the noise, finding the laser spot centre is not straightforward. We could think of several methods: computing the centre of mass or estimating parameters of a two-dimensional Gaussian curve by the application of a least squares method or maximum likelihood method. We compared these methods by simulation (see Appendix C). We found that the maximum likelihood method was the best, but the least-squares method was also acceptable. Because it was simple to implement, we chose the least-squares method in the frame of the PhD thesis.

Subsequently, in order to extract the laser spot centre, we perform a least-squares adjustment of the pixel observations with a two-dimensional elliptical Gaussian curve described by the following formula:

$$I(x, y) = a \cdot e^{-\left[\left(\frac{x - x_1}{s_x} \right)^2 + \left(\frac{y - y_1}{s_y} \right)^2 + \frac{2s_{xy}}{s_x s_y} \left(\frac{x - x_1}{s_x} \right) \left(\frac{y - y_1}{s_y} \right) \right]} \quad (2.27)$$

with (x, y) any point on the camera chip, a the maximal signal intensity, (x_1, y_1) coordinates of the laser spot centre, (s_x, s_y) the parameters characterising the spread of the elliptic Gaussian curve in radial and vertical directions and s_{xy} the parameter characterising the orientation of the elliptic Gaussian curve. The

coordinates of the laser spot centre (x_I, y_I) are going to be further transformed in the next steps.

2.4.4 Correct distortion

As mentioned in Section 2.3, errors due to camera lens distortion are not negligible in view of the accuracy required for our application. Thus, we need to correct the coordinates of the laser spot centre. Let us call (x_C, y_C) the coordinates of the laser spot centre without distortion. In addition, let us call (x_P, y_P) the coordinates of the principal point and $R_0, A_1, A_2, A_3, B_1, B_2, C_1, C_2$ the distortion parameters. We apply the formulas described in Section 2.3 and we find:

$$x_C = x_I - x_P - (\Delta_{\text{rad}} x + \Delta_{\text{tan}} x + \Delta_{\text{aff}} x) \quad (2.28)$$

$$y_C = y_I - y_P - (\Delta_{\text{rad}} y + \Delta_{\text{tan}} y + \Delta_{\text{aff}} y) \quad (2.29)$$

The 10 parameters mentioned above can be determined by camera auto-calibration (see Subsection 2.4.7).

After correcting distortion, coordinates are ready to be reconstructed from the camera chip plane to the shutter plane, which is described in the next section.

2.4.5 Apply inverse perspective projection

So far, we have worked at the level of the camera chip. The next step consists of reconstructing the coordinates of the laser spot centre from camera plane to shutter plane. This can be done by applying the inverse transformation of perspective projection. If we use the formulas given in Section 2.3, we find the coordinates (x_S, y_S, z_S) of the laser spot centre in the shutter coordinate system.

These formulas require to know z_P and z_S . z_P is the principal distance and can be determined by camera auto-calibration (see Subsection 2.4.7). z_S is the z coordinate of the laser spot centre in the shutter coordinate system and can be determined by calibration (see Section 4.3).

2.4.6 Apply rigid body transformation from shutter to frame

Finally, the last step of the image processing consists of computing the coordinates of the laser spot centre in the frame coordinate system. This can be done through a rigid body transformation as follows:

$$x_F = r_{\text{SF } 11} x_S + r_{\text{SF } 12} y_S + r_{\text{SF } 13} z_S + t_{\text{SF } 1} \quad (2.30)$$

$$y_F = r_{\text{SF } 21} x_S + r_{\text{SF } 22} y_S + r_{\text{SF } 23} z_S + t_{\text{SF } 2} \quad (2.31)$$

$$z_F = r_{\text{SF } 31} x_S + r_{\text{SF } 32} y_S + r_{\text{SF } 33} z_S + t_{\text{SF } 3} \quad (2.32)$$

with R_{SF} the rotation matrix from shutter to frame with elements $r_{SF\ ij}$ and T_{SF} the translation vector from shutter to frame with elements $t_{SF\ i}$. The 3 parameters of rotation and the 3 parameters of translation can be determined by calibration (see Section 4.3).

2.4.7 Camera auto-calibration

Camera auto-calibration provides the parameters needed for reconstructing the laser spot centre from the image to the shutter coordinate system. At the beginning of the PhD thesis, we performed camera calibration on a separate plate in order to obtain the coordinates of the principal point (x_P, y_P) and the distortion parameters $R_0, A_1, A_2, A_3, B_1, B_2, C_1, C_2$ (see Appendix D). However, experiments with different types of shutters showed that the camera calibration depends on the shutter (see Section 3.5). Subsequently, performing camera calibration on a separate plate cannot be used for the LAMBDA project.

On the contrary, we developed another solution which consists of calculating all required parameters each time a picture is captured. This solution does not only provide the coordinates of the principal point and the distortion parameters mentioned above, but also the principal distance z_P and the parameters of the transformation between camera and shutter (R_{CS} and T_{CS}). It is based on the targets located on the shutter.

Since targets are disks and the camera observes them with an angle, targets look like ellipses. The preliminary step of the auto-calibration process is the extraction of the target centres. This can be done by ellipse fitting, which consists of a least-squares adjustment between the pixel observations and an ellipse.

The main part of the auto-calibration process is the adjustment of the target positions captured by the camera with the target positions measured by the metrology lab. It is also done by a least-squares adjustment. The function used to transform metrology targets to camera targets is based on the camera model described in Section 2.3. First, shutter targets are transformed from shutter coordinate system to camera coordinate system through perspective projection. Then, distortion is added to all targets.

The least-squares adjustment requires good initial values in order to work properly. For the coordinates of the principal point, the coordinates of the camera chip centre are taken. For the distortion parameters and the rotation angles between shutter and camera, projective geometry is used. For the translation vector between shutter and camera, rough estimates are taken (typically 0 mm for the x and y coordinates, 100 mm for the z coordinate).

In the experiment regarding repositioning (see Section 3.6) and in the sensor calibration (see Section 4.3), we will mention a *full* camera auto-calibration. Compared to the camera auto-calibration presented in the current section, the full camera auto-calibration estimates 6 more parameters, namely the translation vector and the rotation angles between shutter and frame. The principle is the same, except that there are 6 more parameters in the least-squares adjustment.

2.4.8 Conclusion

Image processing is a key part of the measurement process for the LAMBDA project. Indeed, it takes as input pictures captured by the camera and it provides as output coordinates of the laser spot centre in the frame coordinate system, which is also the LAMBDA sensor coordinate system.

Another outcome of the image processing is that it clearly defines which parameters need to be determined before the measurements. Indeed, some parameters can be determined by camera auto-calibration, for instance the coordinates of the principal point, the principal distance, the distortion parameters and the parameters characterising position and orientation of the camera with respect to the shutter. On the contrary, other parameters have to be determined by a separate calibration, for instance the target positions of shutter and frame, as well as the z coordinate of the plane, where the laser beam reflection occurs (z_s). This will be explained in details in the calibration part (see Section 4.3).

2.5 Conclusion

In this chapter, we presented the theoretical aspects of laser and camera that are relevant to our applications. In particular, we described the mathematical form of the laser spot at each stage, from laser beam propagation to interaction with the shutter. As a result, we found that, at shutter level, the laser spot is a two-dimensional circular Gaussian curve corrupted by gamma noise. Furthermore, we detailed the direct and inverse transformations related to the camera, useful for image processing. In the end, this chapter provided us the mathematical reconstruction of the laser spot centre from any captured picture to the frame coordinate system, which is also the sensor coordinate system.

Chapter 3

Experiments

3.1 Introduction

In parallel to the theoretical study, we performed experiments throughout the PhD thesis in order to find the most appropriate material for the LAMBDA alignment system and validate it. Two types of experiments were done. When we wanted to focus on sensor performance, we installed the sensor at a short distance from the laser source (typically between 2 and 3 m). In addition, we worked in an optical lab, which was not ventilated and located in a basement, so that the temperature was stable within 0.1° during our experiments. When we wanted to study the impact of laser beam propagation, we set the sensor at different distances, between 0 and 200 m, from the laser source. In this case, due to space restriction, we could not work in the optical lab anymore. Thus, we installed all the setup in the geodetic base of CERN, which was a 50 m long ventilated tunnel.

We will summarise the main experiments in the present chapter and leave other smaller experiments for the appendix (see Appendix E). First, we will see how simple tests allowed us to build an initial prototype of the LAMBDA sensor. Second, we will deal with experiments regarding the shutter, which is a crucial element of the LAMBDA sensor, since it reflects the laser beam towards the camera. Third, we will report about experiments over long distance in air (up to 200 m) and in vacuum (up to 35 m). Fourth, we will see how tests regarding measurement accuracy helped us not only to improve the reconstruction of the laser spot but also to modify the camera model. Fifth, we will present an experiment regarding repositioning that allows us to determine the parameters of the transformation between shutter and frame as well as their uncertainties.

3.2 Lessons learnt from first experiments

3.2.1 Introduction

Before the beginning of the PhD thesis, F. Lackner from the survey section of CERN carried out several tests with a laser, an optical fibre, a collimator, transparent windows and low-cost cameras in order to develop a laser beam positioning sensor [Lackner and Al Yahyaei, 2010]. These tests were not successful because the transparent windows lowered the laser beam intensity and modified its straightness. However, they gave the idea of replacing the transparent windows by open/close shutters, which triggered the LAMBDA project [Lackner et al., 2010].

At the beginning of the PhD project, we performed simple tests with the material left by F. Lackner in order to have an idea of the measurement precision. In addition, we ordered new material for comparison. Step by step, we made choices regarding camera, shutter, targets and motorised micrometre machine. In the end, the experimental setup was automated, which allowed us to accelerate the measurement process, collect more data and improve the measurement precision. The present section describes this first series of experiments in details.

3.2.2 Camera choice

The cameras left from early tests were quite large (around 15 cm). This did not meet the requirement regarding sensor size (maximum 10 cm for the whole sensor). In addition, these cameras had a quite large pixel size (11 μm) compared to more recent cameras, which could be a drawback in terms of measurement precision. Subsequently, we wanted to find a better option for the cameras.

The first test consisted of comparing two types of cameras in terms of measurement precision and size. It was carried out in the optical lab (see Figure F.1). To simulate LAMBDA sensors, we combined each camera, one after the other, with the same shutter. In order to avoid uncertainty due to laser beam propagation and to focus on sensor performance, we limited the distance of propagation from the laser source to the shutter to 2 m. A schematic overview of the setup is provided in Figure 3.1.

For this first test, we used the red laser described in Figure F.6 in combination with an optical fibre and a collimator (Figure F.12) so that the laser beam diameter is about a few millimetres. In addition, we used an off-the-shelf open/close shutter (see Figure F.32).

As mentioned above, we wanted to compare two types of cameras. The first type was an off-the-shelf camera that had already been used before the beginning of the PhD project [Lackner et al., 2010] and was available in the optical lab (see Figure 3.2 (picture on the left) and Figure F.17). It was approximately 15 cm long and had a pixel size of 11 μm . The second type was also an off-the-shelf camera (see figure 3.2 (picture on the right) and figure F.18). It was chosen because it was available at the survey section from another project. It was

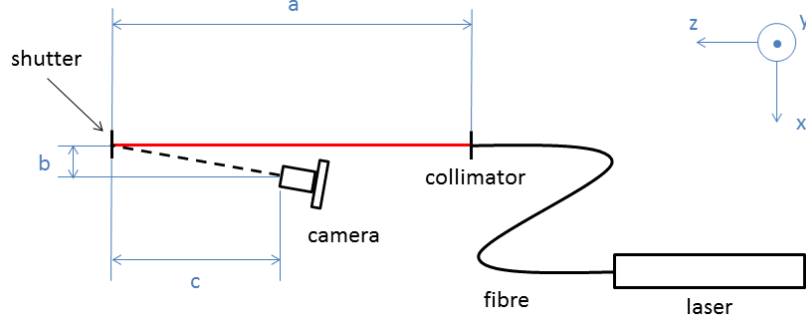


Figure 3.1: First test performed to choose the type of camera. a is the distance of propagation of the laser beam, b and c characterise the position of the camera with respect to the laser beam and the shutter.

approximately 4 cm long and had a pixel size of $3.6 \mu\text{m}$. It had a lens produced by Edmund Optics (no 55-569) with a focal distance of 2.2 mm and an angular field of view of 130° . Both cameras were set on a manual micrometre table.

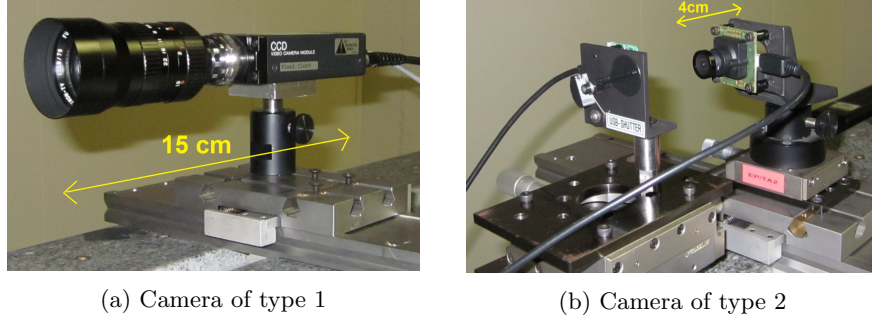


Figure 3.2: Cameras used for first tests

The propagation distance of the laser beam a was 2 m for both cameras. The distance between camera and laser beam b was 1.5 cm for both cameras. Because of different focal lengths, the distance between camera and shutter c was smaller for the second camera (5 cm) than for the first one (50 cm), thus the angle between laser beam and camera axis was larger for the second camera than for the first one.

Starting at an arbitrary position, we manually moved both cameras from $x = 0 \mu\text{m}$ to $50 \mu\text{m}$ in steps of $10 \mu\text{m}$. For each position, we captured 40 pictures, processed them with the Gaussian fitting algorithm (see Subsection 2.4.3) and computed the standard deviation of the x and y coordinates. For each camera, a scale factor could be determined between displacement in the camera plane and displacement in the shutter plane knowing that the total displacement was

50 μm .

As a result, the standard deviations were computed and reached up to 10 μm for camera 1 and up to 5 μm for camera 2. Apart from a better precision, camera 2 has the advantage of being much more compact than camera 1, which is crucial for the future LAMBDA sensor. However, camera 2 had a drawback compared to camera 1. The angle between camera axis and laser beam was larger for camera 2, which made the geometrical configuration more complicated but this could be compensated by appropriate image processing. Since cameras of type 2 brought more advantages than drawbacks, they were used for the rest of the experiments.

3.2.3 Camera lens choice

The camera lens used in the previous test had a small focal length (2.2 mm) and a wide angular field of view (130°). Subsequently, the laser spot captured by the camera occupied only a small part of the picture. We wanted to select another camera lens with a smaller angular field of view, so that the captured picture contained only the laser spot and the shutter.

We tested three types of lenses produced by Edmund Optics (no 58-202, 58-205, 58-207). They had a focal length of 6 mm, 12.5 mm and 25 mm, respectively, and an angular field of view of 47° , 27° and 14° . We repeated the same protocol as in the previous experiment described in Subsection 3.2.2.

As a result, we selected the smallest focal length (6 mm) because it provided the most compact solution for the camera/shutter assembly. In addition, we obtained results regarding measurement precision and repeatability (standard deviations up to 5 mm) and we presented them in [Stern et al., 2012].

3.2.4 Targets and shutter choice

The first tests were done without reference targets on the shutter. The correspondence between camera and shutter was determined by a calibration step. By moving the camera over a small distance, e.g. 50 μm or 100 μm , and measuring the displacement of the laser spot in the camera plane, we could compute a scale factor between camera and shutter.

In order to reduce the uncertainty due to the transformation between camera and shutter, we decided to add circular targets on the shutter [Guillaume, 2011a]. Circular targets had the advantage of looking like ellipses even if the camera axis and the normal vector to the targets presented an angle. Thus, the target centres could be computed by ellipse fitting.

We used an ellipse fitting program developed by [Guillaume, 2011a]. We tested white and retro-reflective targets (see Figures 3.3).

As a result, white targets were detected correctly but not retro-reflective targets. Thus, we decided to keep white targets on black background for future experiments.

However, we had used so far simple open/close shutters (see Figure F.32). These shutters did not have a black background and did not allow to add many

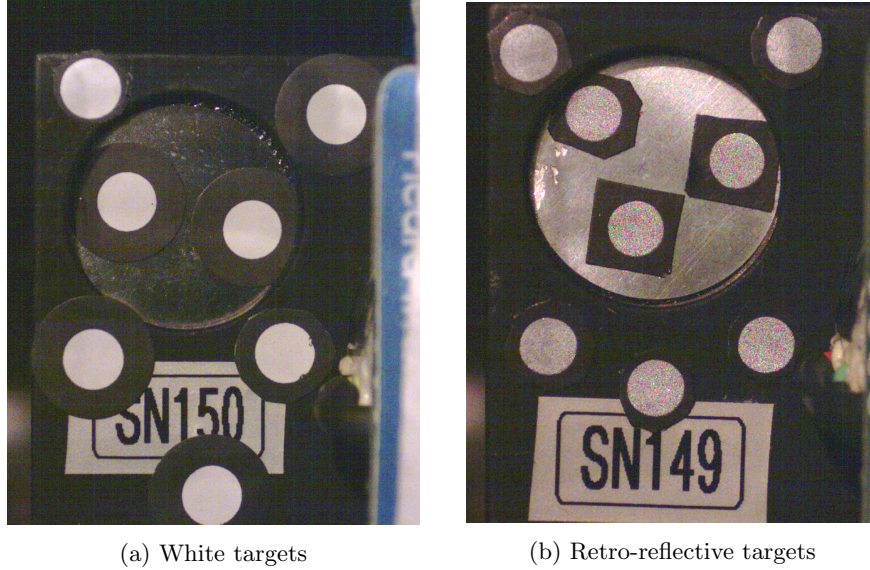


Figure 3.3: Examples of pictures of shutters captured with different targets

targets because of the small aperture (about 2 cm). Subsequently, we decided to make other shutters with aluminium plates and sheets of paper glued on them. The sheets of paper were simple A4 papers. They were originally white but a black background was printed on their surfaces in order to make white disks appear (see Figures F.22 and F.23).

As soon as we had shutters with targets, we had to modify the image processing, in particular the transformation from camera coordinate system to shutter coordinate system. For instance, a transformation of projective geometry was used for many experiments in the optical lab and in the geodetic base (see Subsection 2.3.2). In addition, the targets had to be measured in the metrology lab before the experiments in order to know their relative positions (see for example F.9).

3.2.5 Automation of the measurement process

During the series of first tests, we performed manually small displacements of the cameras and shutters, and we captured manually picture after picture. To make the measurement process easier and faster, as well as to decrease measurement uncertainty, we decided to buy a motorised micrometre table and to control it with a dedicated program in Labview. We attached the camera and the shutter on an aluminium plate and we call this assembly LAMBDA sensor. We installed the LAMBDA sensor on the motorised micrometre table (see Figure F.3). The displacement accuracy of the motorised micrometre table ($0.1\text{ }\mu\text{m}$) was given by the manufacturer and checked at the metrology lab of CERN. Thus, the

motorised micrometre table provided us the reference of displacement.

With this new automatised setup, we performed an experiment with a similar protocol as the one presented in 3.2.2. The transformation between camera and shutter was based on projective geometry. We computed standard deviations of the laser spot coordinates on the shutter surface below $2\text{ }\mu\text{m}$, which is an improvement compared to the manual tests (standard deviations up to $5\text{ }\mu\text{m}$). We described the full experiment and the results in an IPAC paper [Stern et al., 2013].

In parallel to this experiment, another test was performed with the same setup in order to check laser pointing stability over long term. The camera captured one picture per minute during 4000 min (2.5 days). The micrometre table did not move throughout the experiment. The laser source was switched on just before starting the experiment.

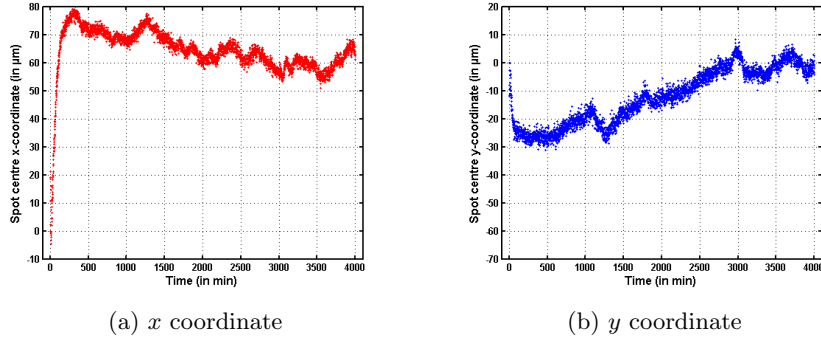


Figure 3.4: Variations of the coordinates of the laser spot centre on the shutter over a week-end.

As a result, the laser spot coordinates presented drifts during the first 300 min, in particular up to $80\text{ }\mu\text{m}$ for the x coordinate (see Figure 3.4). After this period, there were still variations but they were slower and remained within $40\text{ }\mu\text{m}$, probably due to laser beam internal drifts. Since the quick variations at the beginning of the experiment were probably due to warming-up of the laser, we decided for future experiments to switch on the laser source in advance, for instance at least half a day before capturing pictures.

3.2.6 Conclusion

The first months of the PhD project consisted of simple tests in order to select appropriate material for the future experiments. After several iterations, we chose a camera, a lens and a shutter with targets. In addition, we improved the transformation between camera and shutter and we automatised the measurement process with a motorised micrometre table and a Labview program.

We managed to obtain encouraging results in terms of measurement precision, when the LAMBDA sensor was moved over a small distance ($50\text{ }\mu\text{m}$).

Indeed, we computed standard deviations of the laser spot coordinates on the shutter plane below $2\text{ }\mu\text{m}$. These first experiments were the basis for more sophisticated experiments, for example with different types of shutters, over long distance or in a vacuum pipe.

3.3 Experiments regarding shutter

3.3.1 Introduction

First tests provided encouraging results in terms of measurement precision (see Section 3.2). Indeed, when we moved the LAMBDA sensor over $50\text{ }\mu\text{m}$ in steps of $10\text{ }\mu\text{m}$, we found standard deviations of the laser spot coordinates smaller than $2\text{ }\mu\text{m}$.

However, the shutter developed so far had been a sheet of paper glued on top of an aluminium plate. It was a simple solution for first tests but it would not be a solution for a future sensor. Indeed, such a shutter was not stable in time. For example, for another shutter made of an aluminium plate and a sheet of paper, we computed changes in distances between targets up to $76\text{ }\mu\text{m}$ within 6 months (see Appendix F.44). In addition, the order of magnitude of the flatness of the paper surface was between 50 and $100\text{ }\mu\text{m}$, which might modify the shape of the laser spot and make the two-dimensional Gaussian fitting less accurate.

In order to improve the shutter, we decided to manufacture several of them from different materials like metal or ceramic, and to test them in terms of measurement precision. In addition, since the measurement process had been automatised thanks to the motorised micrometre table, we could perform the experiments over a longer range than $50\text{ }\mu\text{m}$, typically 2 mm . The present section aims at presenting these experiments.

3.3.2 Test with respect to shutter material

The first experiment of this series of experiments consisted of capturing pictures of laser spots on three types of shutters (one with paper surface and two with aluminium surfaces) and comparing the standard deviations of the laser spot coordinates as well as the differences with respect to their expected positions.

The setup used for this experiment was similar to that used for the initial tests (see Figure 3.5), especially for laser and camera (see Figures F.6, F.18 and F.20). Three types of shutter were used (see Figures F.23, F.24 and F.25). One aluminium shutter had targets with 2 mm diameter, the other aluminium shutter 3 mm . Each shutter was installed one after the other on the same plate as the camera in order to form a LAMBDA sensor. The LAMBDA sensor was set on the motorised micrometre table (see Figure F.3). A beam expander was added to the setup in order to be in the same conditions as the future LAMBDA system (see Figure F.13).

Thanks to the motorised micrometre machine, the LAMBDA sensor was set to different positions from $x = 0\text{ mm}$ to $x = 2\text{ mm}$ and back to $x = 0\text{ mm}$ in

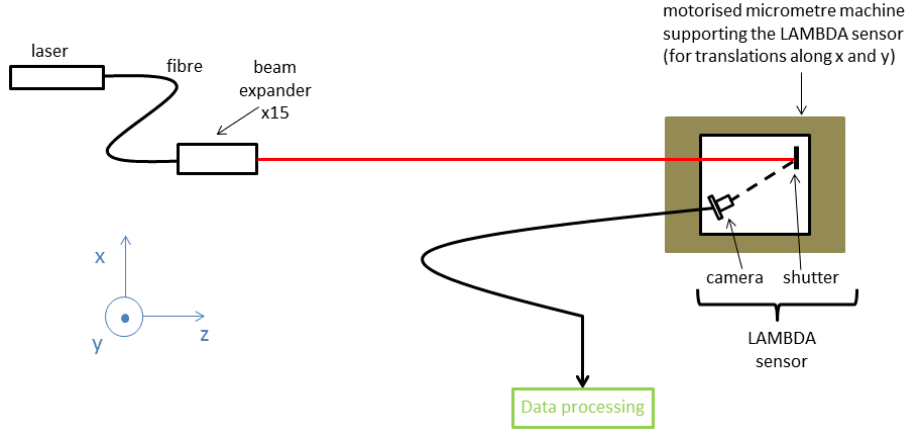


Figure 3.5: Setup used for the experiment at short distance.

steps of $10\text{ }\mu\text{m}$. For each position, a picture was captured. The coordinates of the laser spot centre were determined by Gaussian fitting and the coordinates of the target centres were determined by ellipse fitting. Distortion was corrected on all coordinates (the distortion parameters had been computed before the experiment during the camera calibration step). The transformation between camera and shutter used for this experiment was projective geometry. The values obtained for the laser spot coordinates on the shutter were centred around their mean values, considered as the expected values.

displacement	shutter	errors within		standard deviations below	
		x (mm)	y (mm)	x (μm)	y (μm)
radial	paper	50	40	16	8
	alu. 2 mm	50	80	10	30
	alu. 3 mm	50	60	10	25
vertical	paper	170	25	10	8
	alu. 2 mm	160	30	16	25
	alu. 3 mm	160	30	8	22

Table 3.1: Measurement accuracy and precision with respect to shutter type when the shutter is moved over 2 mm in radial (along the x axis) and in vertical (along y axis) direction. 'alu. 2 mm' (resp. 'alu. 3 mm') refers to the aluminium plate with targets of diameter 2 mm (resp. 3 mm)

As a result, we could notice that the errors between measured and expected laser spot coordinates varied within an interval of $50\text{ }\mu\text{m}$ (see Figures 3.6 and Table 3.1). The standard deviations were slightly larger for the x coordinate (below $16\text{ }\mu\text{m}$) than for the y coordinate (below $8\text{ }\mu\text{m}$). This was probably due to the fact that the displacement was performed along the x axis and not the

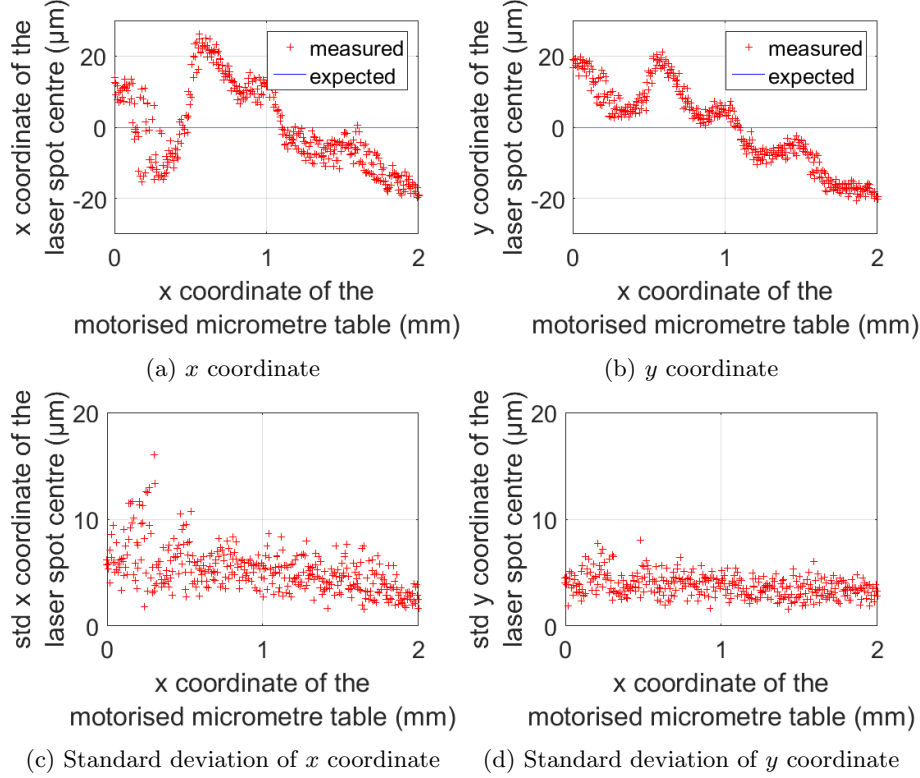


Figure 3.6: Measurement accuracy (top) and precision (bottom) when the LAMBDA sensor with paper surface is moved over 2 mm in radial direction (along x axis)

y axis. We performed similar experiments with the aluminium shutters and we could compare the results.

The paper surface gave slightly better results than the aluminium surfaces, but the variations of the laser spot coordinates combined with their standard deviations were larger than 10 μm , which was not satisfying for the CLIC project.

Since we observed significant differences in radial (x) and vertical (y) directions, we performed the same experiment by moving the LAMBDA sensor in vertical direction instead of the radial direction (see Table 3.1). We could notice that the variations of the laser spot coordinates combined with their standard deviations were still larger than 10 μm , which was not satisfying. In addition, we could see that the standard deviations of the aluminium plates were much larger in y direction than in x direction.

Since the standard deviations of the laser spot coordinates were larger in y direction than x direction for both displacements (along x axis and y axis), there had to be another reason why we observed such differences. We wanted to check what happened by rotating the aluminium shutters by 90°. We found

that the standard deviations were inverted. The standard deviations of the x coordinate remained below 25 μm whereas the standard deviations of the y coordinate remained below 10 μm . Subsequently, when we used the aluminium plates, the shutter orientation had a significant influence. This might be related to the way these shutters were produced. Indeed, contrary to paper, there was a direction of machining for the aluminium plate which had an impact on its inner structure.

To sum up, the paper surface gave better results than the aluminium surfaces in terms of standard deviations of the laser spot coordinates but the results were not stable in time, which was not satisfying for the future LAMBDA sensor. This explained why we performed complementary tests in order to find a more appropriate material.

3.3.3 Complementary tests with respect to shutter material

Before developing a prototype for the LAMBDA sensor, we wanted to quickly check different surfaces in order to see if we could find a better material than paper and aluminium for the shutter. These tests were done without targets on the surface, thus they were associated with high uncertainty. The transformation between camera and shutter was based on parameters of projective geometry found for the previous experiment 3.3.2. We tested several plates made of copper, epoxy, black glass, macor, alumina 99.7%, alumina 30%, sandblasted anodised aluminium and we got the results shown in Table 3.2.

Shutter type	Standard deviations below (μm)
Copper	70
Epoxy	10
Black glass	35
Macor (ceramic)	10
Alumina 99.7% (ceramic)	10
Alumina 30% (ceramic)	10
Sandblasted anodised aluminium	30

Table 3.2: Standard deviations of the laser spot coordinates with different types of shutter material.

Since ceramic plates (macor, alumina) seemed to give interesting results, we manufactured several ceramic plates with targets in order to test them.

3.3.4 Final test with paper, aluminium and ceramic

In the previous tests, we had already tested paper and aluminium plates. Since a quick test with ceramic plates gave encouraging results, we wanted to add targets on them and compare them with paper and aluminium. Subsequently, we prepared 3 shutters for this experiment, in paper, in aluminium and in

ceramic (see Figures F.23, F.25 and F.28). In the following, the aluminium plate will be referred to as metal plate. The goal of the experiment was to determine the most appropriate material for the shutter in terms of shutter flatness and laser pointing stability.

Shutter flatness was measured by the metrology lab of CERN. The metal had the best flatness ($15\text{ }\mu\text{m}$ - $16\text{ }\mu\text{m}$) followed by ceramic ($36\text{ }\mu\text{m}$ - $37\text{ }\mu\text{m}$) and paper ($30\text{ }\mu\text{m}$ - $110\text{ }\mu\text{m}$).

Laser pointing stability was measured in two configurations: (1) sensor at a fixed position and (2) sensor moving over 2 mm along the x axis (radial coordinate). Paper had the best laser pointing stability ($< 5\text{ }\mu\text{m}$) followed by ceramic ($< 6\text{ }\mu\text{m}$) and metal ($< 12\text{ }\mu\text{m}$). These results could be related to material roughness: for paper, it was $2.8\text{ }\mu\text{m}$ - $4.8\text{ }\mu\text{m}$, whereas for ceramic $1.4\text{ }\mu\text{m}$ - $2.2\text{ }\mu\text{m}$ and for metal $0.1\text{ }\mu\text{m}$ - $0.9\text{ }\mu\text{m}$. More details about this experiment can be found in [Stern et al., 2014a].

To sum up, ceramic showed a good compromise between paper and metal surfaces.

3.3.5 Conclusion

We performed a series of experiments in order to determine an appropriate material for the shutter of the future LAMBDA sensor. Our first idea (paper) gave relatively satisfying results in terms of laser pointing stability but presented drawbacks in terms of flatness and stability over long term. Our second idea (metal) was better in terms of flatness and stability over long term but did not show a good laser pointing stability. Our third idea (ceramic) presented a good compromise between paper and metal.

Thus, for the future LAMBDA sensor, we would recommend to use ceramic for the shutter (see also Section 4.2).

3.4 Experiments over long distance

3.4.1 Introduction

In the previous sections, we tested the LAMBDA sensor with the laser beam propagating over short distance, namely up to 3 m (see Sections 3.2 and 3.3). Short distance propagation had the advantage of reducing the uncertainty due to laser beam propagation and allowed to focus on the performance of the LAMBDA sensor.

However, the CLIC project requires pre-alignment of its components over 200 m, which means that the laser beam has to propagate over 200 m. This requirement makes us face two challenges. First, laser theory says that a laser beam diverges over long distance (see Subsection 2.2.3). Since we want the LAMBDA sensor to be compact (see Subsection 1.3.3), we need to make sure that the diameter of the laser beam remain within few centimetres over 200 m. Second, laser theory says that the position of the laser beam varies because of

the instability of the laser source and because of air refraction during laser beam propagation. Since we want to align CLIC components with $10\text{ }\mu\text{m}$ over 200 m , we need to estimate laser pointing stability over 200 m .

To meet these two challenges, we performed two experiments. In the first experiment, we let the laser beam propagate in air over 200 m and we computed the laser beam diameter as well as the laser pointing stability. In the second experiment, we let the laser beam propagate in vacuum over 35 m and we computed the laser pointing stability. In the second case, the distance of propagation was limited by the size of the vacuum pipe.

3.4.2 Experiment in air over 200 m

Experiments at short distance were done in an optical lab. Due to space restrictions, experiments over long distance were carried out in the geodetic base at CERN (see Figure F.5). A rail of 50 m was available in the geodetic base. We set the laser source at one end of the rail and we installed the LAMBDA sensor on a plate that could move along the rail. Since we wanted the laser beam to propagate over 200 m , we added three mirrors at the ends of the rail. The LAMBDA sensor could be rotated of 180° around the y axis so that the laser spot could be seen by the camera for all distances of propagation between 0 m and 200 m . A schematic overview of the experiment setup is given in Figure 3.7.

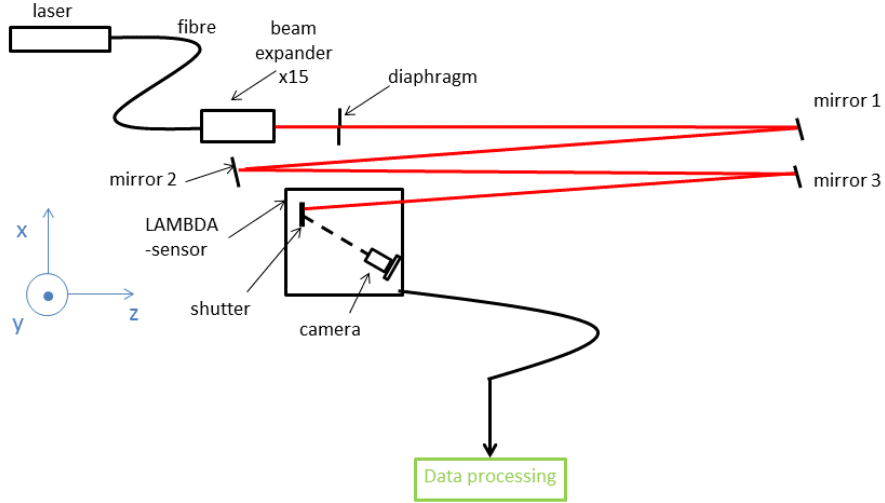


Figure 3.7: Setup for experiments over 200 m . The distance between the laser source and mirror 1 was 50 m .

We used the same laser, camera and shutter as in the previous experiment but we added mirrors to the setup (see figures F.6, F.13, F.18, F.20, F.23, F.16, respectively).

We set the LAMBDA sensor at different positions so that the laser beam propagated from 0 m to 200 m in steps of 5 m. For each position, 40 pictures were captured. Laser spot coordinates were extracted by Gaussian fitting and target coordinates by ellipse fitting. The transformation between camera and shutter was based on projective geometry.

A first outcome of the experiment dealt with the luminosity in the geodetic base. Since it was not the same for all distances of propagation, some targets were not detected at all. To solve this issue, we selected an appropriate threshold background for each distance of propagation and we defined small areas where the targets had to be detected. This was a calibration step that will be needed for all future experiments. Also, we added a diaphragm to the setup in order to filter the laser beam and produce a signal that was close to a two-dimensional Gaussian beam.

As a result, we could see the evolution of the laser beam shape over 200 m (see Figure 3.8). The diameter of the laser beam decreased over the first 50 m of propagation from 2 cm to 1 cm and then increased over the last 150 m of propagation from 1 cm to 4 cm. The order of magnitude obtained with this experiment agreed with the order of magnitude expected in theory (see study regarding beam expander in Appendix A).

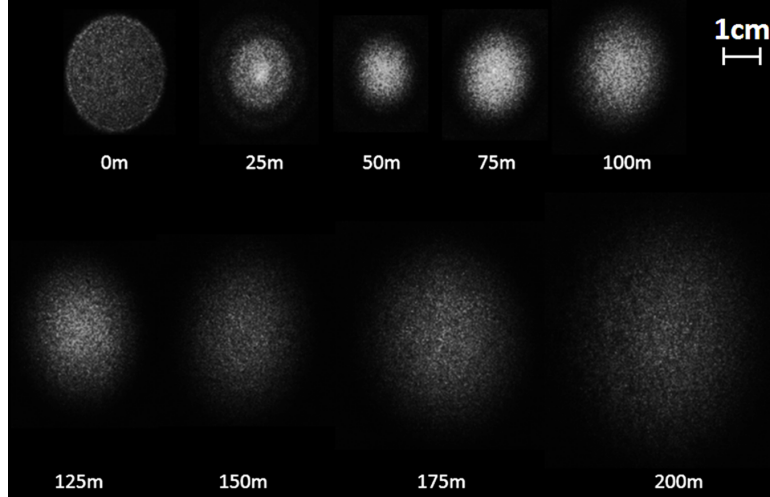


Figure 3.8: Laser beam shape with respect to distance

Besides the laser beam divergence, the other important result from the current experiment dealt with laser pointing stability over 200 m (see Figure 3.9, picture on the left). We could see that the standard deviations of the laser spot coordinates increased by approximately 100 μm every 10 m. These values were much above the CLIC requirements (10 μm over 200 m). Thus, we had to improve the setup, for instance with a vacuum pipe.

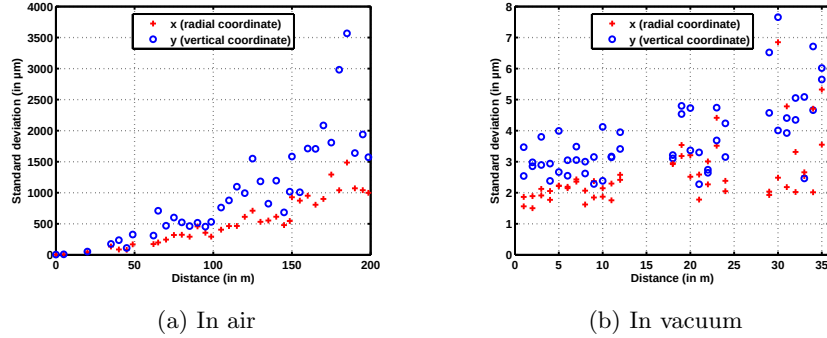


Figure 3.9: Laser pointing stability with respect to distance of propagation (warning: different scales for the x and y axes)

3.4.3 Experiment in vacuum over 35 m

We performed the experiment in vacuum in the geodetic base because a vacuum pipe was available there. It was conceived and implemented by Sébastien Guillaume for the development of a deflectometer [Guillaume et al., 2014]. The length of the vacuum pipe was 12 m.

A schematic view of the experiment setup is given in Figure 3.10. By means of 2 mirrors, we could make the laser beam propagate over 36 m. The cameras and the shutter were installed on a plate that was attached on top of a movable chariot. The chariot could move along x and z so that the laser spot could be observed either by camera 1 or by camera 2 for any distance of propagation between 0 m and 36 m.

The material used for experiments in vacuum are described in the appendix: vacuum pipe, laser, mirrors, shutter, two identical camera chips and two identical camera lenses (see Figures F.31, F.8, F.16, F.26, F.19 and F.21, respectively). Compared to the experiment in air, we used a different laser and camera. The change of the laser was due to the fact that the laser used by S. Guillaume was still available and mounted in front of the vacuum pipe, so it was easier to use it. The change of the camera was due to the connection cable. Indeed, in the optical lab, the distance between camera and computer was about 3 m, which allowed a USB connection. On the contrary, in the vacuum pipe, the distance between camera and computer went up to 12 m, which required another type of connection, for instance with an Ethernet cable. Thus, we selected two cameras with characteristics similar to the camera used in the optical lab but having an Ethernet port.

We set the LAMBDA sensor at different positions so that the laser beam propagated from 0 m to 35 m in steps of 1 m. For each position, 40 pictures were captured. Laser spot coordinates were extracted by Gaussian fitting and target coordinates by ellipse fitting. The transformation between camera and shutter was based on projective geometry.

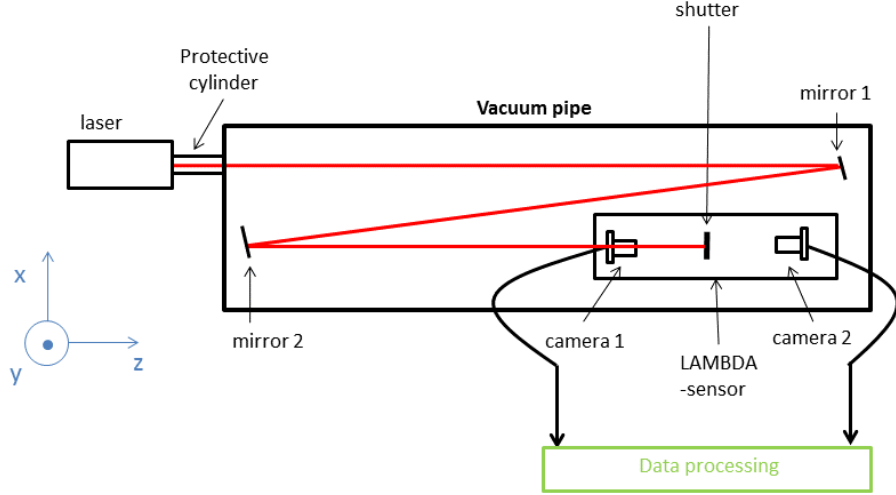


Figure 3.10: Setup for experiments in vacuum over 35 m. The distance between the laser source and mirror 1 was 12 m.

We have to notice that, when the LAMBDA sensor was close to one end of the rail, it sometimes interrupted the laser beam before the reflection on the mirror. This is why we could not get measurement results for the distances of propagation between 13 m and 17 m as well as between 25 m and 28 m.

We obtained results regarding the laser pointing stability over 35 m (see Figure 3.9, picture on the right). For a distance of propagation of 35 m, the standard deviations of the laser spot coordinates were much smaller in vacuum (below $8\text{ }\mu\text{m}$) than in air (below $200\text{ }\mu\text{m}$).

In addition, we performed a least-squares adjustment of the measurements in vacuum with a straight line and we extrapolated it for a distance of propagation of 200 m. Since the mirrors added uncertainty to the measurement process, we performed the least-squares adjustment only over the first 12 m. At 200 m, we found a standard deviation of $9.9 \pm 3.2\text{ }\mu\text{m}$ for the x coordinate and a standard deviation of $8.5 \pm 6.5\text{ }\mu\text{m}$ for the y coordinate. These results were encouraging because they were in the order of magnitude of the requirement of the CLIC project ($10\text{ }\mu\text{m}$ accuracy over 200 m).

3.4.4 Conclusion

We performed experiments over long distance in order to test laser beam divergence and laser pointing stability over 200 m. We found that the diameter of the laser beam could be kept smaller than 4 cm using a beam expander with a magnifying power of 15. We also confirmed the need for a vacuum pipe for the future LAMBDA system. Indeed, when the laser beam propagated in air, the standard deviations of the laser spot coordinates were up to 2 mm at 200 m,

which was much above the CLIC requirement ($10\text{ }\mu\text{m}$ over 200 m). On the contrary, using a vacuum pipe allowed to have standard deviations below $8\text{ }\mu\text{m}$ at 35 m . When we extrapolated the vacuum values up to 200 m , we found standard deviations in the order of magnitude of the CLIC requirement.

Complementary details of experiments over long distance were given in the IPAC paper [Stern et al., 2014b].

3.5 Experiments regarding measurement accuracy

3.5.1 Introduction

With the experiments presented in Sections 3.3 and 3.4, we could improve the design of the LAMBDA sensor in terms of size and measurement precision. However, for the final LAMBDA sensor, we needed to have an idea not only of the measurement precision but also of the measurement accuracy. This is why we performed a complementary series of experiments in order to estimate the measurement accuracy.

3.5.2 Scale factor behaviour

Experiments regarding measurement accuracy were done in the optical lab. The setup was similar to that used for experiments regarding the shutter (see Figures F.10, F.13, F.3, F.29, F.18 and F.20). A schematic overview of the setup is given in Figure 3.11.

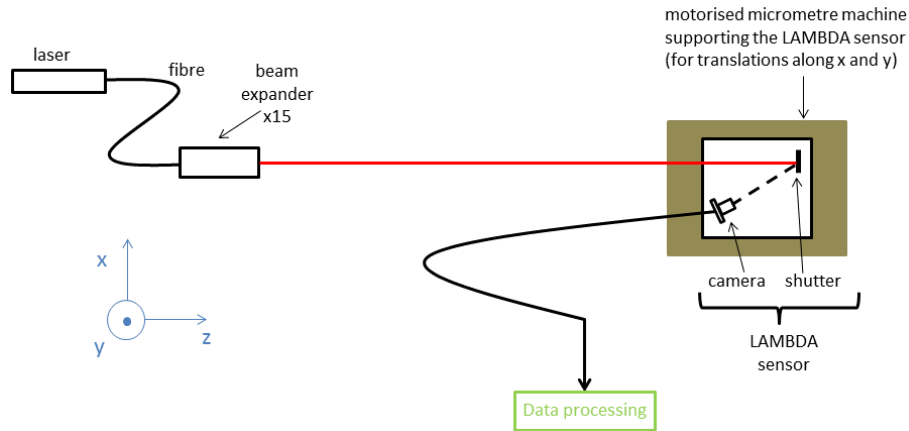


Figure 3.11: Setup used for experiments regarding measurement accuracy.

We set the LAMBDA sensor on the motorised micrometre machine. We moved the LAMBDA sensor to 121 positions (from $x = -1\text{ mm}$ to $x = +1\text{ mm}$

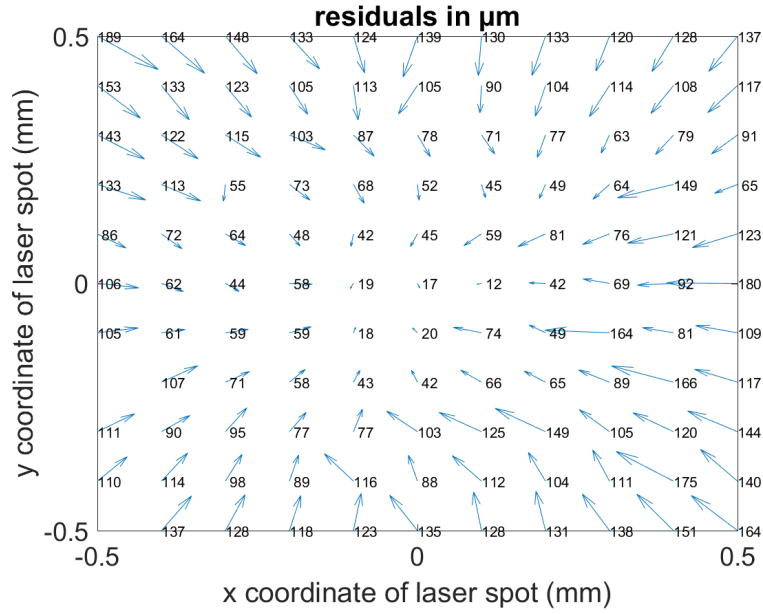
and from $y = -1\text{ mm}$ to $y = +1\text{ mm}$ in steps of 0.1 mm). For each position, we captured one picture. Laser spot coordinates were extracted by Gaussian fitting and target coordinates by ellipse fitting. The transformation between camera and shutter was based on projective geometry. Finally, we performed a least-squares adjustment with three parameters (2 translations along x and y axes and 1 rotation around z axis) between theoretical (given by the motorised micrometre table) and measured positions and we plotted the residuals (see Figure 3.12 as well as Appendix E, report 2).

We could see that the measured values were less spread than the theoretical values, as if there was a scale factor between them. Residuals were between $10\text{ }\mu\text{m}$ and $200\text{ }\mu\text{m}$, which was far above the order of magnitude required by the CLIC project ($5\text{ }\mu\text{m}$).

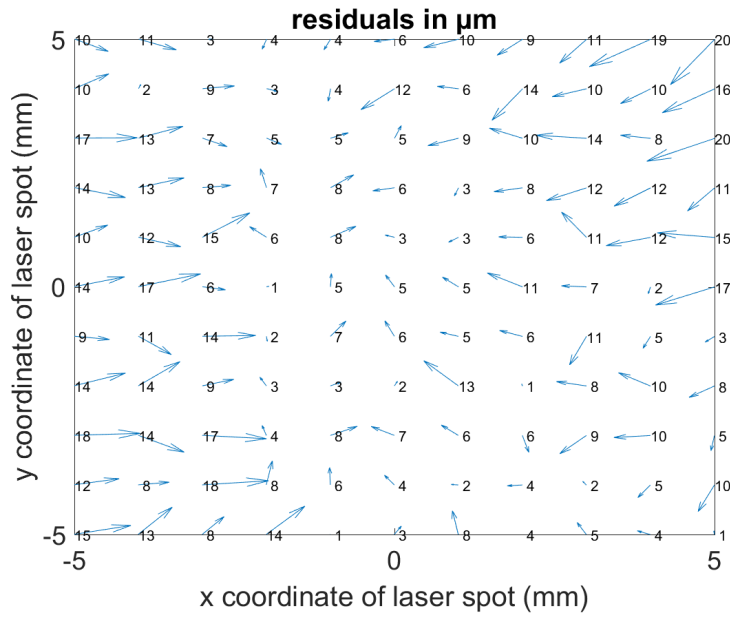
To understand why we got such results, we performed several tests (see Appendix E, reports 3 to 8). Even though the tests did not allow to remove the scale factor shown by the residuals, they brought us to the idea that the problem might come from the Gaussian fitting algorithm, which did not determine the laser spot centre accurately. Indeed, when the camera observed the laser spot pattern from the side, the energy of the laser spot was not distributed like a perfect two dimensional Gaussian curve. On the contrary, the energy profile was distorted, which implied that the determination of the laser spot centre was not accurate. To minimise the effect of the Gaussian fitting algorithm, we decided to reduce the laser spot by removing the beam expander.

The setup used for the experiment with the collimator was similar to that with the beam expander (see Figure 3.11), except that we replaced the beam expander by the collimator (see Figure F.12) and we moved the motorised micrometre table over a longer range (10 mm instead of 1 mm). As a result, even though the displacement range was longer, we obtained smaller residuals but still showing a scale factor (see Figure 3.12 as well as Appendix E, report 9).

Again, we performed several tests to understand why we got such results (see Appendix E, reports 10 to 21). A test with a longer measurement range (25 mm instead of 10 mm) also showed a scale factor between theoretical and measured values (report 11). Another test showed a good repeatability of the laser spot positions when the displacement protocol was repeated 3 times (report 13). Indeed, the standard deviations of the laser spot coordinates were $1.1\text{ }\mu\text{m}$ for x and $1.3\text{ }\mu\text{m}$ for y . A complementary test with the thin ceramic plate described in F.28 gave slightly better results than the thick ceramic plate described in F.29 (report 19). Thus, for the rest of the experiments regarding measurement accuracy, we used the thin ceramic plate. Finally, a test with 5 different camera positions showed that the scale factor behaviour was always present (report 21).



(a) With beam expander



(b) With collimator

Figure 3.12: Residuals in μm between theoretical (given by the motorised micrometre table) and measured (given by the camera and image processing) values, when a beam expander (top) and a collimator (bottom) were used.

3.5.3 Depth correction

If we considered that the laser beam reflection did not take place on the shutter surface but within the shutter, then we could explain the scale factor phenomenon. Indeed, when a laser beam hits a shutter made of ceramic or paper, it penetrates into the material before being reflected [Choudhury, 2014].

A schematic overview of the reflection in depth is presented in Figure 3.13. The laser beam reflection takes place on a virtual plane behind the shutter surface.

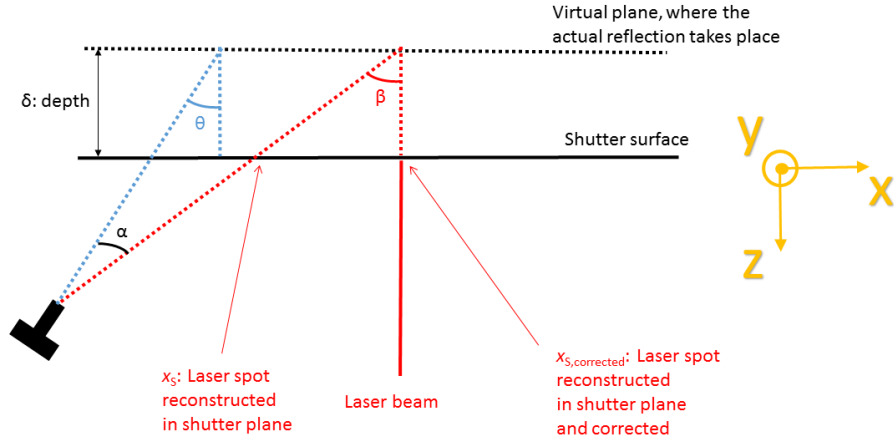


Figure 3.13: Laser beam reflection within the material and not on the surface requires a correction for the laser spot coordinates. Here, only the radial coordinate is represented (along x axis).

Based on this model, we could correct the coordinates of the laser spot centre. For the perspective projection, the solution was to replace $z_s = 0$ by $z_s = \delta$. For the projective geometry, we wrote a small function taking into account the angles β_x (in radial) and β_y (in vertical) between the reflected light beam and the normal to the shutter. This function was based on geometry and resulted in following corrections:

$$x_{\text{corr}} = \delta \cdot \tan(\beta_x) \quad (3.1)$$

$$y_{\text{corr}} = \delta \cdot \tan(\beta_y) \quad (3.2)$$

Both angles β_x and β_y were calculated from the angles θ_x and θ_y between the camera axis and the normal to the shutter, as well as from the angles α_x and α_y between the light beam and the camera axis.

Thus, we corrected the laser spot coordinates for several depth coordinates and we found an optimal value for δ minimising the residuals (see Appendix E, reports 22 and 33). We did this for all camera positions. Apart from an outlier, the optimal values were contained between $-56 \mu\text{m}$ and $-44 \mu\text{m}$, thus

we chose $\delta = -50 \mu\text{m}$ for the rest of the test. Integrating this value into the model improved the residuals and made the scale factors disappear (see Figure 3.14). In addition, the standard deviations of the residuals were below $6 \mu\text{m}$ for all camera positions.

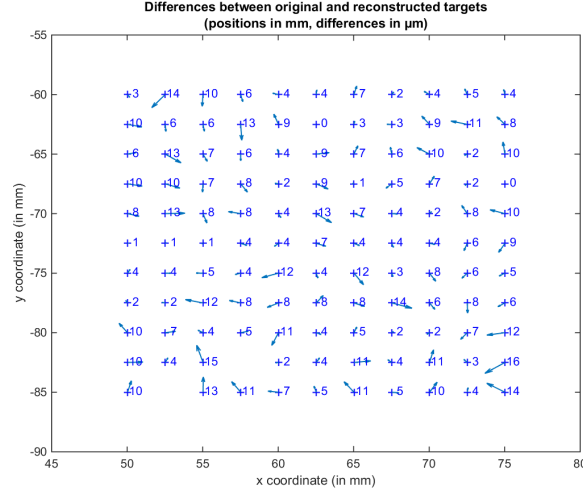


Figure 3.14: Residuals between theoretical and measured values, when the laser spot coordinates are corrected because of reflection in depth.

The experiment presented in this section was done with projective geometry. Later, we improved the software by replacing projective geometry by perspective projection. We integrated the depth value δ into the least squares adjustment and we could estimate it again. For the ceramic shutter, we found a value of $\delta = -69.3 \mu\text{m}$ and an uncertainty of $3.5 \mu\text{m}$. For the paper surface of the open/close shutter, we found a value $\delta = 51.7 \mu\text{m}$ and an uncertainty of $24.9 \mu\text{m}$. The positive value might be surprising but it was related to the flatness of the paper surface. The targets used to define the shutter coordinate system were located below the average plane of the shutter. Thus the laser beam reflection occurred on a plane with a positive coordinate.

3.5.4 Comparison projective geometry / perspective projection

The subsection regarding depth correction (see Subsection 3.5.3) required the knowledge of the exterior orientation of the camera with respect to the shutter. If the transformation used between camera and shutter was projective geometry, the parameters of the exterior orientation could be computed based on the 8 parameters of projective geometry (see [Horn, 1999] as well as Appendix E, reports 23 to 24).

However, in the same article, B. Horn pointed out that the best model for

a camera was perspective projection. Indeed, only 6 parameters were required for this camera model, whereas projective geometry contained 8 parameters. In other words, projective geometry compensated for errors that should not be compensated.

We performed several tests comparing projective geometry and perspective projection. In a first iteration, we did not find satisfying results for perspective projection (see Appendix E, reports 25 to 30). It turned out that camera calibration should not be done before the experiment on a different calibration plate but rather at the beginning of the experiment with the experiment plate. In a second iteration, we wrote a program that does the camera calibration on the experiment plate (see Appendix E, reports 31 to 32). Besides parameters of the interior and exterior orientation of the camera, we could calculate uncertainties associated with target coordinates and laser spot coordinates. We found that, if the laser spot was located in the area between the targets, it could be reconstructed with $4\text{ }\mu\text{m}$ uncertainty using 1 camera position. Increasing redundancy by using up to 5 camera positions made the uncertainty decrease to $2\text{ }\mu\text{m}$.

Finally, we showed that, even though projective geometry was not the most appropriate model for a camera, it could be useful in our application (see Appendix E, report 33). Projective geometry provided indeed a good first approximation for the least-squares algorithm, which helped its convergence [Horn, 1999, Horn, 2000].

Subsequently, for future tests, we recommend to combine projective geometry (in a first iteration) and perspective projection (in next iterations).

3.5.5 Conclusion

With experiments regarding measurement accuracy, we noticed that the residuals between theoretical values (given by the motorised micrometre machine) and measured values (reconstructed from pictures captured by the camera) contained a scale factor behaviour. We showed that we could correct the scale factors with a model, where the laser beam reflection takes place at a plane with a different z coordinate than the average plane of the shutter. For the ceramic shutter, this optimal z coordinate was estimated at $-69.3\text{ }\mu\text{m}$ with $3.5\text{ }\mu\text{m}$ uncertainty. Subsequently, we found standard deviations below $6\text{ }\mu\text{m}$ for the residuals.

Since this model required the accurate knowledge of the radial and vertical angles between camera plane and shutter, we worked on the transformation between camera and shutter. Projective geometry turned out not to be the most accurate model for a camera, even though it could provide a good initial set of parameters. On the contrary, perspective projection gave satisfying results in terms of residuals. In addition, perspective projection delivered uncertainties of the reconstructed laser spot coordinates below $4\text{ }\mu\text{m}$.

3.6 Experiments regarding repositioning

3.6.1 Introduction

So far, we had performed experiments with fixed shutter in order to have a simple experiment and minimise uncertainty due to shutter stability. However, the future LAMBDA sensor will have an open/close mechanism for the shutter displacement, which will bring additional uncertainty in the measurement process. More precisely, the future LAMBDA sensor will be made of a shutter and a frame, both pieces equipped with targets. The shutter is the element, where the laser spot appears and the frame is the element attached to the CLIC component to be aligned.

Since the laser spot centre is reconstructed in the shutter coordinate system but has to be determined in the frame coordinate system, the transformation between shutter and frame needs to be determined. However, with the open/-close mechanism, the transformation between shutter and frame may change after each open/close cycle.

We considered two methods to solve this issue. On the one hand, we could perform a separate calibration step with theodolites before the measurement. On the other hand, we could capture 1 picture with the LAMBDA sensor and estimate the parameters of transformation between shutter and frame based on the targets. We called this method full camera auto-calibration because it estimated all parameters together, from image to shutter and from shutter to frame. The present section aims at presenting results obtained with both methods.

3.6.2 Description of the experiment

Experiments regarding repositioning were done in the optical lab with the help of V. Vlachakis. The setup was similar to that used for the experiments regarding the shutter. A schematic overview of the setup is given in Figure 3.15 and a picture of the real setup is given in Appendix F.4.

The material used for experiments regarding repositioning was similar to that used for the experiments regarding measurement accuracy, except two things. First, we used the LAMBDA sensor with the mobile shutter (see Appendix F.29). Second, we set a theodolite (LEICA, TDA 5005) on each side of the measurement bench in order to capture pictures of the LAMBDA sensor from different angles. This helped us determine accurately not only the radial (x) and vertical (y) coordinates of the targets but also their depth (z) coordinates.

We set the LAMBDA sensor on the motorised micrometre machine, but we did not move it throughout the experiment. Since measuring all target centres with the two theodolites took quite a long time (around 15 min), we decided to perform 8 repetitions in order to finish the series of measurements within 2h. Between two repetitions, we performed an open/close cycle of the shutter. The pictures captured by the theodolites were processed by QDaedalus in order to extract the target centres [Guillaume, 2015]. From both sets of pictures, the

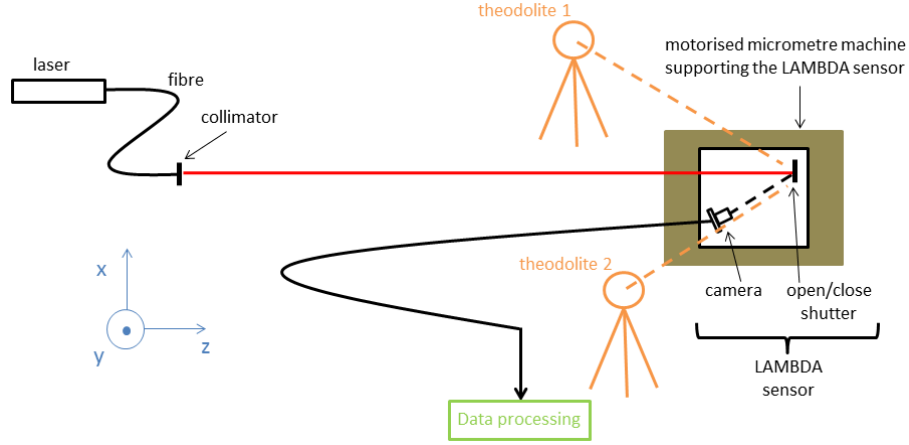


Figure 3.15: Setup used for experiments regarding repositioning.

software reconstructed the target positions in 3 dimensions.

A preliminary result was the measurement precision of the theodolites. It remained in the range 1 - 2 μm , which was satisfying. In addition, if we removed outliers, the target centres were determined with 1 μm uncertainty for the radial and the vertical coordinates and with 5 μm uncertainty for the depth coordinate. Finally, this led us to estimate the transformation parameters between the shutter coordinate system and the frame coordinate system. In parallel, we captured a picture with the LAMBDA sensor, performed a full camera auto-calibration and estimated the same parameters of transformation. As a result, we could see that the values were of a similar order of magnitude but uncertainties were much smaller, when doing a separate calibration with theodolites (see Tables 3.3 and 3.4). However, results obtained for the parameters t_y and a_y showed differences that were much larger than the associated uncertainties. These systematic effects could not be explained. They might be related to the fact that we had two theodolites but only one LAMBDA sensor. Having two different angles instead of one might result in a different lightening of the targets and a different image processing.

	Translation vector (in μm)			Rotation angles (in μrad)		
	t_x	t_y	t_z	a_x	a_y	a_z
theodolites	-15684.5	-6713.2	-30.8	-2060.1	1595.0	-12564.8
auto-calib.	-15688.0	-6739.9	-49.0	-2514.7	3197.6	-12540.8

Table 3.3: Estimated values of the parameters between frame and shutter (auto-calib. is the full camera auto-calibration)

	Translation vector (in μm)			Rotation angles (in μrad)		
	$u(t_x)$	$u(t_y)$	$u(t_z)$	$u(a_x)$	$u(a_y)$	$u(a_z)$
theodolites	0.2	0.2	0.3	6.4	7.1	4.8
auto-calib.	7.3	4.5	16.8	341.4	308.6	119.8

Table 3.4: Estimated uncertainties of the parameters between frame and shutter (auto-calib. is the full camera auto-calibration)

3.6.3 Conclusion

The last series of experiments done within the PhD thesis dealt with repositioning. We could show that the measurement uncertainty in the position of the shutter with respect to the frame is larger for the z coordinate ($5\mu\text{m}$) than for the x and y coordinates ($1\mu\text{m}$). In addition, this experiment allowed us to compute the parameters of the transformation between shutter and frame, necessary for the image processing. We found that performing a separate calibration with theodolites brought less uncertainty than a full camera auto-calibration. This type of experiment will be used for calibration (see Section 4.3).

3.7 Conclusion

We performed several experiments during the PhD thesis. They were useful for the development and the validation of the LAMBDA sensor.

On one hand, they helped us design step-by-step the hardware and the software of the LAMBDA sensor. Concerning the hardware, we selected among different cameras and shutters the most appropriate material in terms of measurement precision and accuracy. We prepared an automatised setup in order to collect data in an easy and fast way. Concerning the software, experiments led us to use perspective projection, which is more accurate than projective geometry.

On the other hand, experiments provided us estimates for measurement precision and accuracy in different configurations. When the laser beam propagated over short distance (about 2 - 3 m), we found a measurement uncertainty of $4\mu\text{m}$ for the coordinates of the laser spot centre on the shutter surface. When the laser beam propagated over long distance in vacuum (about 35 m), we found a measurement precision below $8\mu\text{m}$. If we extrapolated the results of the first 12 m over 200 m, we found a measurement precision around $10\mu\text{m} \pm 6.5\mu\text{m}$, which is the order of magnitude of the requirement of the CLIC project.

Finally, we developed a prototype with open/close shutter and we tested it. We estimated the parameters of transformation between shutter and frame. We found that a separate calibration with theodolites brought less uncertainty than a full camera auto-calibration.

Chapter 4

Sensor implementation

4.1 Introduction

The LAMBDA project consists of studying and developing a new type of sensor for a laser-based alignment. The previous chapters mainly dealt with the *studying* part, like theoretical aspects regarding laser beam propagation, interaction laser beam/material and image processing. The present chapter is about the *developing* part, which means the concrete design of the future sensor.

4.2 Sensor design

4.2.1 Introduction

The present section is based on what we learnt from theory as well as from experiments. It takes into account sensor requirements that were defined in Subsection 1.3.3: the sensor has to be compact ($10\text{ cm} \times 10\text{ cm} \times 10\text{ cm}$), low-cost, with $5\text{ }\mu\text{m}$ accuracy and $1\text{ }\mu\text{m}$ repeatability. It also tackles the fact that, since 50,000 LAMBDA sensors are foreseen within the CLIC project, the production of sensors need to be optimised (e.g. type of material, fabrication method). Finally, this section provides ideas for experiments in order to further improve the sensor.

4.2.2 General description

The LAMBDA sensor is made of a camera, a frame with targets and an open/-close shutter with targets. All these elements are attached to the same support. A picture of the prototype developed during the PhD thesis is given in Figure 4.1. The following subsections give details about the hardware parts of the prototype.

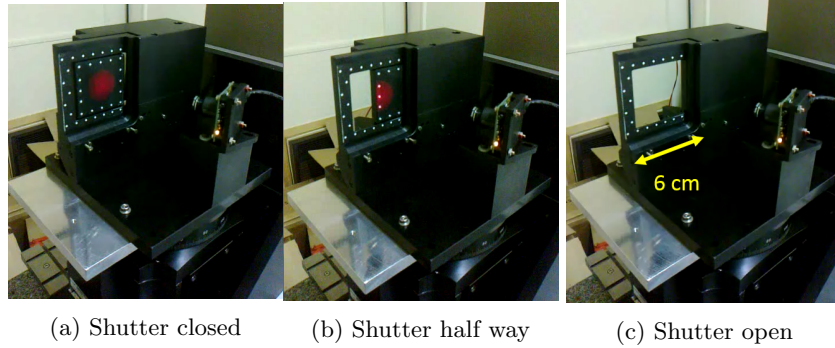


Figure 4.1: Prototype of the LAMBDA sensor with open/close shutter developed during the PhD thesis. It comprises a camera, a shutter with a square shape and a frame with a U shape (around the shutter). The red spot is the laser spot.

4.2.3 Camera

The camera is a key element of the LAMBDA sensor. Two types of camera chips were studied during the PhD thesis. The first one was used for tests at short distance (up to 3 m) in an optical lab as well as at long distance (up to 200 m) in a geodetic base in a tunnel (see Figure F.18). The second one was used for tests in a vacuum pipe (see Figure F.19).

Both cameras are produced by the same manufacturer (IDS imaging) and have similar characteristics. For example, the pixel size is $3.6\text{ }\mu\text{m}$ for the first type, $4.5\text{ }\mu\text{m}$ for the second. The resolution is 1024×1280 for the first type and 1200×1600 for the second. The main reason why we chose a different camera for the vacuum tests was the connection cable. Indeed, for tests in the optical lab or in the geodetic base, we could position the computer close to the LAMBDA sensor and use a USB cable. For tests in the vacuum pipe, the LAMBDA sensor had to move over 12 m, which was a distance too large for a USB connection. Thus, we had to choose a camera with Ethernet connection.

These camera chips have several advantages. They have small sizes (around $4\text{ cm} \times 4\text{ cm} \times 2\text{ cm}$), are relatively low-cost (around 500 CHF per unit) and they can be easily controlled over Labview.

In parallel to the camera chips, we had to select appropriate camera lenses, which forced us to make a compromise. Indeed, the smaller the focal distance, the smaller the distance between camera and shutter, and the more compact the LAMBDA sensor. At the same time, we have to remember that the camera has to be positioned on the side in order to let the laser beam propagate onto the shutter. Thus, the smaller the distance between camera and shutter, the larger the angle between camera axis and normal to the shutter plane, the more blurred the targets on the edges of the pictures.

To have a better idea of the impacts of these phenomena, we tested three lenses with different focal distances (6 mm, 12.5 mm and 25 mm) at the begin-

ning of the PhD thesis. In the end, the smallest focal distance gave the most satisfying results (6 mm). The distance between camera and shutter could be kept smaller than 10 cm, which meets the requirement of having a compact sensor. The angle between camera axis and normal to the shutter plane was about 30° , which limits the effect of blurred targets on the edges of the pictures.

In the end, we chose a camera lens with a focal distance of 6 mm for the experiments in the optical lab and the geodetic base (see Figure F.20). For the camera in the vacuum pipe, since the type of camera chip was slightly different, we had to adapt the camera lens with a focal distance of 8 mm (see Figure F.21). In both cases, the distance between camera and shutter was around 10 cm.

To sum up, the cameras used for the experiments in the optical lab, in the geodetic base and in the vacuum pipe were satisfying in terms of performance, size and price. However, these cameras are not radiation hard, which prevents us from using them in an environment like CLIC. This aspect should be further studied for the future sensor (see also Subsection 4.2.6).

4.2.4 Shutter and frame

Like the camera, the shutter and the frame are key elements of the LAMBDA sensor. The shutter is the small plate that is positioned across the beam in order to have a laser spot on its surface. The frame is around the shutter and is used to make the link between the magnet coordinate system and the shutter coordinate system. Both are visible on the prototype of Figure 4.1.

The shutter and the frame have targets on their surfaces in order to define coordinate systems for both elements. When we capture pictures of the shutter and the frame, we can compute the target centres by image processing and adjust them with the ones measured by the metrology lab. Based on this adjustment, we can determine the transformation between camera coordinate system and shutter coordinate system as well as the transformation between shutter coordinate system and frame coordinate system. In the end, we can compute the position of the laser spot centre in the frame coordinate system. Since the frame coordinate system is directly related to the magnet coordinate system, we can derive the position of the laser spot centre in the magnet coordinate system.

The production of shutter and frame raises several questions. What type of material should be used for them? How many targets should be present on them? What shapes for the targets, what colours for the background and the targets?

First, the flatness of the material is important. Indeed, the laser spot can occupy a quite large area on the shutter (diameter up to 4 cm). If the shutter surface is not flat, the laser spot shape may be distorted. This can lead to errors when determining the coordinates of the laser spot centre by two-dimensional Gaussian fitting. Metal plates or glass would be good candidates in terms of flatness. Second, if we want to see the laser spot with the camera, the shutter material should allow diffuse reflection. Indeed, in case the shutter reflects the light in only one direction (specular reflection), the camera might not see the

laser spot at all. Paper sheet or ceramics would be good candidates in terms of diffuse reflection

We performed an experiment to compare paper, metal and ceramic shutters (see Chapter 3). As a result, ceramic presented a good compromise in terms of flatness and measurement precision.

Compared to the shutter, the frame has less constraints. There is no need of diffuse reflection of the laser beam on the frame. However, in order to compare targets on the frame and targets on the shutter by image processing, it is better to have the same material and the same types of targets for both.

Finally, the target issue remains open for the shutter and for the frame. First of all, are targets needed for all elements? Since the frame coordinate system is linked with the magnet coordinate system, the targets are necessary on the frame. For the shutter, it depends on the method we choose. If we reconstruct the coordinates of the laser spot centre from camera to shutter, and then from shutter to frame, targets are needed on the shutter. If we can guarantee the repositioning of the shutter at micrometre level with respect to the frame, we could remove the targets on the shutter. But this requires an additional calibration step and brings additional constraints for the open/close mechanism.

Concerning the target shapes, disks have interesting properties. If the camera axis is not perpendicular to the shutter plane (or to the frame plane), disks will be seen as ellipses. Ellipse fitting can be applied to determine the target centres.

Concerning the number of targets, there must be enough to compute the parameters of the transformation between camera and shutter (or camera and frame). For example, if 16 parameters have to be determined (10 for interior orientation and 6 for exterior orientation), at least 8 targets (and thus 16 coordinates) are needed. In practice, more targets can be added to increase the redundancy of the system.

Concerning the target positions, they should be spread as much as possible all over the shutter and the frame in order to determine the transformation accurately. If a large region of the picture does not contain targets, the transformation will probably not work correctly in that region.

4.2.5 Open/close mechanism

As presented in Subsection 1.3.3, each LAMBDA sensor requires an open/close mechanism. Indeed, when the LAMBDA sensor performs a measurement, its shutter has to be closed. When it does not perform a measurement, its shutter has to be open in order to let the laser beam propagate until the next closed shutter.

To develop a prototype, our idea was in a first iteration to optimise the mechanics and use standard electronics and in a second iteration to optimise the electronics. Two evaluation criteria are important for the development of an appropriate open/close mechanism: its repositioning and its dynamics.

In case there are targets on the frame and on the shutter of the LAMBDA sensor, there are less constraints regarding repositioning. In case there are targets on the frame but not on the shutter, two conditions need to be fulfilled in order to have satisfying results. First, we need to know the position of the shutter with respect to the frame before the experiment. Second, the repositioning of the shutter after each open/close cycle has to be very accurate.

Indeed, if there is an error in the repositioning of the z position of the shutter, there will be errors in the estimation of the x and y positions of the laser spot centre (see Figure 4.2). These errors will be dependent on the repositioning error in z and on the reflection angle. In addition, if the x and/or y positions of the shutter change before and after an open/close cycle, the reflected beam might also change because of local irregularities of the shutter.

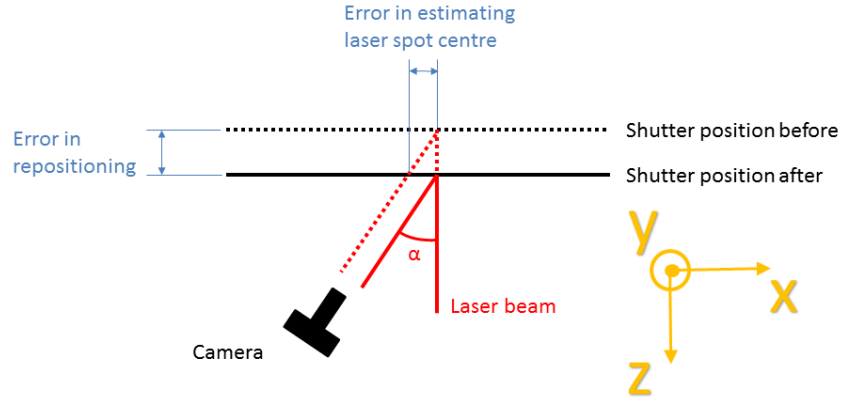


Figure 4.2: Without targets on the shutter, an error in repositioning implies errors in estimating the laser spot centre. For example, in our experiment, the reflection angle around y is close to 30° . Thus, an error of $1\text{ }\mu\text{m}$ in repositioning results in an error in estimating the x position of the laser spot centre of about $0.6\text{ }\mu\text{m}$.

Concerning the dynamics of the system, the original objective of the CERN survey team was 200 measurements every second, so that the alignment of CLIC components over 200 m can be checked every second. Such a frequency would mean 1 measurement every 5 ms, which is in practice impossible. First, capturing a picture lasts several tens to hundreds of milliseconds, depending on the light. Second, even if the picture capture was instantaneous, opening/closing the shutter within 5 ms would mean an acceleration of 8000 m s^{-2} [Sosin, 2012a]. A first solution would be to increase the total measurement interval. This may work as long as we can guarantee that the laser beam has not drifted during the measurement interval. A second solution would be to reduce the number of points being measured within the measurement interval, which means partial alignment check.

In any case, some ideas can be suggested regarding the open/close speed. The smaller the shutter mass, the less the vibrations, the smaller the size of the actuator and the best the dynamics [Sosin, 2012a]. In addition, we can open all shutters at the beginning of the measurement interval and close them one after the other, starting from the furthest shutter. Indeed, the shutters that are far away do not prevent the laser beam from propagating to the closer ones. In this case, we just need to close shutters and not to open them during a measurement interval.

We envisaged three solutions for the open/close mechanism. The first one consisted of having the shutter like a check valve that stops, when it touches the frame F.34. Such a system would have a good repositioning but the open/close movement would be slow. In addition, the fact that the shutter touches the frame would result in mechanical wear for both elements after several thousands of cycles. The second solution was a disk with a hole and a small control sensor F.35. It would have a good repositioning, little wear and a satisfying open/close speed. However, the size of the sensor would be quite large. The third solution consisted of putting the shutter on a rail and translating it between open and close positions. It would have a good repositioning, little wear and an acceptable size but it would be quite slow. In the end, since the repositioning of the open/close mechanism had a higher priority for the prototype tests than its speed, we chose the third solution, namely the shutter on a rail.

We considered then three solutions for the displacement of the shutter on the rail based on three different principles: (1) the printer mechanism, (2) the eccentric mechanism and (3) the voice coil mechanism. The first two solutions have two drawbacks. They have an open/close cycle of 200 ms and are not rigid. The third solution has an open/close cycle of 30 ms. In addition, it can control the position of the shutter on the rail by means of an encoder. In case it fails, it remains in open position and does not prevent the laser beam from propagating. However, it contains a magnet which can cause a leakage magnetic field and have an impact on external instrumentation. Such a phenomenon could be minimised by using mu-metal. In the end, we selected the third solution, namely the voice coil mechanism. It allowed us to have an uncertainty of shutter repositioning of about 2 μm in radial and vertical directions and 5 μm in depth (see Section 3.6).

4.2.6 Resistance to radiation

Radiation is a collateral phenomenon produced by CLIC components while accelerating the particle beam. Since radiation has an impact on CCD and CMOS based cameras, it has to be taken into account for the LAMBDA project.

Two types of radiation effects can be distinguished, namely cumulative effects and single event effects [Faccio, 2001]. Cumulative effects occur during the whole lifetime of an accelerator. They are characterised by TID (Total Ionising Dose) in case of ionisation and by displacement (fluence) in case of non-ionisation. On the contrary, single event effects are caused by single particles. They can occur at any time when an electronic device is used in a radiation

environment.

Simulations were performed to estimate radiation values in the future CLIC tunnel [Aicheler et al., 2012]. In the vicinity of the girder, where the LAMBDA sensors should be positioned, the simulations gave annual doses up to 4 kGy and annual fluences up to 10^{13} cm^{-2} .

Annual doses between 1 kGy and 10 kGy can have different impacts on cameras [Goiffon, 2015]. A CCD camera may not work from 1 kGy on, which means that, before using it, its behaviour with respect to TID has to be known or characterised. A CMOS camera works better for TID around 1 kGy but not towards 10 kGy. Logic circuits should resist but analog parts like ADC (Analog to Digital Converter) may be highly damaged.

Regarding displacement effects, annual fluences up to 10^{13} cm^{-2} cause a non-uniform increase of the dark current, which results in creating hot pixels (saturated pixels). An estimation of the dark current can be done with the model presented in [Virmontois et al., 2012]. With a depleted volume of the in-pixel photodiode of $5 \mu\text{m}^3$, an annealing coefficient of 7 weeks and a temperature of 22° , the mean of the distribution of the dark current is approximately $10 \text{ ke}^- \text{ s}^{-1}$ [Belloir, 2015]. In addition, such fluence values reduce the charge transfer efficiency of CCD cameras.

In terms of single event effects, CCD cameras are not affected but the electronics around may be damaged. In case of CMOS cameras, every type of single event effect is possible, depending on design and technology. In particular, single event upset and single event latchup may occur. These events can be controlled with correction and/or protection systems outside of the imaging system. For instance, a small additional circuit can switch off or limit the power supply in case of a significant increase of the current.

To solve radiation problems, we can come up with several ideas. First, several off-the-shelf CMOS cameras can be tested to check if one of them is satisfying. In particular, there is one hardened CMOS camera called STAR1000 that costs several thousands of CHF per unit. Second, developing a custom camera is another option. If done at CERN, such a study would probably cost between 200,000 and 1,000,000 CHF [Goiffon, 2015]. If a collaboration is established with ISAE (Institut Supérieur de l'Aéronautique et de l'Espace), the cost would be probably reduced since several prototypes have already been developed. For example, a hardened camera with 128×128 pixels is already available and another one with 1 megapixel should be ready in 2017-2018.

To sum up, radiation has a significant impact on LAMBDA sensors when used in an environment like CLIC. The main solution to limit radiation effects consists of hardening the LAMBDA sensors. However, there is still space for studies and improvements in this field.

4.2.7 Conclusion

In the section about sensor design, we gave recommendations for the fabrication of the LAMBDA sensor, based on what we learnt from experiments and from discussions with experts in mechanics or radiation. In particular, we suggested

a special type of camera as well as the best material we found for the shutter. We indicated how to design the targets (number, shape, positions) and where to put them. We presented the open/close mechanism used during the PhD thesis, which gave satisfying results in terms of repositioning. Finally, we summarised the advice regarding resistance to radiation. This is still a field, where improvement needs to be done. Indeed, the LAMBDA sensor developed during the PhD thesis is not radiation hard.

4.3 Sensor calibration

4.3.1 Introduction

Sensor calibration consists of all the preliminary measurements that have to be performed before using the sensor. Indeed, in the image processing part (see Section 2.4), we performed adjustments between targets measured in the metrology lab and targets captured by the camera. We also corrected the z coordinate of the laser spot centre because of the laser beam reflection at a different plane than the average plane of the shutter. We could not do these operations with only the pictures captured by the camera. On the contrary, we had to perform preliminary measurements on the sensor.

The present section describes all the steps of the LAMBDA sensor calibration. First, the frame targets need to be determined with respect to the kinematic mount and the shutter targets with respect to their own coordinate system, which can be done by the metrology lab. Second, we need to establish correspondences between targets coming from ellipse fitting and targets measured by metrology. Third, the correction factor due to laser beam reflection on a different plane than the average plane of the shutter needs to be estimated. Fourth, the repositioning of the shutter with respect to the frame needs to be estimated. Since the manufacturing of the LAMBDA sensors does not provide identical sensors, such a calibration process has to be done with each sensor separately.

4.3.2 Measure frame targets and shutter targets

Knowing the positions of the targets on the frame and on the shutter is necessary for adjusting them with the targets captured by the camera. For the frame, we need to determine the target centres with respect to the kinematic mount. For the shutter, we need to determine the target centres in their own coordinate system.

This can be done by the metrology lab and consists of two parts [Cherif and Glaude, 2015]. The sensor is put on its back so that the targets can be seen from above and the kinematic mount can be seen from the side. On one hand, the Coordinate Measuring Machine (CMM) mechanically measures the three balls of the kinematic mount and defines the sensor coordinate system. On the other hand, the CMM optically measures the target centres of the frame

and the shutter by ellipse fitting. It provides the 3D coordinates of the frame targets in the coordinate system of the kinematic mount. It also provides the 3D coordinates of the shutter targets in their own coordinate system. The uncertainty associated with this operation depends on the CMM and on the target circularity. For our prototype of the LAMBDA sensor, it was estimated to be smaller than $2\text{ }\mu\text{m}$ for the radial and vertical directions, and $5\text{ }\mu\text{m}$ for the depth.

As an output, the metrology lab delivers coordinates of the target centres in mm (see Appendix F.9). These coordinates are used for image processing (see Section 2.4).

4.3.3 Establish correspondences between targets

During the PhD thesis, we did not use coded targets, except for one calibration plate (see Appendix D). This has the drawback that we do not know in which order the targets are detected. For example, when the algorithm of ellipse fitting processes an image, it delivers as output the target centres in a specific order [Guillaume, 2011b], which is not necessarily the same as the order of the targets measured by metrology. Thus we have to establish correspondences between targets. This is done by capturing a picture with the camera, processing it with ellipse fitting and visually determining which target corresponds to which target. Each time we change the position of the camera with respect to the shutter and/or the frame, we have to re-establish correspondences between targets.

Such a calibration step could be avoided by adding coded targets on the shutter and on the frame. Another solution would be to organise the targets in a non-symmetrical way so that their identifications would be unambiguous.

4.3.4 Estimate correction factor due to reflection on a different plane than average plane

A calibration step is also needed to determine the correction factor due to the laser beam reflection on a different plane than the average plane. It consists of (1) installing a laser source, (2) placing the LAMBDA sensor at several known positions, (3) measuring the corresponding laser spot centres and (4) finding the optimal correction factor during the adjustment between theoretical and measured laser spot centres. We performed such a calibration step in the optical lab. We found a depth value of $-50\text{ }\mu\text{m}$ for a 2 mm thin ceramic shutter (see Section 3.5). In the following, we will provide more details about each step.

The first operation consists of installing a laser source in a stable environment, for example on a marble bench. The laser beam has to propagate up to the shutter of the LAMBDA sensor over a short distance to avoid air turbulences. In our experiments, the distance was about 2 m. The laser spot that appears on the shutter should be located between the targets and should not overlap with them.

The second operation consists of placing the LAMBDA sensor at several known positions. This can be done by means of a motorised micrometre table.

In our experiments, we used 11 positions for the radial coordinate over a range of 25 mm and 11 positions for the vertical coordinate over a range of 25 mm. Thus, we had 121 known positions. We chose a range of 25 mm by 25 mm because it allows the laser spot to visit different positions between the targets without overlapping with them.

The third operation consists of measuring the laser spot centres on the shutter surface for all sensor positions. This is achieved with the algorithm described in Section 2.4. After this step, we have a set of coordinates in the shutter coordinate system. If we adjust them with the theoretical positions given by the motorised micrometre table, we observe a scale factor.

The fourth operation consists of finding the optimal correction factor during the adjustment of the laser spot centres. It can be done by testing different depth values and computing the corresponding residuals. In this case, the minimum standard deviation of residuals provides the optimal depth. Otherwise, it can be done by adding a parameter during the adjustment between theoretical and measured values.

The outcome of this calibration step is the parameter z_s of the image processing (see Section 2.4).

4.3.5 Estimate shutter repositioning

The last calibration step aims at estimating the parameters of the transformation between shutter and frame as well as their uncertainties. These uncertainties are mainly due to shutter repositioning. As mentioned in Section 3.6, this can be done using theodolites or using a full camera auto-calibration. The theodolite method is described in the following. The full camera auto-calibration consists of adding parameters to the image processing and is not described here.

The calibration step consists of (1) installing the LAMBDA sensor at a fixed position, (2) installing two theodolites, one on each side of the LAMBDA sensor, so that they can see the targets on the shutter and on the frame, (3) capturing pictures of the targets with the theodolites, (4) opening and closing the shutter, (5) repeating steps (3) and (4) several times, (6) processing pictures and calculating the 3D coordinates of the targets and finally (7) determining the parameters of the transformation between shutter and frame as well as their uncertainties.

During the PhD thesis, we performed an experiment of repositioning with V. Vlachakis (see Section 3.6 and Appendix F.4). This experiment can be used as a model for the present calibration step.

The first operation consists of installing the LAMBDA sensor at a fixed position, for example on a marble bench. In our experiment, we set in on the motorised micrometre machine but we did not move it.

The second operation consists of installing two theodolites, one on each side of the LAMBDA sensor, so that they can see the targets on the shutter and on the frame. The idea is to determine not only the radial and the vertical coordinates but also the depth coordinate. Thus, the angle between the two theodolite axes should be around 90° .

The third operation consists of capturing pictures of the targets with the theodolites. It can be done with the software QDaedalus written by S. Guillaume [Guillaume, 2015]. In our experiment, this step lasted around 15 min.

The fourth step consists of opening and closing the shutter. It can be done remotely thanks to the software developed by M. Sosin [Sosin, 2012b]. It lasts approximately 10 s.

The number of repetitions of steps (3) and (4) depends on the desired accuracy. In our experiment, we chose 8 repetitions because it gave us enough data to compute uncertainties and it did not last too long (2h in total).

The sixth and the seventh steps consist of data analysis, which can be performed with a software package like MATLAB.

The outcome of the calibration step are the rotation matrix R_{SF} and the translation vector T_{SF} as well as their uncertainties, used in the image processing (see Figure 2.6).

We should notice that theoretically, this calibration step could be done with reference pictures captured by the camera of the LAMBDA sensor with different angles. This would avoid using theodolites but it would be also complicated to implement. Indeed, the camera would have to be set at different locations, which requires time to mount and unmount. In addition, for each reference picture, the correspondences between captured targets and metrology targets would have to be established again. Thus, during the PhD thesis, we chose to work with theodolites.

4.3.6 Conclusion

In the section regarding image processing, we became aware of the parameters that are missing for the reconstruction of the laser spot centre in the frame coordinate system (see Section 2.4). In the section regarding sensor calibration, we gave answers for the determination of these parameters. In particular, we described two calibration protocols for the estimation of the z coordinate of the laser spot centre in the shutter coordinate system and the estimation of the parameters of transformation between shutter and frame.

4.4 Measurement uncertainty of the sensor

The measurement uncertainty of the sensor can be computed from the uncertainties of the parameters involved in the reconstruction of the laser spot from camera to frame using a proper error propagation. In this section, we will deal with uncertainty in two steps, first the reconstruction from image to shutter, and then the reconstruction from shutter to frame.

In experiments regarding measurement accuracy (see Section 3.5), we could compute the coordinates of the laser spot centre in the shutter coordinate system with uncertainties below $4\text{ }\mu\text{m}$. In experiments regarding repositioning (see Section 3.6), we distinguished two cases. In case of a separate calibration with

theodolites, we could compute the parameters of transformation between shutter and frame with uncertainties below $0.3\text{ }\mu\text{m}$ for the translation vector and below $7.1\text{ }\mu\text{rad}$ for the rotation angles. In case of a full camera auto-calibration, these uncertainties amounted to $16.8\text{ }\mu\text{m}$ for the translation vector and up to $341.4\text{ }\mu\text{rad}$ for the rotation angles.

If we make the assumption that both sets of parameters (from image to shutter and from shutter to frame) are independent from each other, we can compute the uncertainties of the coordinates of the laser spot centre in the frame coordinate system. In case of a separate calibration, we find uncertainties below $4\text{ }\mu\text{m}$ for all coordinates. In case of a full camera auto-calibration, we find uncertainties up to $10\text{ }\mu\text{m}$ for the radial and the vertical coordinates and up to $20\text{ }\mu\text{m}$ for the depth coordinate.

The separate calibration allows us to meet the sensor requirements in terms of measurement accuracy (limit set at $5\text{ }\mu\text{m}$, see Subsection 1.3.3) but it has two drawbacks. It requires time to perform the calibration before the measurements and it requires an accurate repositioning of the shutter during the measurements. On the contrary, the full camera auto-calibration avoids the separate calibration step and does not need an accurate repositioning of the shutter, but it does not meet the sensor requirements.

However, we should notice that the uncertainties have been estimated on two different shutters: the ceramic shutter for the transformation from image to shutter and the paper shutter of the open/close sensor for the transformation between shutter and frame. In order to fully validate the future LAMBDA sensor, another prototype should be built combining ceramic shutter and open/close mechanism.

4.5 Conclusion

The present chapter dealt with the concrete implementation of the LAMBDA sensor. The first step consisted of fabricating LAMBDA sensors and was described in the sensor design. We gave recommendations for the hardware and discussed limitations as well as possible improvements. The second step consisted of calibrating the LAMBDA sensors. We explained which preliminary steps are necessary for a correct use of the sensors, in particular determining parameters that cannot be estimated accurately by the image processing. Finally, we focused on the measurement uncertainty of the sensor and we distinguished two cases. When a separate calibration was done with theodolites, the estimated uncertainty of the laser spot centre in the sensor coordinate system was $4\text{ }\mu\text{m}$. When a full camera auto-calibration was performed, the estimated uncertainty went up to $10\text{ }\mu\text{m}$ for the radial and the vertical coordinates and up to $20\text{ }\mu\text{m}$ for the depth coordinate.

Chapter 5

Conclusion

5.1 Summary of main results

The PhD thesis dealt with the study and the development of a laser-based alignment system for the Compact Linear Collider. It was launched in 2010 under the name *LAMBDA project*.

The idea is to have the laser beam under vacuum as a straight line reference and to use LAMBDA sensors as beam positioning sensors. A LAMBDA sensor is a new type of sensor comprising a camera, an open/close shutter and a frame. It can measure the radial and the vertical offsets of the laser beam with respect to the sensor coordinate system by means of image processing.

First, we analysed the problem from a theoretical point of view. We showed that the shape of the laser spot on the shutter can be described mathematically by a two-dimensional circular Gaussian curve corrupted by gamma noise. In addition, we presented two camera models, projective geometry and perspective projection. The first one is easy to implement but the second one is more accurate. Subsequently, projective geometry was used, when a good first approximation was needed, and perspective projection was used for the final adjustment. Then, we used the mathematical descriptions of the theoretical study to define the image processing. This part was necessary to reconstruct the coordinates of the laser spot centre from camera chip to frame coordinate system, which is also the sensor coordinate system. In addition, it made clear which parameters had to be determined by calibration.

After the theoretical study and image processing, we presented the experiments performed throughout the PhD thesis. On one hand, the experiments contributed to the implementation of the prototype LAMBDA sensor, in terms of hardware and of software. On the other hand, they delivered estimates of the sensor performance under different conditions. For example, an experiment at short distance (about 2 - 3 m) with a ceramic shutter gave 4 μm for the measurement uncertainty of the sensor in the shutter coordinate system. Another experiment at short distance using the prototype with open/close shutter

gave results in the frame coordinate system, which is also the sensor coordinate system. These results depended on the way of estimating the parameters of the transformation between shutter and frame. For a separate calibration with theodolites, an uncertainty of $4\text{ }\mu\text{m}$ was estimated for all coordinates. For a full camera auto-calibration, an uncertainty of $10\text{ }\mu\text{m}$ was estimated for the radial and the vertical coordinates and $20\text{ }\mu\text{m}$ for the depth coordinate. In addition, an experiment over long distance in vacuum (35 m) gave $8\text{ }\mu\text{m}$ for the measurement precision of the sensor. In particular, we stated that the total error budget of the laser-based alignment system should be in the same order of magnitude as the wire-based system, under the strong assumption that our extrapolation from 12 m to 200 m was correct.

Following the theoretical study and the experiments, we presented a chapter regarding the implementation of the future LAMBDA alignment system. The section about sensor design summarised suggestions for the fabrication of future LAMBDA sensors. In the section about sensor calibration, we explained how to determine parameters necessary for the image processing part. Such a calibration needs to be done for each future LAMBDA sensor. In the section about sensor uncertainty, we discussed the best results obtained through experiments.

5.2 Practical implementation of the LAMBDA alignment system within CLIC

Throughout the PhD report, we focused on the study and the development of the LAMBDA sensor. In the present section, we tackle its practical implementation into the whole alignment system.

First of all, we should notice that each CLIC component has 6 degrees of freedom. In the baseline, the alignment is done by means of articulation points, which requires to fix 3 degrees of freedom per component. This can be achieved by 1 LAMBDA sensor and 1 inclinometer. Apart from the baseline, we need to fix 5 degrees of freedom (3 rotations and 2 translations) in order to provide a correct alignment. The 6th degree of freedom that does not need to be determined with high accuracy is the translation along the propagation axis of the particle beam. Thus, the idea is to combine 2 LAMBDA sensors (each of them providing 2 coordinates in radial and vertical) and 1 inclinometer (providing 1 angle).

The practical implementation of the LAMBDA alignment system requires (1) to install LAMBDA sensors on top of metrological plates and girders and (2) to install a vacuum pipe between the sensors so that the laser beam propagates in a straight line. Like WPS, installing LAMBDA sensors on top of metrological plates and girders can be done with kinematic mounts.

Regarding the vacuum pipe, the solution is not straightforward. Indeed, the laser beam needs to be in the vacuum and the LAMBDA sensors need to be linked with the CLIC components. If the vacuum pipe is attached to the component and is rigid, then it will add a mechanical constraint on the CLIC

components. A solution would be to have bellows between the different parts of the vacuum pipe (see Figure 5.1, [Bestmann, 2014]). This solution would work if the LAMBDA sensors are attached on the CLIC components or on the metrological plates.

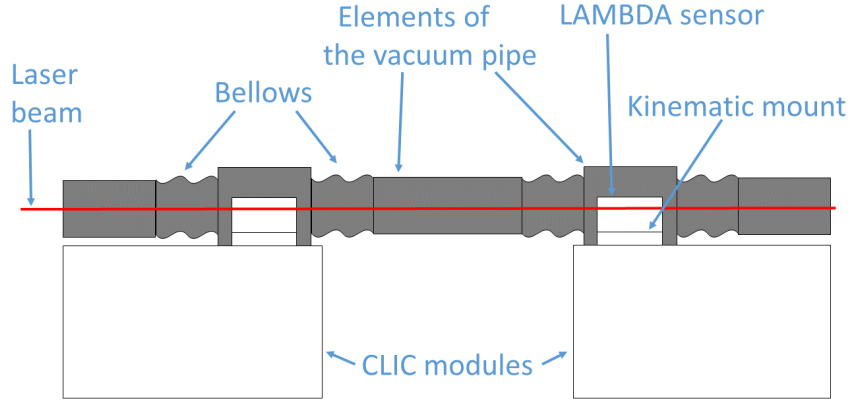


Figure 5.1: Proposition of vacuum pipe with bellows to avoid mechanical constraints from the vacuum pipe on the CLIC components

5.3 Full answer to the objective of the PhD thesis

The objective of the PhD thesis was to estimate the measurement accuracy of the LAMBDA system over 200m and to propose a prototype of a LAMBDA sensor (see Subsection 1.3.4). We presented the prototype in Chapter 3 and we estimated the measurement uncertainty of the sensor in Subsection 4.4 but we did not link it with the error budget of the whole alignment system mentioned in Subsection 1.3.2. The present section fills this gap.

For the wire-based system, we saw that five steps entered into the calculation of the total error budget. We can now compare it with the laser-based system.

The first step is about fiducialisation of the components with respect to their zeros. This does not depend on the sensor.

The second step deals with linking the component fiducials to the sensor interfaces. Since WPS and LAMBDA sensors have similar kinematic mounts, there is no difference between them.

The third step focuses on the link between kinematic mount and zero of the sensor. This occurs through a calibration step for both sensors (see Section 4.3 for the LAMBDA sensor). It consists of determining the target centres of the frame with respect to the three balls of the kinematic mount. It can be done at the metrology lab [Cherif and Glaude, 2015]. For our prototype of the LAMBDA sensor, the uncertainty related to this calibration step was estimated

smaller than $2\text{ }\mu\text{m}$ in radial and vertical directions, and smaller than $5\text{ }\mu\text{m}$ in depth.

The fourth step is about the measurement of the sensor with respect to the straight line. For LAMBDA sensors, it is done by image processing and it comprises uncertainties due to reconstruction from image to shutter as well as uncertainties due to repositioning (see Section 4.3). With a separate calibration, it was estimated at $4\text{ }\mu\text{m}$. With a full camera-auto-calibration, it was estimated at $10\text{ }\mu\text{m}$ in radial and vertical coordinates, and $20\text{ }\mu\text{m}$ in depth. For the WPS, it is estimated at $5\text{ }\mu\text{m}$.

The fifth and last step deals with the stability of the straight line. For the wire, it was estimated to be $10\text{ }\mu\text{m}$. For the laser beam, the experiment in vacuum allowed us to extrapolate laser pointing stability at $10\text{ }\mu\text{m}$ for a distance of propagation of 200 m (see Section 3.4). However, we have no concrete indication about the straightness itself. Our reasoning is based on laser theory stating that a laser beam propagates in a straight line but we did not confirm it experimentally.

In case our extrapolation over 200 m and our assumption regarding laser beam straightness are correct, the total error budget of the laser based alignment system should be in the same order of magnitude as that of the wire-based system.

However, these error budgets need to be confirmed by an inter-comparison between wire-based and laser-based alignment systems over 200 m . Indeed, since both systems are based on two different principles (mechanical for the wire, optical for the laser beam), if they give similar results in terms of positions and uncertainties, then they would mutually validate each other. To do this, a special experiment needs to be implemented with metrological plates containing WPS and LAMBDA sensors at the same time.

5.4 Outlook

Even though we took the first step towards a LAMBDA alignment system with the present PhD thesis, many questions remain open and research can be done in many fields.

5.4.1 Image processing

We assume in the thesis that the laser spot is a two-dimensional elliptical Gaussian curve on the camera chip and we reconstruct its centre from camera to shutter. A more accurate way of doing would be to reconstruct the signal intensity pixel-by-pixel and then adjusting the observations at shutter level with a two-dimensional circular Gaussian curve.

In addition, as mentioned in Section 4.3, an automatic target recognition can be implemented in order to eliminate the calibration step consisting of establishing correspondences between targets.

Furthermore, another improvement of the image processing would be to write the code in a different language than MATLAB, for example C++, in order to accelerate the calculations.

5.4.2 Experiments

At the level of the LAMBDA sensor, different experiments could be performed. We assumed throughout the PhD report that the shutter is flat, which is never the case in practice. The impact of flatness on the laser spot shape can be studied in more details. To minimise the impact of flatness, we could try to further improve the shutter by testing other materials. For example, white marble (like that used for the Taj Mahal) may have similar characteristics as ceramic in terms of laser pointing stability but may have a better flatness than ceramic. Besides, we could study the impact of temperature, pressure, magnetic and radiation on the LAMBDA sensor. Indeed, we tested the sensor at 20° in an environment without magnetic fields and radiation but the CLIC working temperature is 40° and its magnetic fields as well as its radiation are likely to damage the sensor.

At the level of the laser, we could try another laser beam with wide spectrum in order to avoid speckle and have an homogeneous Gaussian pattern.

At the level of the LAMBDA alignment system, we did not have time to develop a full system with a 200 m long vacuum pipe. This would be a necessary step to validate the full LAMBDA alignment system, in particular through inter-comparison with a wire-based alignment system.

5.4.3 Sensor design

At the level of the LAMBDA sensor, we could think of modifying the design. For example, adding a second camera would be an interesting option because it would decrease measurement uncertainty. However, this would imply an increase of the size of the LAMBDA sensor.

At the level of the LAMBDA alignment system, in order to increase the redundancy of the measurements, we could think of having two laser beams, so that we can see two laser spots on each LAMBDA sensor. However, this would also increase the size of the LAMBDA sensor. In addition, overlaps between laser spots could occur, which would also modify the LAMBDA sensor measurements.

5.4.4 Next steps

From all the possible ideas, the most important one is probably developing a LAMBDA alignment system over 200 m and comparing it to a wire-based and/or a water-based alignment system. Indeed, since each system is based on a different physical principle, they would validate each other mutually.

For the concrete development of such an experiment, the TT1 (Tunnel Transfer 1) at CERN would offer a good start because it contains a 140 m long vacuum

pipe. It does not have the required 200 m but it would allow us to make a more accurate extrapolation than the 12 m vacuum pipe of the geodetic base.

In a first iteration, a LAMBDA sensor could be set at different positions in the vacuum pipe between 0 m and 140 m. Similar to the experiments described in Section 3.4, the laser pointing stability could be estimated with respect to the distance of propagation of the laser beam.

In a second iteration, LAMBDA sensors, WPS and/or HLS could be mounted on the same metrological plates. These plates could be installed on displacement tables in order to move all sensors together. If the vacuum pipe of the TT1 is used, this would imply to develop special metrological plates enabling the links between the inside and the outside of the vacuum pipe. If such a development is too complicated to envisage for the TT1, an experiment with several sensors mounted on the same plates could be performed at least over short distance (2 m-3 m) in an environment like the optical lab at CERN.

Appendix A

Study of beam expanders

A.1 Introduction

In the LAMBDA project, we need to minimise the size of the laser beam over 200 m in order to minimise the size of the LAMBDA sensor. We can do this with a beam expander.

Different beam expanders exist with different magnifying powers. In the present study, we provide details regarding beam expanders, we simulate laser beam diameters over 200 m and we select two beam expanders that meet the requirements of our project. The theoretical aspects regarding beam expanders are extracted from the website of Edmund Optics.

A.2 Keplerian and Galilean beam expanders

A beam expander is the inverse of a telescope. Two types of beam expander exist: Keplerian and Galilean. A Keplerian beam expander has two focusing lenses. Since all the energy is concentrated in one point between both lenses, heating problems can occur around this point. A Galilean beam expander has a defocusing and a focusing lens. In this case, the energy is not concentrated in one single point. Therefore, Galilean beam expanders are often preferred to Keplerian ones.

A.3 Beam expander key-parameters

Beam divergence and beam diameter between input and output are linked through the following relationship:

$$MP = \frac{\theta_i}{\theta_o} = \frac{D_o}{D_i}$$

where MP is the magnifying power of the beam expander, θ the beam divergence and D the beam diameter (see Figure A.1).

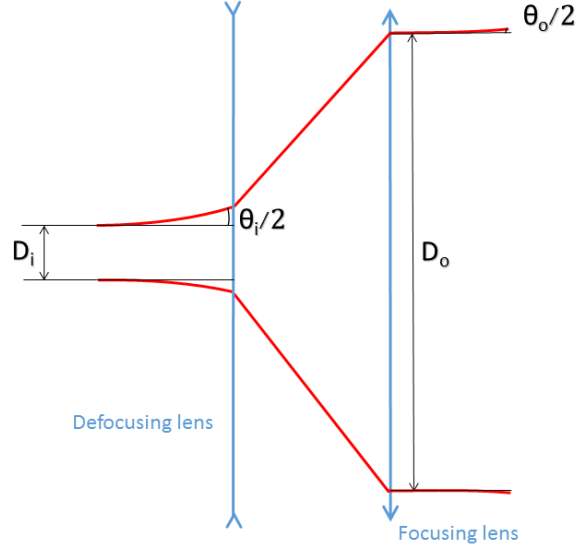


Figure A.1: Schematic view of a Galilean beam expander

The index i stands for input and the index o for output. It can be seen with this relationship that a smaller diameter means a larger divergence.

Moreover, if the beam is observed at a working distance L , then its diameter is given by the following equation:

$$D(L) = MP \cdot D_i + L \cdot \tan \frac{\theta_i}{MP}$$

A.4 Application to lab experiments

In the optical lab, the laser has a beam divergence $\theta_i = 0.66 \text{ mrad}$ and a beam diameter $D_i = 1.23 \text{ mm}$. Edmund Optics offers several beam expanders for HeNe laser with following magnifying powers: 3, 5, 10, 15 and 20. With such parameters, it is possible to compute the theoretical beam divergence at different working distances: 0, 50, 100, 150 and 200 m. Results are presented in Figures A.2 and A.3 (Figure A.3 is a zoom of Figure A.2).

Beam expanders of magnifying powers $\times 10$ and $\times 15$ are good compromises, because they allow to have laser beams with diameters stable between 1 cm and 3 cm.

A.5 Conclusion

For future experiments over long distance, we will buy beam expanders with magnifying powers $\times 10$ and $\times 15$.

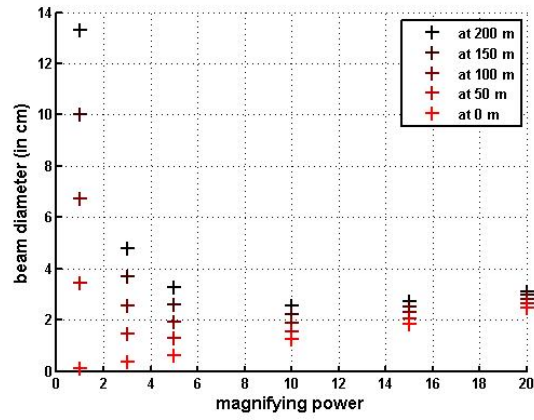


Figure A.2: Beam diameter vs magnifying power

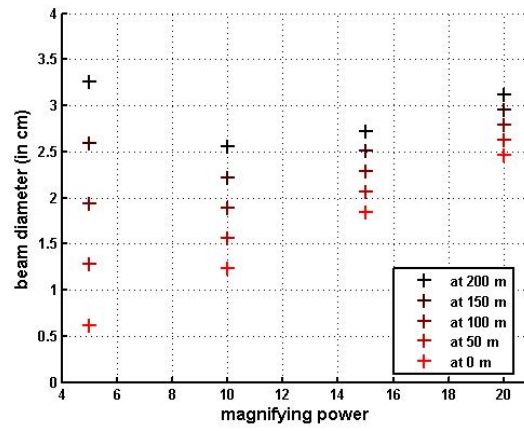


Figure A.3: Beam diameter vs magnifying power (zoom)

Appendix B

Calculations regarding laser spot on shutter

B.1 Introduction

In Section 2.2.3 about laser beam propagation, we showed that the intensity of the laser beam can be expressed mathematically as follows:

$$I(x_L, y_L, z_L) = I_0 \left(\frac{\omega_0}{\omega(z_L)} \right)^2 e^{-\left[\frac{2(x_L^2 + y_L^2)}{\omega(z_L)^2} \right]} \quad (\text{B.1})$$

with (x_L, y_L, z_L) any point in the laser coordinate system, I_0 the intensity at the origin point $(x_L, y_L, z_L) = (0, 0, 0)$, ω_0 the spot size at distance $z_L = 0$, $\omega(z_L)$ the beam size at distance z_L and z_0 the Rayleigh length.

We aim at demonstrating the mathematical form of the signal intensity when we put a shutter across the laser beam. In other words, we want to mathematically transform the signal intensity from the laser coordinate system to the shutter coordinate system.

The strategy is the following: first, we will define laser and shutter coordinate systems, and present the transformation between them. Second, we will study the beam size ω and show how to simplify its expression. Third, we will study the distance from the propagation axis $r^2 = x_L^2 + y_L^2$ and show how to pass from an expression describing a circle to an expression describing an ellipse.

B.2 Definition of laser and shutter coordinate systems

We have already defined the laser coordinate system with the z axis coinciding with the propagation axis and with the origin point where the beam size is minimal. Let us now define the shutter coordinate system so that the shutter surface

is located at $z_s = 0$ and the origin point at a random point, not necessarily on the propagation axis. Let us set the LAMBDA sensor across the laser beam, at a distance between 0 m and 200 m. Figure B.1 gives a schematic view of the laser and shutter coordinate systems.

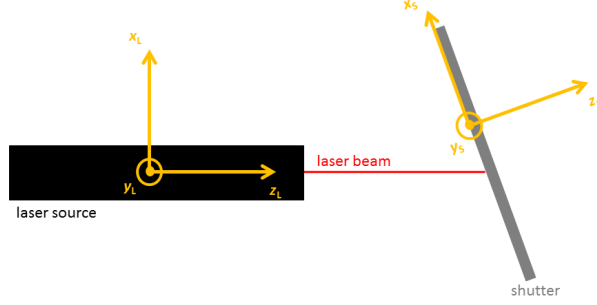


Figure B.1: Schematic overview of the laser coordinate system and the shutter coordinate system. Only a rotation around y axis is presented, but rotations around x and z axes are also possible.

Let us define the rotation matrix $R = \begin{pmatrix} r_{11} & r_{12} & r_{13} \\ r_{21} & r_{22} & r_{23} \\ r_{31} & r_{32} & r_{33} \end{pmatrix}$ and the translation vector $T = \begin{pmatrix} t_1 \\ t_2 \\ t_3 \end{pmatrix}$ characterising the transformation from the shutter coordinate system to the laser coordinate system so that:

$$x_L = r_{11}x_s + r_{12}y_s + r_{13}z_s + t_1 \quad (\text{B.2})$$

$$y_L = r_{21}x_s + r_{22}y_s + r_{23}z_s + t_2 \quad (\text{B.3})$$

$$z_L = r_{31}x_s + r_{32}y_s + r_{33}z_s + t_3 \quad (\text{B.4})$$

Since $z_s = 0$, we can simplify these equations to:

$$x_L = r_{11}x_s + r_{12}y_s + t_1 \quad (\text{B.5})$$

$$y_L = r_{21}x_s + r_{22}y_s + t_2 \quad (\text{B.6})$$

$$z_L = r_{31}x_s + r_{32}y_s + t_3 \quad (\text{B.7})$$

B.3 Study of the beam size

In this section, we want to transform the beam size from the laser coordinate system to the shutter coordinate system.

The beam size is defined as follows:

$$\omega(z_L) = \omega_0 \sqrt{1 + \frac{z_L^2}{z_0^2}} \quad (\text{B.8})$$

If we insert z_L of Equation B.7 into this equation and if we develop it, we obtain:

$$\omega(z_L) = \omega_0 \sqrt{1 + \frac{(r_{31}x_s + r_{32}y_s)^2}{z_0^2} + \frac{2(r_{31}x_s + r_{32}y_s)t_3}{z_0^2} + \frac{t_3^2}{z_0^2}} \quad (\text{B.9})$$

In order to simplify this expression, let us deal with the orders of magnitude of all terms. Since R is a rotation matrix, its elements are smaller than 1 in absolute values. x_s and y_s are smaller than 0.1 m in absolute values because they are limited by the size of the LAMBDA sensor. Furthermore, laser theory says that the Rayleigh length is defined as follows:

$$z_0 = \frac{\pi \omega_0^2 n}{\lambda} \quad (\text{B.10})$$

with ω_0 the minimum beam size, n the refraction index in air and λ the laser wavelength. In our application, we have:

$$z_0 = \frac{3.14 \times 1 \text{ cm}^2 \times 1}{633 \text{ nm}} \approx 500 \text{ m} \quad (\text{B.11})$$

Finally, the distance of propagation t_3 is comprised between 0 m and 200 m.

With these hypotheses, we see that the second and the third terms of Equation B.9 are negligible with respect to 1, which simplifies the formula as follows:

$$\omega(t_3) = \omega_0 \sqrt{1 + \frac{t_3^2}{z_0^2}} \quad (\text{B.12})$$

This relationship shows that, for a given distance of propagation t_3 , we can assume that the beam size is constant. Let us call it simply ω from now on.

B.4 Study of the distance from the propagation axis

In this section, we want to transform the numerator in the exponential of the signal intensity presented in Equation B.1 from the laser coordinate system to the shutter coordinate system. Let us call r the distance from the propagation axis.

$$r^2 = x_L^2 + y_L^2 \quad (\text{B.13})$$

If we combine this equation with Equations B.5 and B.6, we obtain:

$$r^2 = (r_{11}x_s + r_{12}y_s + t_1)^2 + (r_{21}x_s + r_{22}y_s + t_2)^2 \quad (\text{B.14})$$

If we develop this expression, we find:

$$\begin{aligned} r^2 = & (r_{11}^2 + r_{21}^2)x_s^2 + (r_{12}^2 + r_{22}^2)y_s^2 + 2(r_{11}r_{12} + r_{21}r_{22})x_sy_s \\ & + 2(t_1r_{11} + t_2r_{21})x_s + 2(t_1r_{12} + t_2r_{22})y_s + t_1^2 + t_2^2 \end{aligned} \quad (\text{B.15})$$

Since the column vectors of the rotation matrix R are unit vectors, their norms are 1 and their scalar products with each other are 0. Thus we can further simplify :

$$\begin{aligned} r^2 = & (1 - r_{31}^2)x_s^2 + (1 - r_{32}^2)y_s^2 - 2(r_{31}r_{32})x_sy_s \\ & + 2(t_1r_{11} + t_2r_{21})x_s + 2(t_1r_{12} + t_2r_{22})y_s + t_1^2 + t_2^2 \end{aligned} \quad (\text{B.16})$$

We can see that the squared distance from the propagation axis r^2 is a linear combination of x_s^2 , y_s^2 , x_sy_s , x_s , y_s and a constant. If we eliminate special cases where $r_{31}^2 = 1$ and/or $r_{32}^2 = 1$ (corresponding to shutter surface parallel to propagation axis), r^2 has the equation of an ellipse.

So far, we have worked with random rotations around the x , y and z axes. If we make complementary assumptions, we can simplify Equation B.16. Let us call a_x , a_y and a_z the rotation angles corresponding to the rotation matrix R (see [Slabaugh, 1999]).

The first assumption deals with the rotation around the z axis. Since the laser beam is symmetrical with respect to its propagation axis, we can arrange the laser coordinate system and the shutter coordinate system so that $a_z = 0$.

The second assumption deals with the rotations around the x and the y axes. Since the shutter is intended to be perpendicular to the propagation axis of the laser beam, we can assume that a_x and a_y are small with respect to 1. Thus, we can do a first-order approximation of the elements of R as follows:

$$R \sim \begin{pmatrix} 1 & 0 & a_y \\ 0 & 1 & -a_x \\ -a_y & a_x & 1 \end{pmatrix}$$

Equation B.16 becomes:

$$r^2 = x_s^2 + y_s^2 + 2(a_x a_y)x_sy_s + 2t_1x_s + 2t_2y_s + t_1^2 + t_2^2 \quad (\text{B.17})$$

Because of the small angle approximation, $2(a_x a_y)x_sy_s$ is negligible compared to $x_s^2 + y_s^2$, which allows us to simplify the expression. After factorising, we obtain:

$$r^2 = (x_s + t_1)^2 + (y_s + t_2)^2 \quad (\text{B.18})$$

In this case, we can see that the squared distance from the propagation axis r^2 has the equation of a circle, translated from the origin by $(-t_1, -t_2)$.

B.5 Conclusion

In this appendix, we wanted to calculate the mathematical form of a laser spot on a shutter with a random position and a random tilt.

On one hand, we showed that, for a given propagation distance, we can assume that the beam size ω is constant. On the other hand, we found that the squared distance from the propagation axis r^2 can be described by the equation of an ellipse in general case and by the equation of a circle in case of the small angle approximation.

Subsequently, in the ellipse case, we can define six parameters s_x , s_y , s_{xy} , x_{cent} , y_{cent} and a and rewrite the signal intensity Equation B.1 as follows:

$$\begin{aligned}
 I(x_s, y_s) &= a \cdot e^{-\left[\left(\frac{x - x_{\text{cent}}}{s_x} \right)^2 + \left(\frac{y - y_{\text{cent}}}{s_y} \right)^2 + \frac{2s_{xy}}{s_x s_y} \left(\frac{x - x_{\text{cent}}}{s_x} \right) \left(\frac{y - y_{\text{cent}}}{s_y} \right) \right]} \\
 &\quad (B.19)
 \end{aligned}$$

This equation corresponds to a two-dimensional elliptic Gaussian curve. The parameters s_x , s_y , s_{xy} , x_{cent} , y_{cent} and a depend on r_{31} , r_{32} , r_{31} , r_{32} , r_{31} , r_{32} , t_1 , t_2 , t_3 , I_0 , ω_0 and z_0 . The exact correspondences between these parameters can be determined by comparing Equations B.16 and B.19.

In the circle case, we can rewrite the signal intensity as follows:

$$I(x_s, y_s) = I_0 \left(\frac{\omega_0}{\omega} \right)^2 e^{-\left[\frac{2((x_s + t_1)^2 + (y_s + t_2)^2)}{\omega^2} \right]} \quad (B.20)$$

This equation corresponds to a two-dimensional circular Gaussian curve.

Appendix C

Simulation: extraction of laser spot centre coordinates with respect to algorithm

C.1 Introduction

The simulation objective is to model a laser spot corrupted by noise, to extract the coordinates of its centre with three different algorithms and to compare them. The tested algorithms are: (1) calculation of the centre of mass, (2) approximation of a two-dimensional Gaussian curve with least-squares method and (3) approximation of a two-dimensional Gaussian curve with maximum likelihood method. Three criteria are used to evaluate the algorithms: accuracy (root-mean-square error), bias and standard deviation.

C.2 Simulation of a laser spot pattern

The camera chip used for the experiments has 1024 rows and 1280 columns. However, since most of the energy of the laser spot pattern is concentrated in a limited area, the simulation is done with a reduced image of 300×300 pixels. This operation saves time during the estimation of parameters. In practice, the limited area has to be detected first before extracting the laser spot coordinates.

Thus, let us model the CCD chip as a matrix M with $n_{\text{rows}} = 300$ rows and $n_{\text{columns}} = 300$ columns. The laser spot pattern is imaged on that CCD chip.

As described in Section 2.2.4, the laser beam profile in a plane can be mod-

elled as a two-dimensional elliptical Gaussian curve:

$$I(x, y) = b + a \cdot \exp - \left[\left(\frac{x - x_{\text{cent}}}{s_x} \right)^2 + \left(\frac{y - y_{\text{cent}}}{s_y} \right)^2 + \frac{2s_{xy}}{s_x s_y} \left(\frac{x - x_{\text{cent}}}{s_x} \right) \left(\frac{y - y_{\text{cent}}}{s_y} \right) \right] \quad (\text{C.1})$$

with (x, y) the coordinates of any point of the plane, $(x_{\text{cent}}, y_{\text{cent}})$ the coordinates of the centre of the two-dimensional elliptical Gaussian curve (also the intensity peak), (s_x, s_y) parameters characterising how much the intensity is spread in x and y directions, s_{xy} the parameter characterising the orientation of the ellipse, (a, b) the scaling and background factors and $I(x, y)$ the beam intensity at point (x, y) .

The parameters are generated randomly at the beginning of the simulation in order to avoid particular cases. Their mean values and standard deviations are chosen so that the position of the simulated laser spot pattern is likely to be located in the middle of the CCD chip and so that its light intensity and size are likely to be similar to those observed during experiments (see code for more details in Section C.4).

In addition, as explained in Section 2.2.5, the noise due to speckle can be modelled by a gamma probability density function as follows:

$$p_s(I_s) = \frac{I_s}{\bar{I}^2} \exp \left(-\frac{I_s}{\bar{I}} \right)$$

In this case, the shape parameter of the gamma distribution is 2 and its scale parameter is the intensity $\bar{I}$.

Finally, in addition to the Gaussian beam and the gamma noise, the CCD saturation is modelled by setting an upper bound to intensity values at 255. Let i be the row index ($i \in \llbracket 1, n_{\text{rows}} \rrbracket$) and j the column index ($j \in \llbracket 1, n_{\text{columns}} \rrbracket$). The matrix elements $(Y_{\text{sat}})_{ij}$ are pixel values between 0 and 255 .

C.3 Algorithms

Once the laser spot pattern is created, noise added and intensity values limited to 255, the image can be processed by three different algorithms extracting the laser spot coordinates.

The first algorithm consists of finding the centre of mass, which is the weighted average of the pixel values. Mathematically, the coordinates of the centre of mass are:

$$\left\{ \begin{array}{l} x_{\text{centre of mass}} = \frac{1}{S} \sum_{i=1}^{n_{\text{rows}}} \left(i \sum_{j=1}^{n_{\text{columns}}} (Y_{\text{sat}})_{ij} \right) \\ y_{\text{centre of mass}} = \frac{1}{S} \sum_{j=1}^{n_{\text{columns}}} \left(j \sum_{i=1}^{n_{\text{rows}}} (Y_{\text{sat}})_{ij} \right) \end{array} \right\}$$

with the sum of all pixel values: $S = \sum_{i=1}^{n_{\text{rows}}} \sum_{j=1}^{n_{\text{columns}}} (Y_{\text{sat}})_{ij}$.

The second algorithm consists of approximating the laser spot pattern with a two-dimensional Gaussian curve and minimising the sum of squared errors. The two-dimensional Gaussian curve has seven parameters, two of them being the coordinates of the laser spot centres. The approximation is done with Newton's method.

The third algorithm also consists of approximating the laser spot pattern with a two-dimensional Gaussian curve but the optimisation is done with maximum likelihood method. To do this, the minimisation function takes the gamma noise into account. Two cases are tested: first the gamma distribution alone, second the gamma distribution truncated at the saturation level of the CCD. The functions to minimise over p are the following:

$$f_{\text{gamma}}(p) = \sum_{i=1}^{n_{\text{rows}}} \sum_{j=1}^{n_{\text{columns}}} \frac{(Y_{\text{sat}})_{ij}}{F_{ij}(p)} + 2 \ln (F_{ij}(p))$$

$$f_{\text{gamma truncated}}(p) = \left\{ \begin{array}{l} \text{if } (Y_{\text{sat}})_{ij} < b \\ \sum_{i=1}^{n_{\text{rows}}} \sum_{j=1}^{n_{\text{columns}}} -\ln (\text{dgamma}((Y_{\text{sat}})_{ij}, 2, F_{ij}(p))) \\ \text{if } (Y_{\text{sat}})_{ij} \geq b \\ \sum_{i=1}^{n_{\text{rows}}} \sum_{j=1}^{n_{\text{columns}}} -\ln (1 - \text{pgamma}(b, 2, F_{ij}(p))) \end{array} \right.$$

with F_{ij} the two-dimensional Gaussian curve without noise sampled at the CCD pixel elements (i, j) , $(Y_{\text{sat}})_{ij}$ the two-dimensional Gaussian curve corrupted by gamma noise and sampled at the CCD pixel elements (i, j) , p the vector of 7 parameters to be estimated, $b = 255$ the saturation level of the CCD, dgamma the gamma probability density function and pgamma gamma probability distribution function.

Each algorithm provides coordinates for the laser spot centre. Simulating 100 times the laser spot pattern results in 100 estimates of the coordinates of the laser spot centre. Based on them and since the true value of the laser spot centre is known, accuracy, bias and standard deviation can be computed.

C.4 Code

The main function used for the simulation is the following:

```
1 ## SIMULATION GAUSSIAN FITTING
2
3 # Removing all variables
4 rm(list=ls())
5
6 # Starting clock
7 ptm = proc.time()
8
9 # Sourcing cost functions
10 source("Gamma7paracost.R")
11 source("GammaTruncated7paracost.R")
12 source("Gaussian7paracost.R")
13
14 # Sourcing additional functions
15 source("computeCentreOfMass.R")
16 source("Gaussian7paraij.R")
17 source("computeAccuracyBiasStDev.R")
18
19 #####
20 # DEFINITION OF CAMERA PARAMETERS
21
22 nb_pixel_x = 300 # Number of pixels in x direction (CCD chip width)
23 nb_pixel_y = 300 # Number of pixels in y direction (CCD chip height)
24 max.intensity = 255 # Maximal intensity before CCD saturation
25
26 #####
27 # SIMULATION:
28 # -GENERATING LASER SPOT PATTERN
29 # -ADDING GAMMA NOISE
30 # -EXTRACTING LASER SPOT COORDINATES
31
32 # Defining bounds for parameters of the 2D Gaussian curve
33 # a, b, xp, yp, sx, sy, sxy
34 lb = c( 80, 0, 101, 101, 40, 40, -100) # Lower bound
35 ub = c( 160, 10, 200, 200, 80, 80, 100) # Upper bound
36
37 # Defining parameters of the 2D Gaussian curve
38 a = runif(1, min = lb[1], max = ub[1])
39 b = runif(1, min = lb[2], max = ub[2])
40 xp = runif(1, min = lb[3], max = ub[3])
41 yp = runif(1, min = lb[4], max = ub[4])
42 sx = runif(1, min = lb[5], max = ub[5])
43 sy = runif(1, min = lb[6], max = ub[6])
44 sxy = runif(1, min = lb[7], max = ub[7])
45 para = c(a,b,xp,yp,sx,sy,sxy)
46
47 # Defining parameters of the 2D Gaussian curve for first approximation
48 para.initial = (lb + ub)/2
49
50 # Computing intensity profile of the 2D Gaussian curve
51 Fij = outer(1:nb_pixel_x, 1:nb_pixel_y, Gaussian7paraij, para)
52 #image(Fij)
```

```

53 |
54 | # Defining number of simulations
55 | N = 3
56 |
57 | # Initialising vector of results containing estimates of (xp,yp) for
    | the following algorithms:
58 | # -centre of mass
59 | # -least-squares-method
60 | # -maximum likelihood method with gamma
61 | # -maximum likelihood method with gamma truncated at saturation level
    | of CCD chip
62 | estimates_xp_yp = matrix(NA,N, 8)
63 |
64 | for (n in 1:N){
65 |
66 |   # Computing intensity profile corrupted by gamma noise
67 |   Yij=matrix(rgamma(nrow(Fij)*ncol(Fij), 2, scale=Fij),nrow(Fij),ncol(
    | Fij))
68 |
69 |   # Computing intensity profile saturated at 255 (due to camera chip)
70 |   Yijsat=Yij
71 |   Yijsat[Yijsat>max.intensity] = max.intensity
72 |   #image(Yijsat)
73 |
74 |   # Extracting laser spot coordinates with centre of mass method
75 |   cm = computeCentreOfMass(Yijsat)
76 |   estimates_xp_yp[n,1:2] = cm
77 |
78 |   # Extracting laser spot coordinates with least-squares-method
79 |   out_gaussian = nlmnb(para.initial, Gaussian7paracost, Yij=
    | Yijsat, lower=lb, upper=ub)
80 |   estimates_xp_yp[n,7:8] = out_gaussian$par[3:4]
81 |
82 |   # Extracting laser spot coordinates with maximum likelihood method (
    | based on gamma noise)
83 |   out_gamma = nlmnb(para.initial, Gamma7paracost, Yij=
    | Yijsat, lower=lb, upper=ub)
84 |   estimates_xp_yp[n,3:4] = out_gamma$par[3:4]
85 |
86 |   # Extracting laser spot coordinates with maximum likelihood method (
    | based on gamma noise, truncated at b=255)
87 |   out_gamma_tr = nlmnb(para.initial, GammaTruncated7paracost, Yij=
    | Yijsat, b=max.intensity, lower=lb, upper=ub)
88 |   estimates_xp_yp[n,5:6] = out_gamma_tr$par[3:4]
89 | }
90 | #####
91 | # PROCESSING SIMULATION RESULTS
92 |
93 | # Computing accuracy, bias and standard deviation
94 | a_b.sd = matrix(NA,4,6)
95 | colnames(a_b.sd) = c("accuracy x","accuracy y","bias x","bias y","st.
    | dev. x","st. dev. y")
96 | rownames(a_b.sd) = c("centre of mass", "gamma", "gamma truncated", "
    | gaussian")
97 | a_b.sd[1,] = round(computeAccuracyBiasStDev(estimates_xp_yp[,1],
    | estimates_xp_yp[,2],xp,yp),2)
98 | a_b.sd[2,] = round(computeAccuracyBiasStDev(estimates_xp_yp[,3],

```

```

    estimates_xp_yp[,4],xp,yp),2)
99 a_b.sd[3,] = round(computeAccuracyBiasStDev(estimates_xp_yp[,5],
    estimates_xp_yp[,6],xp,yp),2)
100 a_b.sd[4,] = round(computeAccuracyBiasStDev(estimates_xp_yp[,7],
    estimates_xp_yp[,8],xp,yp),2)
101
102 # Displaying graphs
103 image(Fij)
104 hist(Yijsat,255)
105 image(Yijsat)
106
107 #####
108 # Stopping clock
109 proc.time() - ptm

```

The cost functions are the following ones:

```

1 ## COST FUNCTION BASED ON GAMMA NOISE AND 7 PARAMETERS
2 Gamma7paracost = function(para, Yij){
3
4     Fij = outer(1:nrow(Yij), 1:ncol(Yij), Gaussian7paraij, para)
5
6     return(sum( Yij/Fij + 2*log(Fij)))
7 }

```

```

1 ## COST FUNCTION BASED ON GAMMA NOISE TRUNCATED AND 7 PARAMETERS
2 GammaTruncated7paracost =function(para, Yij, b){
3
4     Fij = outer(1:nrow(Yij), 1:ncol(Yij), Gaussian7paraij, para)
5
6     binary_variable = (Yij<b)
7
8     return(sum(-log(dgamma(Yij, 2, scale=Fij)*binary_variable + (1-
9         binary_variable) * (1-pgamma(b, 2, scale=Fij)))))
10 }

```

```

1 ## COST FUNCTION BASED ON GAUSSIAN NOISE AND 7 PARAMETERS
2 Gaussian7paracost=function(para, Yij){
3
4     Fij = outer(1:nrow(Yij), 1:ncol(Yij), Gaussian7paraij, para)
5
6     return( sum( (Yij-Fij)^2 ) )
7 }

```

Additional functions were used to make the simulation simpler:

```

1 ## FUNCTION COMPUTING CENTRE OF MASS
2 computeCentreOfMass = function(matrix){
3
4     S = sum(matrix)
5     xc = (sum((1:nrow(matrix))*rowSums(matrix)))/S
6     yc = (sum((1:ncol(matrix))*colSums(matrix)))/S
7
8     return(c(xc,yc))
9 }

```

```

1 ## FUNCTION COMPUTING INTENSITY OF TWO-DIMENSIONAL GAUSSIAN CURVE AT
  PIXEL [i,j]
2 Gaussian7para1j=function(i,j,para){
3     a=para[1]
4     b=para[2]
5     xp=para[3]
6     yp=para[4]
7     sx=para[5]
8     sy=para[6]
9     sxy=para[7]
10    tp1=(i-xp)/sx
11    tp2=(j-yp)/sy
12    Ixy=b+a*exp(-(tp1^2+tp2^2+2*sxy/sx/sy*tp1*tp2))
13    return(Ixy)
14 }

```

```

1 ## FUNCTION COMPUTING ACCURACY, BIAS AND STANDARD DEVIATION
2 computeAccuracyBiasStDev = function(x_obs, y_obs, x_true, y_true){
3
4     # Accuracy
5     a_x = sqrt(mean((x_obs-x_true)^2))
6     a_y = sqrt(mean((y_obs-y_true)^2))
7     # Bias
8     b_x = abs(mean(x_obs) - x_true)
9     b_y = abs(mean(y_obs) - y_true)
10    # Standard deviation
11    s_x = sqrt(mean(x_obs^2) - (mean(x_obs))^2)
12    s_y = sqrt(mean(y_obs^2) - (mean(y_obs))^2)
13
14    return(c(accuracy_x = a_x, accuracy_y = a_y, bias_x = b_x, bias_y =
15            b_y, stdev_x = s_x, stdev_y = s_y))
16 }

```

C.5 Simulation results and interpretation

Several sets of parameter values were tested, all leading to similar results. In the following, we are only going to show the results obtained for one set of parameters values.

The parameter values (in pixel) of the two-dimensional Gaussian curve chosen randomly at the beginning of the simulation are:

$$\begin{array}{lcl} a & = & 101.16 \\ b & = & 4.61 \end{array} \left| \begin{array}{lcl} x_p & = & 143.06 \\ y_p & = & 146.61 \end{array} \right| \begin{array}{lcl} s_x & = & 35.86 \\ s_y & = & 60.70 \\ s_{xy} & = & -15.40 \end{array}$$

Results regarding accuracy, bias and standard deviation of the coordinates of the laser spot centre are contained in Table C.1.

	accuracy		bias		standard deviation	
	x	y	x	y	x	y
centre of mass method	2.89	1.54	2.89	1.53	0.11	0.16
least-squares method	0.23	0.38	0.02	0.05	0.23	0.38
max. likelihood method						
(1) gamma	0.13	0.22	0.03	0.01	0.12	0.22
(2) gamma truncated	0.13	0.22	0.03	0.01	0.12	0.22

Table C.1: Simulation results (all values in pixel)

From the three methods, the centre of mass is the least accurate, even though its standard deviation is the best. The maximum likelihood method with a gamma or gamma truncated distribution is better than the least-squares method by a factor 2 to 3. Finally, there is no significant difference between gamma or gamma truncated. This can be interpreted by the fact that the amplitude of the signal ($a = 101.16$) is quite small with respect to the maximal intensity (255), which means that few pixels reach the upper bound of saturation.

C.6 Conclusion

A simulation was performed in order to compare three methods for the extraction of laser spot centre coordinates. The maximum likelihood method turned out to be the best solution, followed by the least-squares method and finally the centre of mass method. Even though the least-squares method did not provide the best accuracy and precision, its results are satisfying enough to be considered for our application.

Appendix D

Distortion study

D.1 Introduction

This chapter describes several aspects of the distortion study. First, it quickly explains how we calibrated the camera for our application. Second, it describes the calculation of the Jacobian matrix related to the distortion correction. Third, it gives the MATLAB code used for the thesis regarding the distortion correction.

D.2 Calibration step

Camera calibration is necessary to estimate the distortion parameters. We follow the same procedure for each camera we calibrate.

First, we glue the camera lens on its mount so that it does not move with respect to the camera chip. Then, we set the camera on a magnetic arm in order to capture pictures from stable positions. Finally, we capture pictures of a calibration plate with around 30 different camera positions and orientations (see Figures D.1 and D.2). The calibration plate is a pattern made of a black background and white targets. It is printed on a sheet of paper and then glued on an aluminium plate. The white disks in the middle are non-coded targets used for the determination of the distortion parameters. The white disks with bar code all around are coded targets used for the orientation of each picture. The plate size is about $12\text{ cm} \times 12\text{ cm} \times 1\text{ cm}$.

For the determination of the distortion parameters, a ‘good’ set of pictures is needed. The pictures should not be blurred. The white disks should not saturate the camera chip. Since the camera chip delivers intensity values between 0 for completely black and 255 for completely white, ideal intensity values are around 150-180 for white targets and 20-30 for black background. In addition, different camera orientations should be chosen in order to increase the redundancy of the system. We capture approximately 30 pictures satisfying these conditions. Finally, we give the pictures to the AICON 3D program and we re-

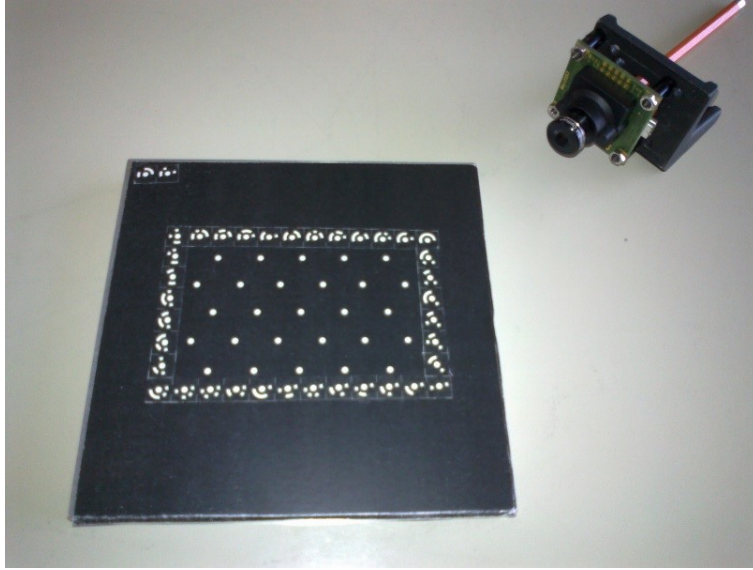


Figure D.1: Plate for distortion study and camera

ceive the distortion parameters, their uncertainties and the correlations between parameters.

As an example, Table D.1 contains the distortion parameters of the camera used in the optical lab. A first calibration was performed in July 2013, a second one in January 2015. An uncertainty value of 0 means that the value was chosen and not estimated. We can notice significant differences between parameter values of July 2013 and January 2015, which means that the calibration step should be performed regularly. In the extreme case, the distortion parameters can be estimated for each picture. Of course, this requires to have enough targets on the shutter.

D.3 Uncertainty related to the distortion correction

The goal of this section is to explain how to compute the Jacobian matrix related to the distortion correction in order to compute the corresponding covariance matrix. Thus, we are going to show how to compute the first derivatives of the output coordinates with respect to the input parameters and the distortion parameters.

In Section 2.3, we gave the relationships between coordinates before and

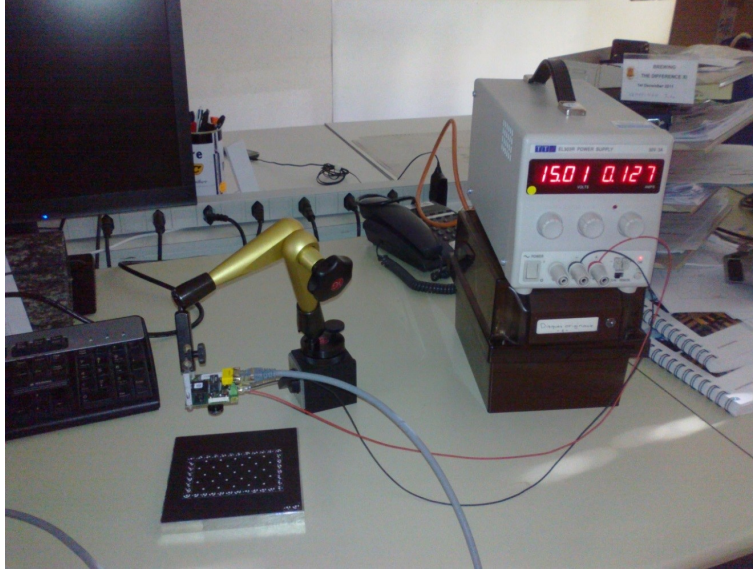


Figure D.2: For the calibration step, the camera is set on a magnetic arm which enables to capture pictures in stable positions.

after the distortion correction:

$$x_C = x_I - x_P - (\Delta_{\text{rad}} x + \Delta_{\text{tan}} x + \Delta_{\text{aff}} x) \quad (\text{D.1})$$

$$y_C = y_I - y_P - (\Delta_{\text{rad}} y + \Delta_{\text{tan}} y + \Delta_{\text{aff}} y) \quad (\text{D.2})$$

with

$$\Delta_{\text{rad}} x = x_C (A_1(r_C^2 - R_0^2) + A_2(r_C^4 - R_0^4) + A_3(r_C^6 - R_0^6)) \quad (\text{D.3})$$

$$\Delta_{\text{rad}} y = y_C (A_1(r_C^2 - R_0^2) + A_2(r_C^4 - R_0^4) + A_3(r_C^6 - R_0^6)) \quad (\text{D.4})$$

$$\Delta_{\text{tan}} x = B_1(r_C^2 + 2x_C^2) + 2B_2x_Cy_C \quad (\text{D.5})$$

$$\Delta_{\text{tan}} y = B_2(r_C^2 + 2y_C^2) + 2B_1x_Cy_C \quad (\text{D.6})$$

$$\Delta_{\text{aff}} x = C_1x_C + C_2y_C \quad (\text{D.7})$$

$$\Delta_{\text{aff}} y = 0 \quad (\text{D.8})$$

$$r_C^2 = x_C^2 + y_C^2 \quad (\text{D.9})$$

$$(\text{D.10})$$

If we develop both relationships, we obtain linear combinations of $x_C^i y_C^j$ with $(i, j) \in \llbracket 0, 7 \rrbracket$. Thus, we can rewrite them as follows:

$$x_C = x_I - x_P - V_Y^T M_X V_X \quad (\text{D.11})$$

$$y_C = y_I - y_P - V_Y^T M_Y V_X \quad (\text{D.12})$$

Param.	Unit	July 2013		January 2015	
		Value	Uncertainty	Value	Uncertainty
R_0	mm	1.728	0	1.728	0
z_p	mm	-5.9446	0.0031	-5.9009	0.0048
x_p	mm	-0.1148	0.0029	-0.0979	0.0037
y_p	mm	-0.0623	0.0024	-0.0592	0.0010
A_1	mm ⁻²	-1.5×10^{-2}	6.0×10^{-5}	-1.5×10^{-2}	1.3×10^{-5}
A_2	mm ⁻⁴	1.8×10^{-4}	6.0×10^{-6}	2.2×10^{-4}	2.0×10^{-6}
A_3	mm ⁻⁶	0	0	0	0
B_1	mm ⁻²	9.1×10^{-5}	1.7×10^{-5}	1.8×10^{-4}	4.7×10^{-5}
B_2	mm ⁻²	3.4×10^{-5}	1.7×10^{-5}	-2.5×10^{-5}	1.1×10^{-5}
C_1	mm ⁻¹	9.0×10^{-5}	8.2×10^{-5}	4.3×10^{-5}	3.4×10^{-5}
C_2	mm ⁻¹	49×10^{-5}	7.1×10^{-5}	1.6×10^{-6}	8.7×10^{-6}

Table D.1: Distortion parameters computed during camera calibration. z_p is the principal distance, (x_p, y_p) the coordinates of the principal point with respect to the centre of the camera chip.

with

$$V_X = (1 \quad x_c \quad x_c^2 \quad x_c^3 \quad x_c^4 \quad x_c^5 \quad x_c^6 \quad x_c^7)^T \quad (D.13)$$

$$V_Y = (1 \quad y_c \quad y_c^2 \quad y_c^3 \quad y_c^4 \quad y_c^5 \quad y_c^6 \quad y_c^7)^T \quad (D.14)$$

$$M_X = \begin{pmatrix} 0 & C_1 - (A_1 R_0^2 + A_2 R_0^4 + A_3 R_0^6) & 3B_1 & A_1 & 0 & A_2 & 0 & A_3 \\ C_2 & 2B_2 & 0 & 0 & 0 & 0 & 0 & 0 \\ B_1 & A_1 & 0 & 2A_2 & 0 & 3A_3 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & A_2 & 0 & 3A_3 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & A_3 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{pmatrix} \quad (D.15)$$

$$M_Y = \begin{pmatrix} 0 & 0 & B_2 & 0 & 0 & 0 & 0 & 0 \\ -(A_1 R_0^2 + A_2 R_0^4 + A_3 R_0^6) & 2B_1 & A_1 & 0 & A_2 & 0 & A_3 & 0 \\ 3B_2 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ A_1 & 0 & 2A_2 & 0 & 3A_3 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ A_2 & 0 & 3A_3 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ A_3 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{pmatrix} \quad (D.16)$$

Let us call p' the first derivative of p with respect to one parameter among

$(x_i, y_i, x_p, y_p, A_1, A_2, A_3, B_1, B_2, C_1, C_2)$. We have:

$$x'_c = x'_i - x'_p - ((V_Y^T)' M_X V_X + V_Y^T M'_X V_X + V_Y^T M_X V'_X) \quad (D.17)$$

$$y'_c = y'_i - y'_p - ((V_Y^T)' M_Y V_X + V_Y^T M'_Y V_X + V_Y^T M_Y V'_X) \quad (D.18)$$

If we compute the derivatives of V_X and V_Y , we find:

$$V'_X = x'_c W_X \quad (D.19)$$

$$V'_Y = y'_c W_Y \quad (D.20)$$

with

$$W_X = (0 \quad 1 \quad 2x_c \quad 3x_c^2 \quad 4x_c^3 \quad 5x_c^4 \quad 6x_c^5 \quad 7x_c^6)^T \quad (D.21)$$

$$W_Y = (0 \quad 1 \quad 2y_c \quad 3y_c^2 \quad 4y_c^3 \quad 5y_c^4 \quad 6y_c^5 \quad 7y_c^6)^T \quad (D.22)$$

Finally, if we use these results and reorganise the equations, we find:

$$x'_c a_X + y'_c b_X = c_X \quad (D.23)$$

$$x'_c a_Y + y'_c b_Y = c_Y \quad (D.24)$$

with

$$a_X = 1 + V_Y^T M_X W_X \quad (D.25)$$

$$b_X = W_Y^T M_X V_X \quad (D.26)$$

$$c_X = x'_i - x'_p + V_Y^T M'_X V_X \quad (D.27)$$

$$a_Y = V_Y^T M_Y W_X \quad (D.28)$$

$$b_Y = 1 + W_Y^T M_Y V_X \quad (D.29)$$

$$c_Y = y'_i - y'_p + V_Y^T M'_Y V_X \quad (D.30)$$

It is a system of two equations with two unknowns. Let us call its determinant $D = a_X b_Y - a_Y b_X$. The general form of the solutions is:

$$x'_c = \frac{c_X b_Y - c_Y b_X}{D} \quad (D.31)$$

$$y'_c = \frac{a_X c_Y - a_Y c_X}{D} \quad (D.32)$$

The terms (a_X, a_Y, b_X, b_Y) are independent of the first derivatives of the parameters, thus we are going to focus on (c_X, c_Y) for the calculation of the Jacobian matrix.

For the input coordinates, we find:

$$c_X(x_i) = 1 \quad (D.33)$$

$$c_Y(x_i) = 0 \quad (D.34)$$

$$c_X(y_i) = 0 \quad (D.35)$$

$$c_Y(y_i) = 1 \quad (D.36)$$

Furthermore, for the principal point coordinates, we have:

$$c_X(x_p) = -1 \quad (\text{D.37})$$

$$c_Y(x_p) = 0 \quad (\text{D.38})$$

$$c_X(y_p) = 0 \quad (\text{D.39})$$

$$c_Y(y_p) = -1 \quad (\text{D.40})$$

Finally, for the remaining distortion parameters $(A_1, A_2, A_3, B_1, B_2, C_1, C_2)$, we can show that:

$$c_X(A_1) = -R_0^2 x_c + x_c^3 + x_c y_c^2 \quad (\text{D.41})$$

$$c_Y(A_1) = -R_0^2 y_c + y_c^3 + y_c x_c^2 \quad (\text{D.42})$$

$$c_X(A_2) = -R_0^4 x_c + x_c^5 + x_c^3 y_c^2 + x_c y_c^4 \quad (\text{D.43})$$

$$c_Y(A_2) = -R_0^4 y_c + y_c^5 + y_c^3 x_c^2 + y_c x_c^4 \quad (\text{D.44})$$

$$c_X(A_3) = -R_0^6 x_c + x_c^7 + 3x_c^5 y_c^2 + 3x_c^3 y_c^4 + x_c y_c^6 \quad (\text{D.45})$$

$$c_Y(A_3) = -R_0^6 y_c + y_c^7 + 3y_c^5 x_c^2 + 3y_c^3 x_c^4 + y_c x_c^6 \quad (\text{D.46})$$

$$c_X(B_1) = 3x_c^2 + y_c^2 \quad (\text{D.47})$$

$$c_Y(B_1) = 2x_c y_c \quad (\text{D.48})$$

$$c_X(B_2) = 2x_c y_c \quad (\text{D.49})$$

$$c_Y(B_2) = 3y_c^2 + x_c^2 \quad (\text{D.50})$$

$$c_X(C_1) = x_c \quad (\text{D.51})$$

$$c_Y(C_1) = 0 \quad (\text{D.52})$$

$$c_X(C_2) = y_c \quad (\text{D.53})$$

$$c_Y(C_2) = 0 \quad (\text{D.54})$$

In the end, if we concatenate all c_X 's into a vector K_X of size 1×11 and all c_Y 's into a vector K_Y of size 1×11 , we can write the Jacobian matrix as follows:

$$A = \frac{1}{D} \begin{pmatrix} b_Y K_X - b_X K_Y \\ a_X K_Y - a_Y K_X \end{pmatrix} \quad (\text{D.55})$$

which is equivalent to:

$$A = \frac{1}{D} \begin{pmatrix} b_Y & -b_X \\ -a_Y & a_X \end{pmatrix} \begin{pmatrix} K_X \\ K_Y \end{pmatrix} \quad (\text{D.56})$$

D.4 Distortion correction code

```
1 function [object, fig_distortion_correction] = correctDistortion(c,
    object, max_nb_iterations)
```

```

2
3 %% Pre-processing steps
4 % Store input values
5 X_input_pixel = object.x;
6 Y_input_pixel = object.y;
7
8 % Since the camera calibration is performed in mm,
9 % convert pixel to mm
10 object = convertPixel2mm(c,object);
11
12 % Translate input coordinates in order to have principal point
13 % as origin of the coordinate system
14 object = changeOriginCoordinateSystemFromChipCentreToPrincipalPoint(c,
    object);
15
16 %% Correct coordinates by iteration
17
18 % Define camera parameters
19 % Radius0
20 R0 = c.r0;
21 % Parameters
22 A1 = c.a1;
23 A2 = c.a2;
24 A3 = c.a3;
25 B1 = c.b1;
26 B2 = c.b2;
27 C1 = c.c1;
28 C2 = c.c2;
29
30 % Initialisation
31 X_init = object.x;
32 Y_init = object.y;
33
34 X = X_init;
35 Y = Y_init;
36 DeltaX_old = zeros(size(X));
37 DeltaY_old = zeros(size(Y));
38
39 stop_condition = 1e-6; % in mm
40 nb.iterations = 0;
41 continue.iteration.distortion = true;
42
43 % Iteration
44 while continue.iteration.distortion == true
45     nb.iterations = nb.iterations + 1;
46     % Distance image coordinates - principal point
47     R = sqrt(X.^2 + Y.^2);
48     %-----
49     % RADIAL DISTORTION
50     % Correction along image vector
51     DeltaRadial = A1*R.*(R.^2-R0^2) + A2*R.*(R.^4-R0^4) + A3*R.*(R.^6-
        R0^6);
52     % Correction along X axis
53     DeltaRadialX = X.*DeltaRadial./R;
54     % Correction along Y axis
55     DeltaRadialY = Y.*DeltaRadial./R;
56     %-----

```

```

57 % TANGENTIAL DISTORTION
58 % Correction along X axis
59 DeltaTangentialX = B1.*(R.^2+2*X.^2) + 2*B2*X.*Y;
60 % Correction along Y axis
61 DeltaTangentialY = B2.*(R.^2+2*Y.^2) + 2*B1*X.*Y;
62 %-----
63 % AFFINITY AND SHEAR
64 % Correction along X axis
65 DeltaAffinityX = C1*X + C2*Y;
66 % Correction along Y axis
67 DeltaAffinityY = zeros(size(X));
68 %-----
69 % TOTAL CORRECTION
70 DeltaX = DeltaRadialX + DeltaTangentialX + DeltaAffinityX;
71 DeltaY = DeltaRadialY + DeltaTangentialY + DeltaAffinityY;
72 %-----
73 % CHECK IF DELTA X and DELTA Y HAVE CHANGED BETWEEN TWO
74 % ITERATIONS
75 continue_iteration_distortion = (max([DeltaX(:) - DeltaX_old(:);
    DeltaY(:) - DeltaY_old(:)]) > stop_condition) && (
    nb_iterations < max_nb_iterations);
76 % Updating vectors
77 X = X_init - DeltaX;
78 Y = Y_init - DeltaY;
79 DeltaX_old = DeltaX;
80 DeltaY_old = DeltaY;
81 end
82
83 %% Compute covariance matrices
84 nb_pictures = size(X,1);
85 nb_targets = size(X,2);
86
87 k = A1*R0^2 + A2*R0^4 + A3*R0^6;
88 mx = [ 0 C1-k 3*B1 A1 0 A2 0 A3; ...
89       C2 2*B2 0 0 0 0 0 0; ...
90       B1 A1 0 2*A2 0 3*A3 0 0; ...
91       0 0 0 0 0 0 0 0; ...
92       0 A2 0 3*A3 0 0 0 0; ...
93       0 0 0 0 0 0 0 0; ...
94       0 A3 0 0 0 0 0 0; ...
95       0 0 0 0 0 0 0 0];
96 my = [ 0 0 B2 0 0 0 0 0; ...
97       -k 2*B1 A1 0 A2 0 A3 0; ...
98       3*B2 0 0 0 0 0 0 0; ...
99       A1 0 2*A2 0 3*A3 0 0 0; ...
100      0 0 0 0 0 0 0 0; ...
101      A2 0 3*A3 0 0 0 0 0; ...
102      0 0 0 0 0 0 0 0; ...
103      A3 0 0 0 0 0 0 0];
104
105
106 Cpp = c.cov; % Covariance matrix coming from calibration step
107 Cpp(1,:) = []; % Remove terms related to focal length
108 Cpp(:,1) = []; % Remove terms related to focal length
109
110 for p = 1:nb_pictures
111     for t = 1:nb_targets

```

```

112 % Define corrected point
113 x = X(p,t);
114 y = Y(p,t);
115 % Define auxiliary vectors
116 vx = [1 x x^2 x^3 x^4 x^5 x^6 x^7]';
117 vy = [1 y y^2 y^3 y^4 y^5 y^6 y^7]';
118 wx = [0 1 2*x 3*x^2 4*x^3 5*x^4 6*x^5 7*x^6]';
119 wy = [0 1 2*y 3*y^2 4*y^3 5*y^4 6*y^5 7*y^6]';
120 % Define ax, bx, ay, by, from the system of
121 % 2 equations and 2 unknowns (see annex of thesis report)
122 ax = 1+(vy')*mx*wx;
123 bx = (wy')*mx*vx;
124 ay = (vy')*my*wx;
125 by = 1+(wy')*my*vx;
126 % Define corresponding determinant
127 d = ax*by - ay*bx;
128 % Define Kx, Ky concatenating cx, cy from the system of
129 % 2 equations and 2 unknowns
130 Kx = [1, 0, ax-1, bx,...
131       -R0^2*x + x^3 + x*y^2, ...
132       -R0^4*x + x^5 + x^3*y^2 + x*y^4, ...
133       -R0^6*x + x^7 + 3*x^5*y^2 + 3*x^3*y^4 + x*y^6, ...
134       3*x^2 + y^2, 2*x*y, x, y];
135
136 Ky = [0, 1, ay, by-1,...
137       -R0^2*y + y^3 + y*x^2, ...
138       -R0^4*y + y^5 + y^3*x^2 + y*x^4, ...
139       -R0^6*y + y^7 + 3*y^5*x^2 + 3*y^3*x^4 + y*x^6, ...
140       2*x*y, 3*y^2 + x^2, 0, 0];
141 % Compute Jacobian matrix
142 A = (1/d)*[by, -bx; -ay, ax]*[Kx; Ky];
143
144 % Compute covariance matrix of considered point
145 C11 = reshape(object.cov(p,4*t-3:4*t),2,2);
146 C22 = A*[C11 zeros(2,9); zeros(9,2) Cpp]*A';
147 object.cov(p,4*t-3:4*t) = C22(:)';
148 end
149 end
150
151 %% Post-processing steps
152
153 % Translate corrected coordinates in order to have chip centre
154 % as origin of the coordinate system
155 object.x = X;
156 object.y = Y;
157 object = changeOriginCoordinateSystemFromPrincipalPointToChipCentre(c,
158     object);
159
160 % Convert from mm to pixel
161 object = convertMm2Pixel(c,object);
162
163 % Store corrected coordinates
164 X_corrected.pixel = object.x;
165 Y_corrected.pixel = object.y;
166
167 %% Display targets corrections
168 display_target_corrections = 1;

```

```

168
169 % Choose picture to be displayed
170 p = 1;
171
172 if display_target_corrections
173
174     x = X_input_pixel(p,:);
175     y = Y_input_pixel(p,:);
176     xc = X_corrected_pixel(p,:);
177     yc = Y_corrected_pixel(p,:);
178
179     residuals = sqrt((xc-x).^2 + (yc-y).^2);
180     labels = cellstr(num2str(residuals','%.1f'));
181
182     fig_distortion_correction = figure;
183     quiver(x, y, xc - x, yc - y)
184     text(x,y,labels)
185     hold on
186     plot(c.xh/c.pixel_size,c.yh/c.pixel_size,'k+')
187     text(c.xh/c.pixel_size + 20 ,c.yh/c.pixel_size + 20,'principal
188         point')
189     hold on
190     rectangle('Position',[-c.nb_pixel_X/2 ...
191         -c.nb_pixel_Y/2 ...
192         c.nb_pixel_X ...
193         c.nb_pixel_Y])
194     xlabel('x position (in pixel), residuals (in pixel)')
195     ylabel('y position (in pixel), residuals (in pixel)')
196     grid on
197     axis([-1.2*c.nb_pixel_X/2 1.2*c.nb_pixel_X/2 ...
198         -1.2*c.nb_pixel_Y/2 1.2*c.nb_pixel_Y/2])
199     axis equal
200
201     title('Distortion correction')
202 else
203     fig_distortion_correction = 0;
204 end
205
206
207 end

```

matlab\code\correctDistortion.m

Appendix E

Reports related to experiments regarding measurement accuracy

This appendix contains all small reports related to experiments regarding measurement accuracy.

1. Experiment over long period with plate 33 (macor)

History

2015-04-14: started report, performed experiment, started MATLAB code

2015-04-15: processed captured pictures, continued report

2015-04-16: finished report

Context

So far, we have worked on measurement precision. We want to do complementary experiments to check measurement accuracy of the LAMBDA sensor. Since plate 33 has not been tested yet, a series of measurements will be first done over long period.

Objective

We want to determine laser pointing stability in shutter plane over several hours.

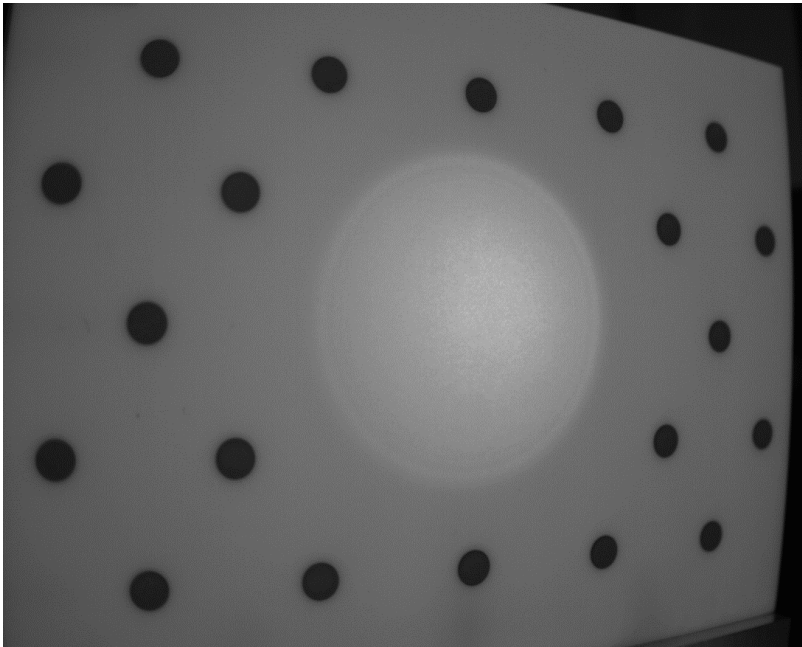
Method

We set plate 33 on the motorised micrometre machine. We capture 1000 pictures every 30 s (around 8 hours). We process pictures with the usual steps and we reconstruct laser spot coordinates on the shutter.

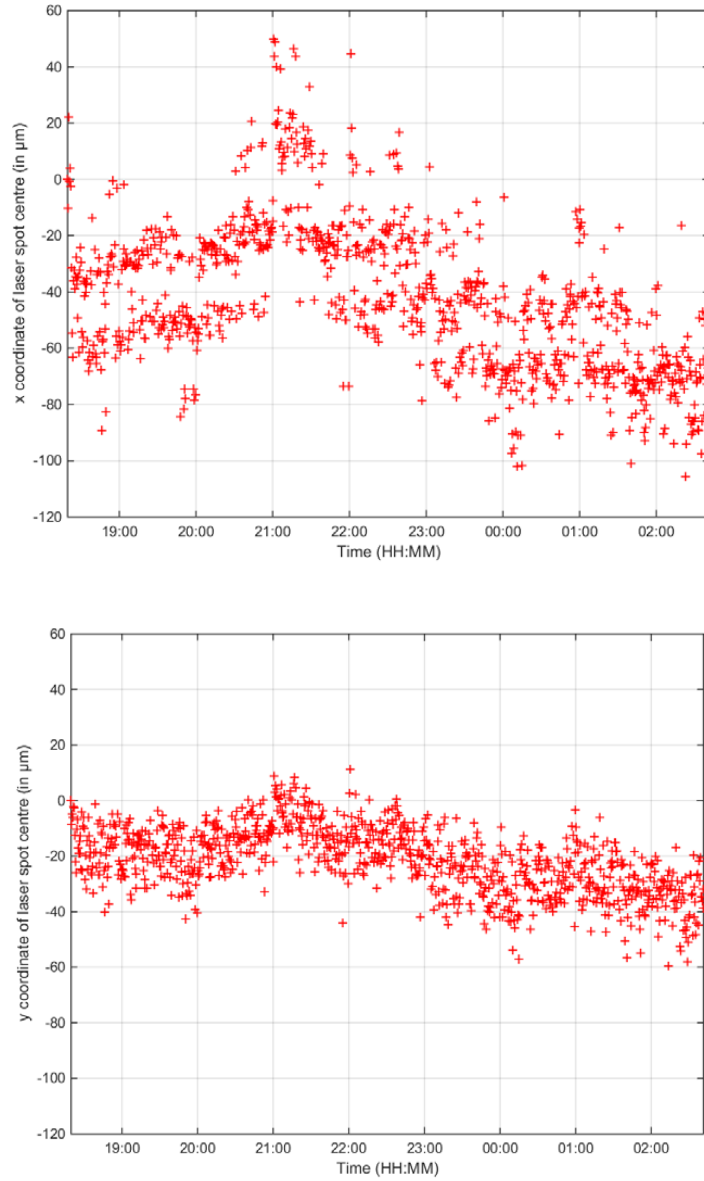
We show the variation of the laser spot coordinates and we compute their standard deviations.

Results

Typical picture captured by camera



Variation of the laser spot coordinates in shutter plane with respect to time



We can see that the y coordinate (st. dev. = 12 μm) is much more stable than the x coordinate (st. dev. = 27 μm).

Conclusion

Results are not as good as expected. Standard deviations (12 μm and 27 μm for x and y) are larger than the required 5 μm within CLIC project. The same experiment will be done with paper surface in order to compare results.

2. Experiment laser spot with respect to shutter displacement

History

2015-04-15: started report, captured pictures

2015-04-16: wrote MATLAB code

2015-04-17: finished report

Context

We want to determine measurement accuracy of the LAMBDA sensor when we move the sensor in x and y position.

Objective

We want to determine residuals between positions of the motorised micrometre table (= true values) and positions measured by the LAMBDA sensor (= measured values).

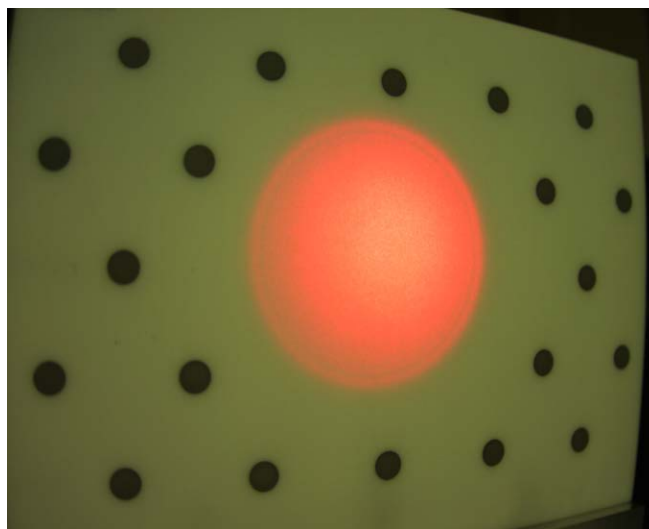
Method

We set the LAMBDA sensor with plate 33 (macor) on the motorised micrometre machine. We move the LAMBDA sensor in 121 positions ($x = -1 \text{ mm} \dots +1 \text{ mm}$, $y = -1 \text{ mm} \dots +1 \text{ mm}$ in steps of $100 \mu\text{m}$). For each position, we capture pictures and we process them with the usual steps (Gaussian fitting for the laser spot, ellipse fitting for the targets, projective geometry for the transformation between camera and shutter) in order to extract the positions of the laser spot centre.

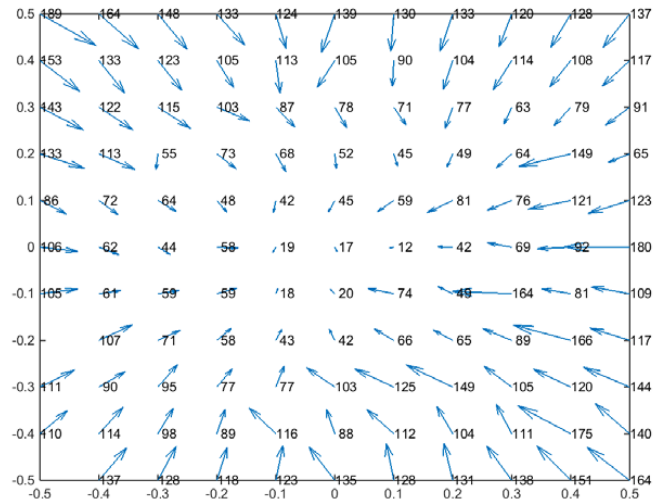
Finally, we compute differences between theoretical and measured positions and we show residuals.

Results

Typical picture captured by camera (position $x = -0.5 \text{ mm}$, $y = -0.5 \text{ mm}$)



Residuals between theoretical and measured values



We can see that measured values are less spread than theoretical values, as if there was a scale factor between them. This should not be the case and is still not understood.

In addition, 2 positions were removed because they were outliers: $x = -0.5, y = -0.2$ and $x = -0.5, y = -0.5$. This is due to the fact that the displacement of the motorised micrometre machine was not finished but the camera was already capturing picture.

Conclusion

Results are not satisfying. A short test done with paper surface gave similar results.

This has to be understood before going on.

3. Study pictures captured by camera

History

2015-04-17: started report, captured pictures, wrote MATLAB code, finished report

Context

The previous experiment gave bad results regarding measurement accuracy. The positions of the laser spot centres on the camera chip were not symmetric, thus the problem might come from pictures captured by camera.

The pictures show that they are sometimes taken before the displacement of the sensor ends, which results in errors. This was especially the case for displacements over 1 mm.

Objective

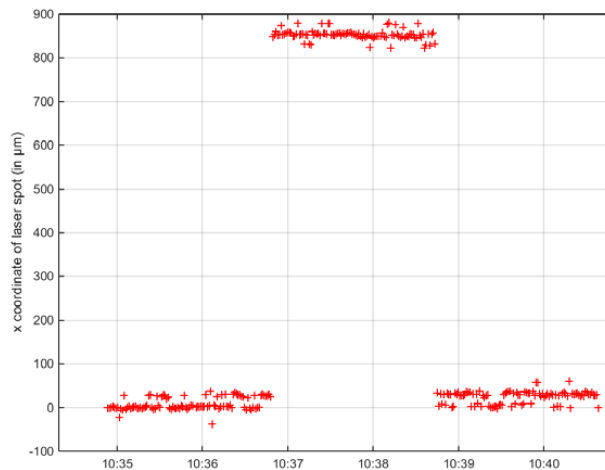
We want to know how much time is needed to have the laser spot stable after the sensor has moved.

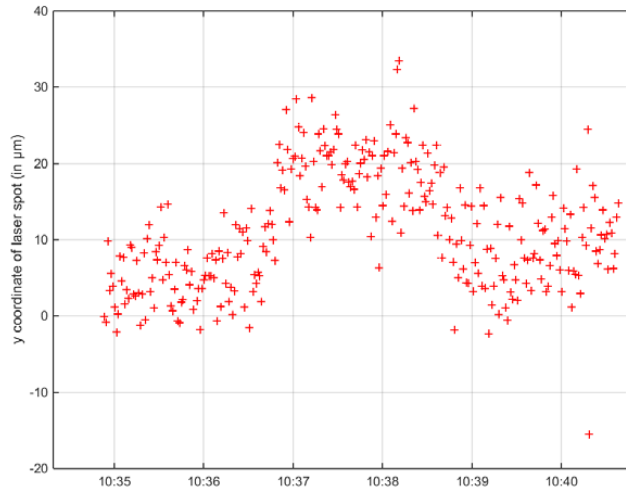
Method

We capture 100 pictures in a first position. We make a movement of the motorised micrometre table over 1mm and we capture 100 pictures in the second position. We make then the movement back to the first position and we capture 100 pictures. The time between picture capture is set at 100 ms.

We process the pictures with the usual steps and we determine how much time is needed to have the laser spot in a stable situation.

Results





These graphs do not show particular problems when the sensor is displaced. On the contrary, the laser spot seems to be relatively stable for $x = 0$ mm and $x = 1$ mm. Following standard deviations were computed:

	St. dev. X (μm)	St. dev Y (μm)
Pictures 1 to 100	14	4
Pictures 101 to 200	11	5
Pictures 201 to 300	14	6

We can notice for the x coordinate that within each position ($x = 0$ mm, $x = 1$ mm), the laser spot switches between several intermediate positions (mostly around $x = 0$ mm but also $x = 0.030$ mm and $x = -0.030$ μm).

In addition, for the x coordinate, the total distance between both positions should be 1 mm but only 0.85 mm is observed. This was already seen in the previous experiment but could not be explained so far.

Conclusion

The parameters chosen for this test (time between pictures = 100 ms, 100 pictures captured for each position) seem to work regarding laser spot stability. However, there is still an error of detection of about $(1000 \mu\text{m} - 850 \mu\text{m})/1000 \mu\text{m} = 15 \%$

4. Pixel by pixel reconstruction and then Gaussian fitting

History

2015-04-20: started report, wrote MATLAB code

2015-04-22: realised that algorithm in MATLAB out of memory because least-squares method applied on too many observations, decided to write Gaussian fitting with R and with small images (300 by 300 pixels) -> see separate folder on April 22

Context

Previous results regarding measurement accuracy showed that the laser spot is reconstructed with a scale factor in radial direction (x) and not in vertical direction (y). Since the reconstruction of targets works well, the problem might come from the way the camera sees the laser spot.

Indeed, the camera axis and the laser beam axis present an angle of about 30° in x direction (the camera is placed on the left side of the laser beam). Thus, the intensity observed by the camera is more concentrated on the left side than on the right side of the picture. Since the intensity pattern covers almost 100 000 pixels, this may result in significant error in the determination of the laser spot centre by Gaussian fitting.

Objective

We want to compare two algorithms in terms of measurement accuracy of the laser spot centre: (1) Gaussian fitting applied on the image captured by the camera, (2) Gaussian fitting applied on an image where each pixel has been reconstructed separately.

Method

We use grayscale pictures captured in a previous study (April 15, 2015 : Experiment laser spot wrt shutter displacement).

We write the new algorithm which consists of correcting the position of each pixel first, and then applying Gaussian fitting.

Finally, we process the results with the usual steps and we determine measurement accuracy with both algorithms.

5. Comparison camera on the side and camera on the top

History

2015-04-21: started report, captured pictures, wrote MATLAB code

2015-04-22: finished MATLAB code, finished report

Context

Previous results regarding measurement accuracy showed asymmetrical results in radial (x) and vertical (y) directions, which was probably related to camera position. This can be confirmed if we change camera position.

Objective

We want compare two configurations in terms of measurement accuracy: (1) camera on the (left) side w.r.t. shutter, (2) camera on the top w.r.t. shutter.

Method

In a first iteration, we set the camera on the magnetic arm so that it is on the top w.r.t. shutter. We set the shutter in position (0mm, 0mm) and we move it to positions (0,1), (1,1), (1,0) and finally back to (0,0). For each position, we capture 100 pictures and we process them with the usual steps.

In a second iteration, we put the camera on the left side w.r.t. shutter and we do the same procedure.

Finally, we show the variation of the x and y coordinates in the shutter plane w.r.t. time.

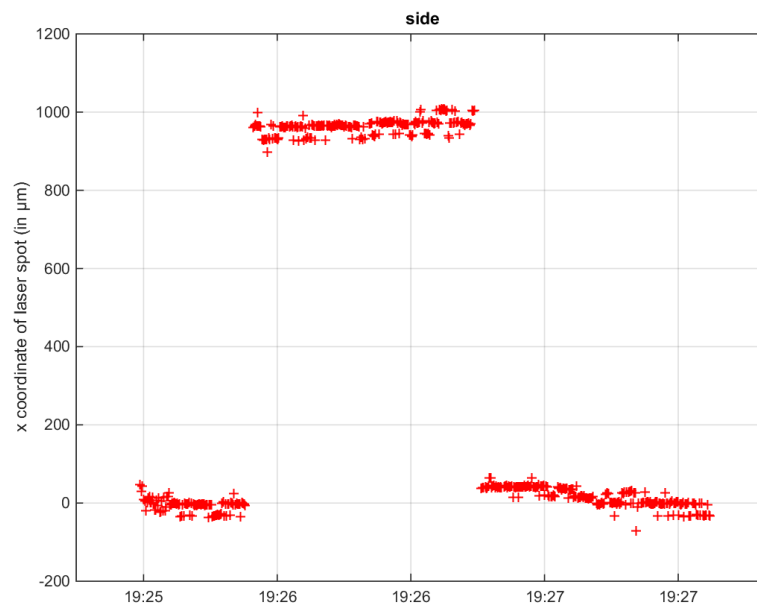
NB: following camera parameters were chosen: pixel clock 10 / time exposure 160 / frame rate 6.25

Results

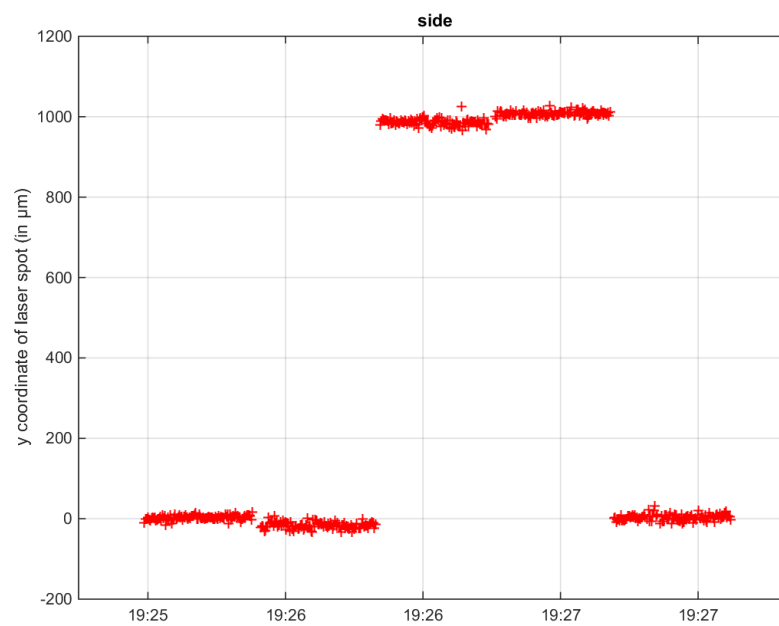
Standard deviations of x and y

Camera position	Position table (mm)	St. dev. x (μm)	St. dev. y (μm)
Side	(0,0)	16.9	5.5
Side	(1,0)	16.9	8.1
Side	(1,1)	19.2	8.2
Side	(0,1)	13.0	5.8
Side	(0,0)	18.3	7.8
Top	(0,0)	6.7	7.7
Top	(1,0)	2.4	6.2
Top	(1,1)	4.5	8.3
Top	(0,1)	3.4	6.2
Top	(0,0)	3.1	6.2

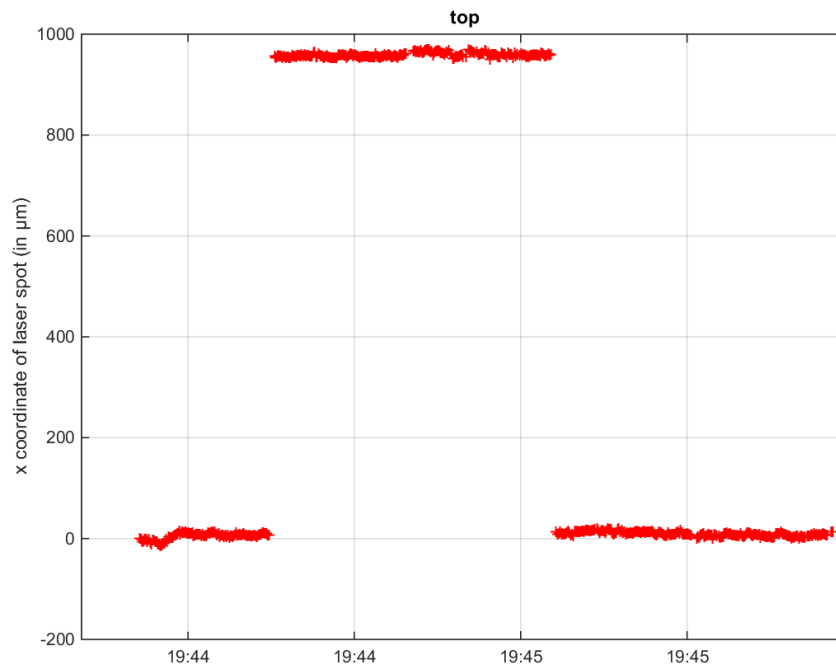
Camera on the side (x coordinate)



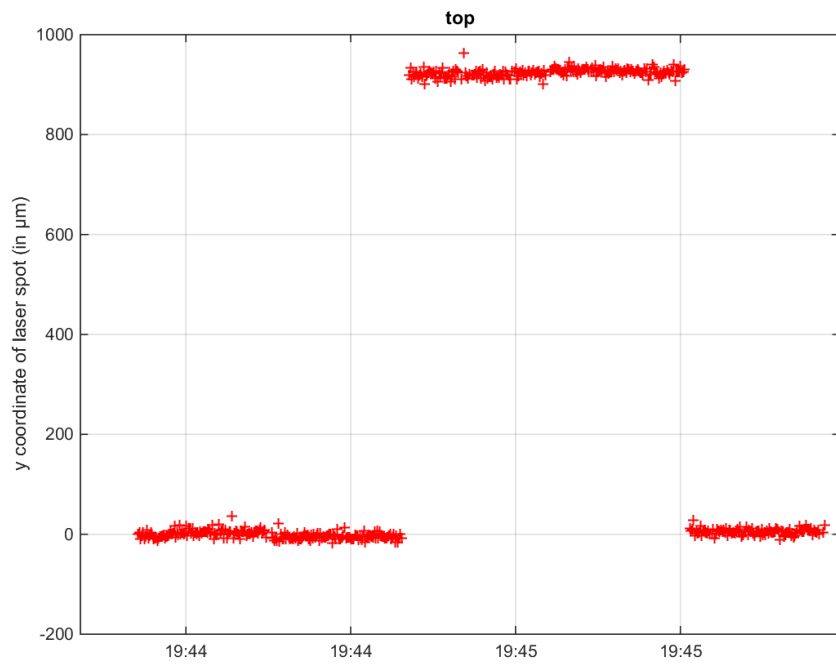
Camera on the side (y coordinate)



Camera on the top (x coordinate)



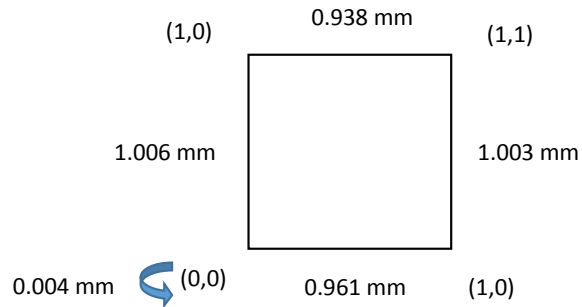
Camera on the top (y coordinate)



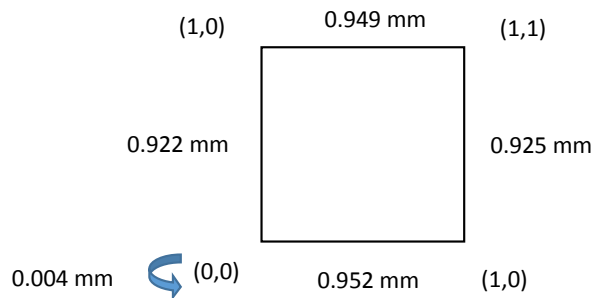
Measured distances between table positions

For each table position, we compute the mean of the laser spot coordinates over 100 pictures. Then, we compute the distances between two successive positions.

Camera on the side



Camera on the top



Conclusion

We can see several positions for the x coordinate when the camera is set on the left but not for the y coordinate when the camera is set on the top. Thus, this phenomenon seems to be not symmetric, contrary to what we thought. It has not been explained so far.

A scale factor between what we expect and what we obtain is present for the x coordinate (side and top), as well as for the y coordinate (top), but not for the y coordinate (side). This remains unexplained.

6. Gaussian fitting with R

History

2015-04-22: started report, wrote MATLAB and R codes

2015-04-23 - 2015-04-24 : continued MATLAB and R codes

2015-04-25: finished MATLAB and R codes, finished report

Context

Previous results regarding measurement accuracy showed that there were scale factors between theoretical values and measured values of the laser spot coordinates. Gaussian fitting might be the reason (see folder pixel by pixel reconstruction for more details, April 20). Since the MATLAB algorithm ran out of memory when applying least-squares-method on large images, Gaussian fitting is going to be performed with R.

Objective

We want to compare two algorithms in terms of measurement accuracy of the laser spot centre: (1: Sébastien's program) Gaussian fitting applied on the image captured by the camera, (2: R program) Gaussian fitting applied on an image where each pixel has been reconstructed separately.

Method

We use pictures captured in the previous study (comparison camera on the side and on the top, April 21).

We write the new algorithm which consists of reducing picture resolution from 1280x1024 to 300x300 around the laser spot, correcting the position of each pixel, and then applying Gaussian fitting.

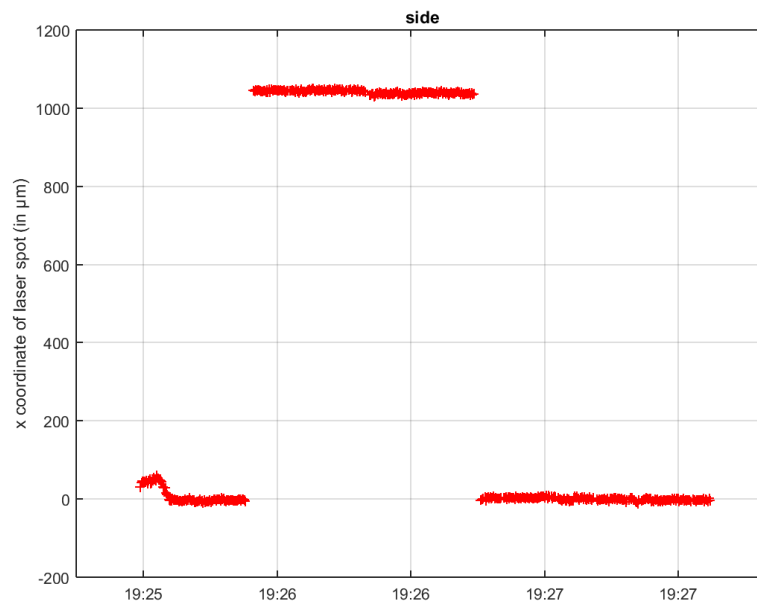
Finally, we process the results with the usual steps and we compare variations of x and y coordinates with the previous study.

Results

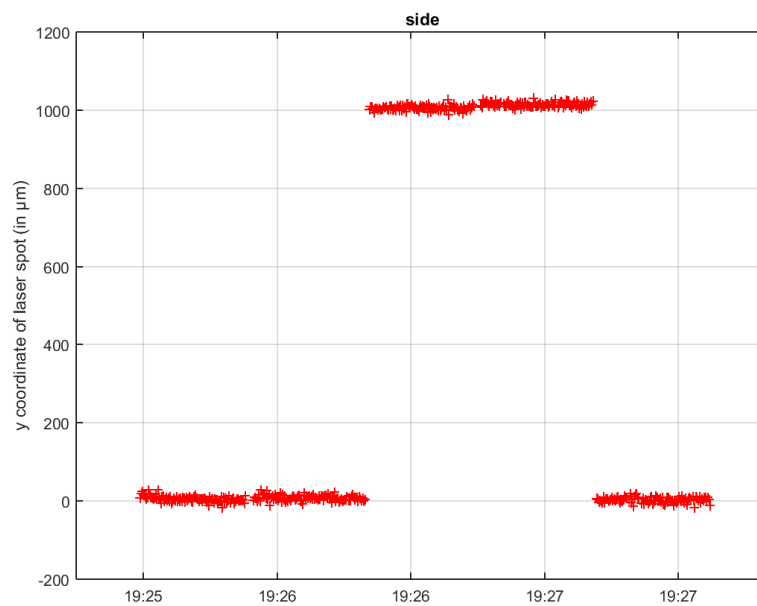
Standard deviations of x and y

Camera position	Position table (mm)	St. dev. x (μm)	St. dev. y (μm)
Side	(0,0)	20.8	7.3
Side	(1,0)	2.5	7.0
Side	(1,1)	2.8	6.2
Side	(0,1)	3.3	6.1
Side	(0,0)	2.7	7.1
Top	(0,0)	11.9	7.6
Top	(1,0)	3.7	7.3
Top	(1,1)	3.8	7.5
Top	(0,1)	4.3	8.2
Top	(0,0)	3.7	7.9

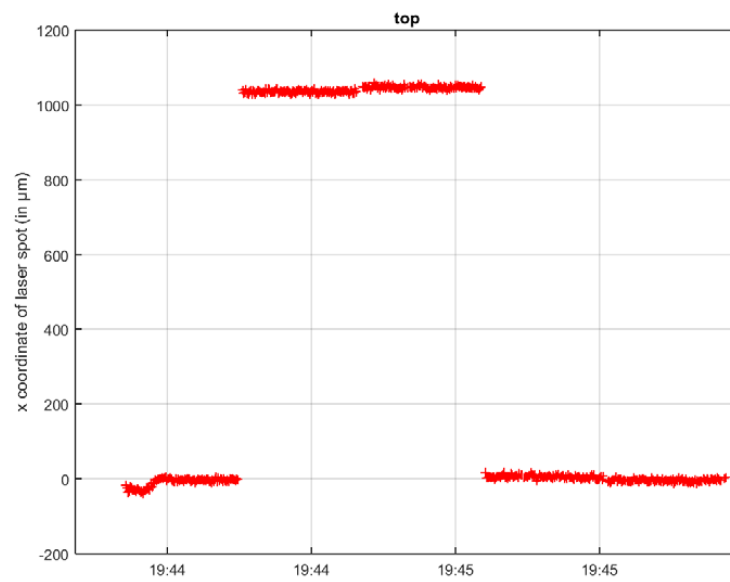
Camera on the side (x coordinate)



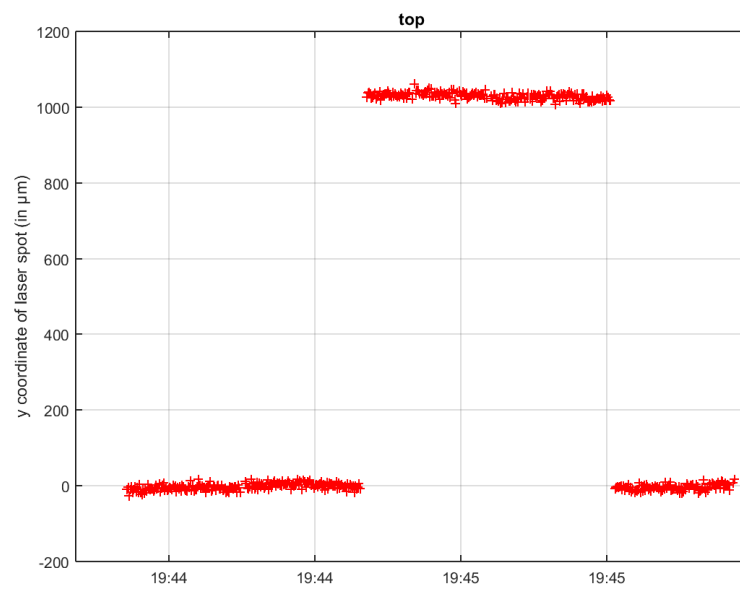
Camera on the side (y coordinate)



Camera on the top (x coordinate)



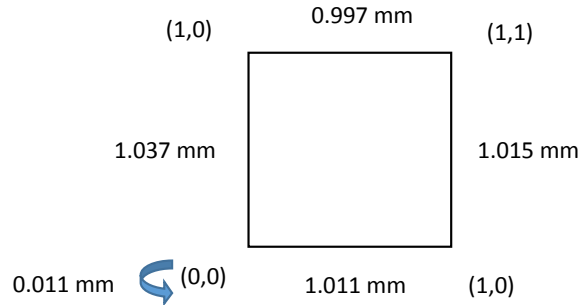
Camera on the top (y coordinate)



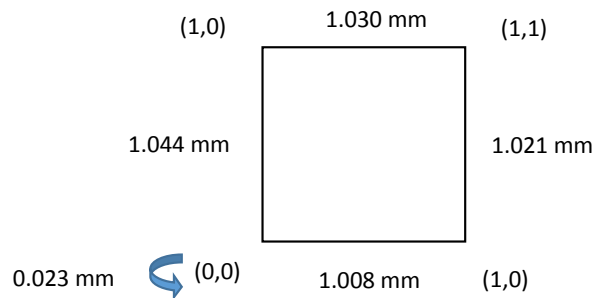
Measured distances between table positions

For each table position, we compute the mean of the laser spot coordinates over 100 pictures. Then, we compute the distances between two successive positions.

Camera on the side



Camera on the top



Conclusion

First, we can see that reconstructing pixel by pixel and then applying Gaussian fitting stabilises the x position when the camera is on the side. Instead of having 3 different positions, there is only one. However, the graph of the x coordinate when the camera is on the side also presents a small drift of about 50 μm at the beginning, which remains unexplained.

Regarding standard deviations, the y coordinate shows the same order of magnitude as in the previous study (5 μm - 8 μm). For the x coordinate, if we put aside the first position (0 mm, 0 mm) disturbed by the small drift, standard deviations are much better now (3 μm - 4 μm) than in the previous study (3 μm - 19 μm).

Regarding measurement accuracy, we can still see a scale factor between theoretical and measured values. Before, the scale factor was smaller than 1 (between 0.92 and 1), now it is larger than 1 (between 1 and 1.05). This phenomenon remains unexplained so far.

7. Reduction of the number of observations

History

2015-04-27: started report, wrote R code

2015-04-28: finished report

Context

Reconstructing pixel by pixel and then applying Gaussian takes a lot of computing time because of the number of pixels (90 000). However, since there are only 7 parameters to be determined for the two dimensional Gaussian curve, the number of observations might be reduced. The idea would be to select randomly a certain number of pixels among the 90 000 available pixels and to apply Gaussian fitting on them.

Objective

We want to find a compromise between measurement accuracy and precision, and computing time with respect to the number of pixels chosen randomly.

Method

We use one picture captured in the study (comparison camera on the side and on the top, April 21). We write the code in R. We set a threshold at 120. All pixel values under that threshold are eliminated. This allows us to have mainly the laser spot and not the side reflections.

In a first iteration, we randomly choose 1000 pixels among the available pixels. We apply Gaussian fitting on them and we determine the centre coordinates of the laser spot. We repeat this operation 100 times and we compute mean and standard deviations of the centre coordinates. In addition, we register the computing time.

In further iterations, we repeat the same process with 2000, 5000, 10000, 20000 and 50000 pixels.

Results

	Error x (μm)	Error y (μm)	St. dev. X	St. dev.	Time elapsed (s)
1000	4.0	0.2	30.4	28.4	8
2000	1.6	0.9	17.8	21.3	16
5000	1.7	1.0	12.6	12.1	42
10000	0.7	0.4	9.3	7.8	86
20000	0.5	0.9	5.9	5.9	192
50000	0.4	0.1	2.5	2.6	679

The error in x (resp. in y) is the absolute difference between the mean of x (resp. of y) over 100 simulations and the x coordinate computed from all pixels.

Conclusion

The standard deviations remain relatively large for all sample sizes. Thus it is not enough to take a sample of pixels and apply Gaussian fitting on them. The whole picture will be used for further tests.

8. Measurement accuracy when sensor moved in x and y over 10 mm

History

2015-04-27: captured pictures

2015-04-28: started report, wrote MATLAB code

2015-04-30: finished report

Context

Previous experiments showed a scale factor between measured values and theoretical values. These experiments were performed on relatively small range (-0.5 mm ... +0.5 mm in x and in y directions).

In order to see if the scale factor is still visible on long range, we perform a similar experiment than the one on April 15, which consisted of estimating measurement accuracy when the LAMBDA sensor moves in x and y directions.

Objective

We want to determine residuals between positions of the motorised micrometre table (= theoretical values) and positions measured by the LAMBDA sensor (= measured values).

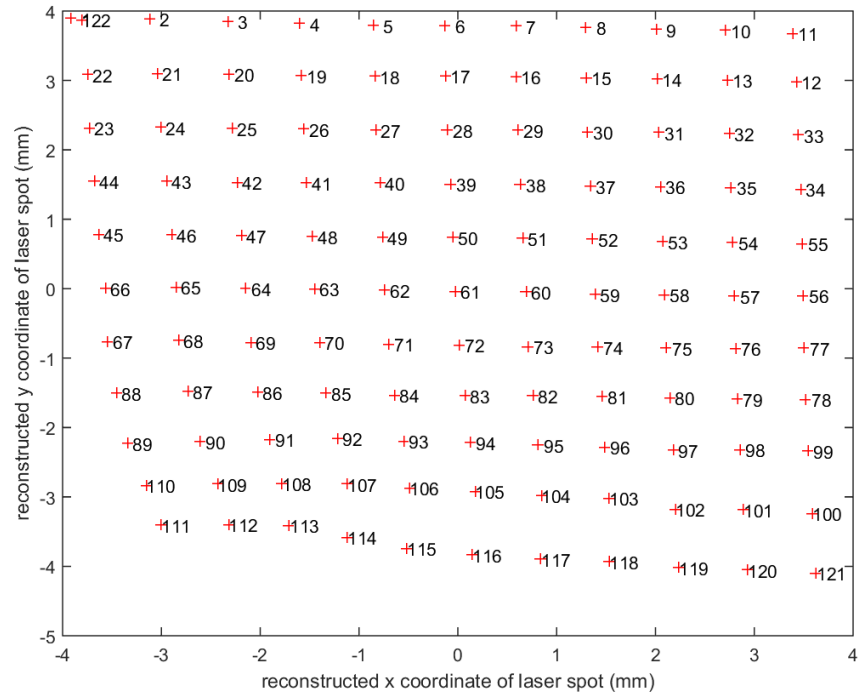
Method

We set the LAMBDA sensor with plate 33 (macor) on the motorised micrometre machine. We move the LAMBDA sensor in 121 positions ($x = -5 \text{ mm} \dots +5 \text{ mm}$, $y = -5 \text{ mm} \dots +5 \text{ mm}$ in steps of 1 mm). For each position, we capture pictures and we process them with the usual steps in order to extract the positions of the laser spot centre.

Finally, we compute differences between theoretical and measured positions and we show residuals.

Results

Measured values



Conclusion

Results are not satisfying. On one hand, we can see that the pattern has a weird behaviour in the bottom left part (x towards -5mm, y towards -5mm). On the other hand, there seems to be a scale factor between theoretical values (10 mm range) and measured values (8 mm range).

If the problem comes from applying Gaussian fitting on a large laser spot, we could try with a smaller spot. If the problem comes from coordinate system related to laser beam, coordinate system related to shutter and coordinate system related to micrometre table, we should realign these 3 elements.

9. Measurement accuracy when sensor moved in x and y over 10 mm (small laser spot)

History

2015-05-04: started report, captured pictures, wrote MATLAB code

2015-05-05: finished MATLAB code, finished report

Context

The previous experiment showed a scale factor between measured values and theoretical values and a weird behaviour in the bottom left part of the ceramic plate.

In order to see if these phenomena are related to the size of the laser spot, we remove the beam expander and we use a collimator.

Objective

We want to determine residuals between positions of the motorised micrometre table (= theoretical values) and positions measured by the LAMBDA sensor (= measured values).

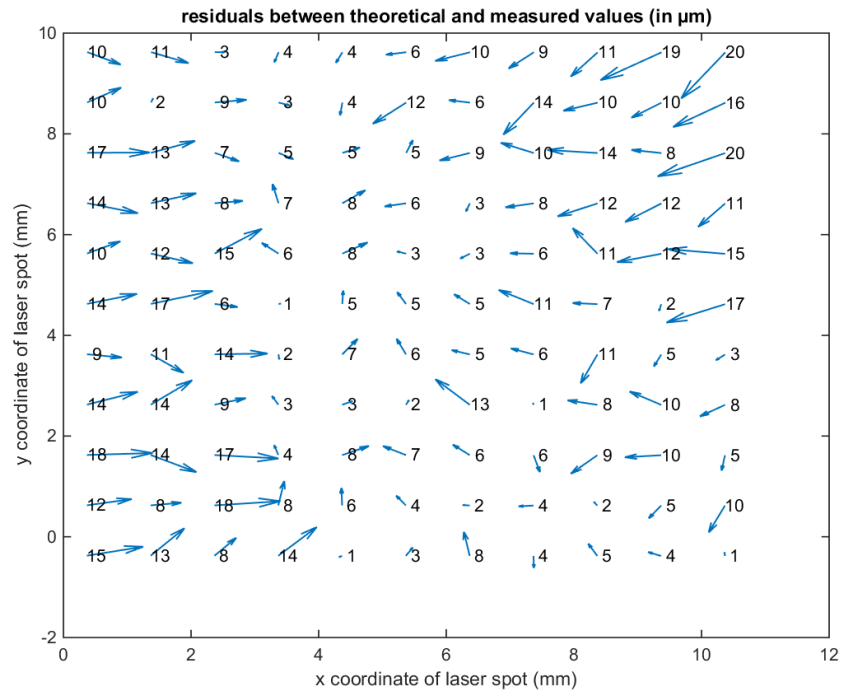
Method

We set the collimator used by Friedrich at the end of the optical fibre. We set the LAMBDA sensor with plate 33 (macor) on the motorised micrometre machine. We move the LAMBDA sensor in 121 positions ($x = -5 \text{ mm} \dots +5 \text{ mm}$, $y = -5 \text{ mm} \dots +5 \text{ mm}$ in steps of 1 mm). For each position, we capture pictures and we process them in order to extract the positions of the laser spot centre.

Finally, we compute differences between theoretical and measured positions and we show residuals.

Results

Residuals between theoretical and measured values



Conclusion

Measurements with the small laser spot give better results than with the large laser spot. Residuals are smaller than $20\ \mu\text{m}$ and still show scale factors in radial and vertical direction. These scale factors may be related to existing angles between laser beam axis, shutter plane and displacement plane of the micrometre table.

10. Impact of angles between laser beam, shutter and camera axis

History

2015-05-05: started report, completed MATLAB code, finished report

Context

The previous experiment showed a small scale factor between measured values and theoretical values that may come from misalignment between laser beam axis, shutter plane and / or displacement plane of the micrometre table.

5 configurations can be actually distinguished:

- 1) *Perfect situation: laser beam perpendicular to shutter plane, shutter plane parallel to displacement plane.*

This situation does not present any error when the sensor is moved over a small distance.

- 2) *Laser beam perpendicular to shutter plane, displacement plane random.*

This situation presents a scale factor smaller than 1 when the sensor is moved over a small distance. If there is an angle α (resp. β) between shutter plane and displacement plane affecting the x direction (resp. the y direction), then the scale factor is $\cos(\alpha)$ in x direction (resp. $\cos(\beta)$ in y direction).

This situation can be interpreted as a displacement in x and z direction (resp. in y and z direction).

- 3) *Shutter plane perpendicular to displacement plane, laser beam random.*

In this case, there is no scale factor. The laser spot is elliptic due to the angle between shutter plane and laser beam, but the laser spot centre presents the same displacement as the micrometre table.

- 4) *Laser beam perpendicular to displacement plane, shutter plane random.*

This situation presents a scale factor larger than 1 when the sensor is moved over a small distance. If there is an angle α (resp. β) between shutter plane and displacement plane affecting the x direction (resp. the y direction), then the scale factor is $1/\cos(\alpha)$ in x direction (resp. $1/\cos(\beta)$ in y direction).

- 5) *Everything random.*

This situation is a mix of configurations 2, 3 and 4 thus we have 4 scale factors, two of them being smaller than 1, two of them being larger than 1.

Since the previous experiment showed a scale factor in x and y smaller than 1, there should have been a small angle between shutter plane and displacement plane.

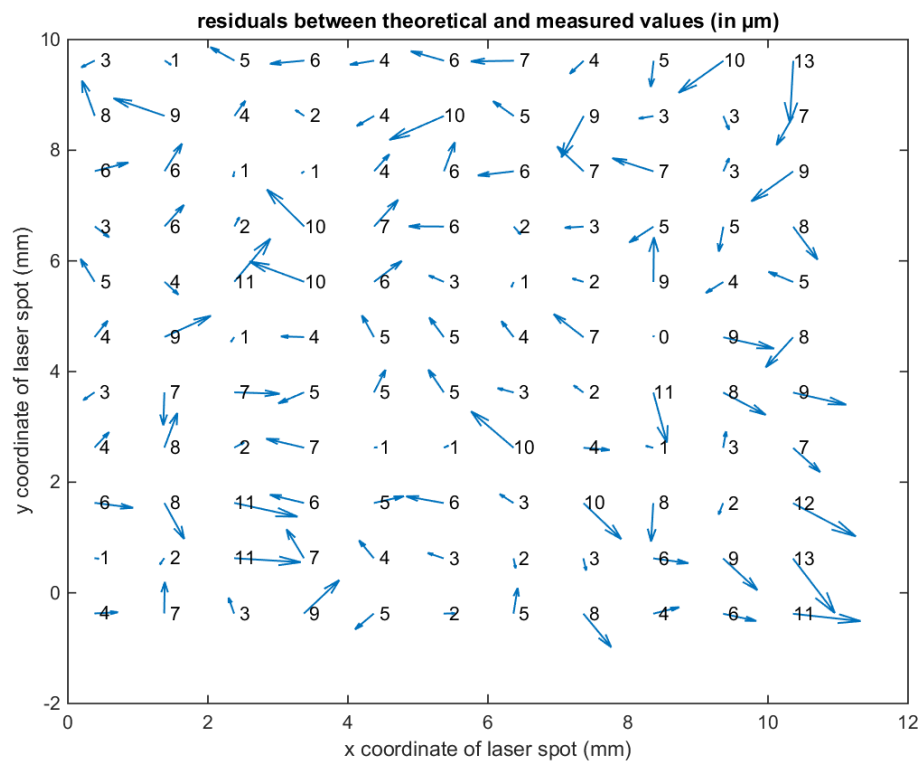
Objective

We want to determine the small angle between shutter plane and displacement plane.

Method

We use the pictures and the algorithm from the previous test. We add two parameters in the final adjustment (two angles).

Results



Angles between shutter plane and displacement plane computed from the adjustment:

In x: 3.8° // In y: 1.9°

Conclusion

Adding two parameters to the adjustment make the residuals look random and their standard deviation decrease ($3.0 \mu\text{m}$). However, the two angles we computed are quite large, which may mean that the model with two extra-parameters is not adapted to our problem.

11. Measurement accuracy over 25 mm

History

2015-05-06: started report, captured pictures, wrote MATLAB code, finished report

Context

The previous experiments were done on a relatively small range (1 mm). We want to increase that range in x and y to have a surface of 25 mm x 25 mm covered and estimate measurement accuracy.

Objective

We compute residuals between theoretical values (given by the table) and measured values (given by the pictures).

Method

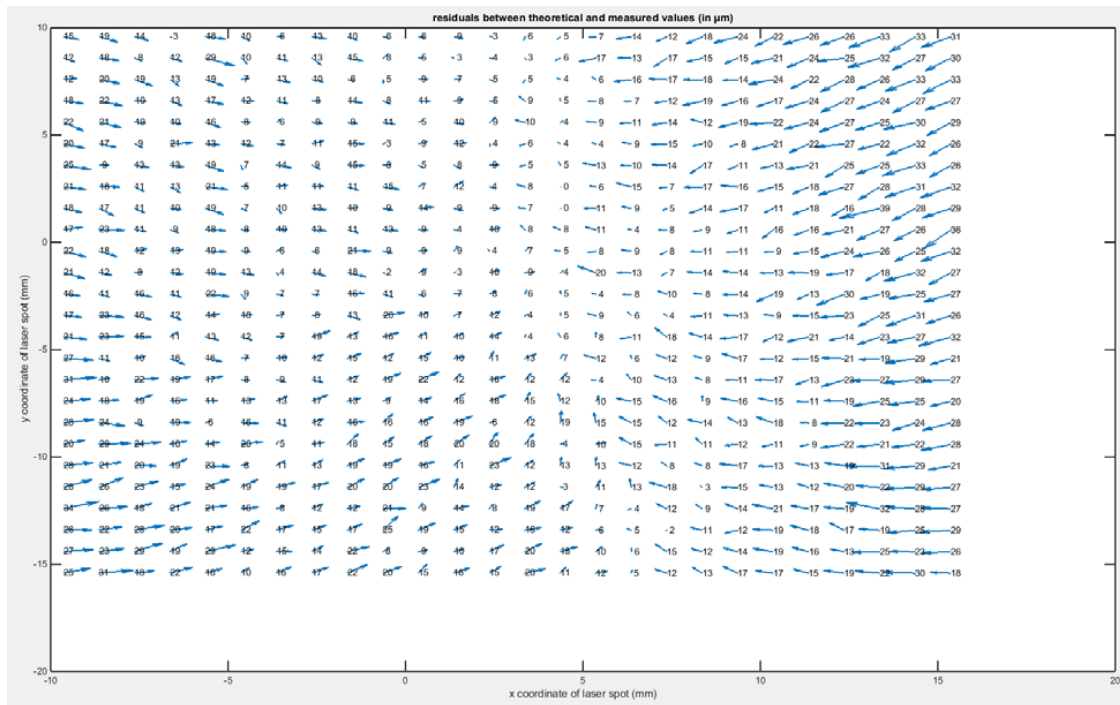
We move the sensor over 25 mm in x and y in steps of 1 mm. For each position, we capture 3 pictures and we keep only the third one in order to have the laser spot stable. Time between pictures is 100 ms. We process pictures with the usual step and we reconstruct the laser spot centres in the shutter plane.

Finally, we adjust laser spot coordinates with theoretical values given by the micrometre table and we present residuals as well as their standard deviations.

Parameters used for the camera: pixel clock 10, time exposure 160, frame rate 6.25

Results

Residuals (standard deviation 7.3 μm)



Conclusion

Residuals still show scale factors that are not explained so far. Local differences that might be related to plate flatness.

12. Measurement accuracy over 25 mm

with corrections due to imperfections of the motorised micrometre table

History

2015-05-07: started report, modified MATLAB code, finished report

Context

The Aerotech table presents scale factors in x and y, as well as an angle error between x and y axes. Based on Viven's calculation, the scale factors are -201 ppm for x, -25 for y and 289 μrad for the angle.

Before working on long range, these errors were negligible. But in a previous experiment (May 6, 2015), we tested a range of 25 mm x 25 mm. With these values, we can expect following errors, which are not negligible anymore:

In x: $0.000201 \cdot 25000 = 5.0 \mu\text{m}$

In y: $0.000025 \cdot 25000 = 0.6 \mu\text{m}$

Angle between x and y: $0.000289 \cdot 25000 = 7.2 \mu\text{m}$

Objective

We want to take into account these factors and this angle in order to improve measurement accuracy.

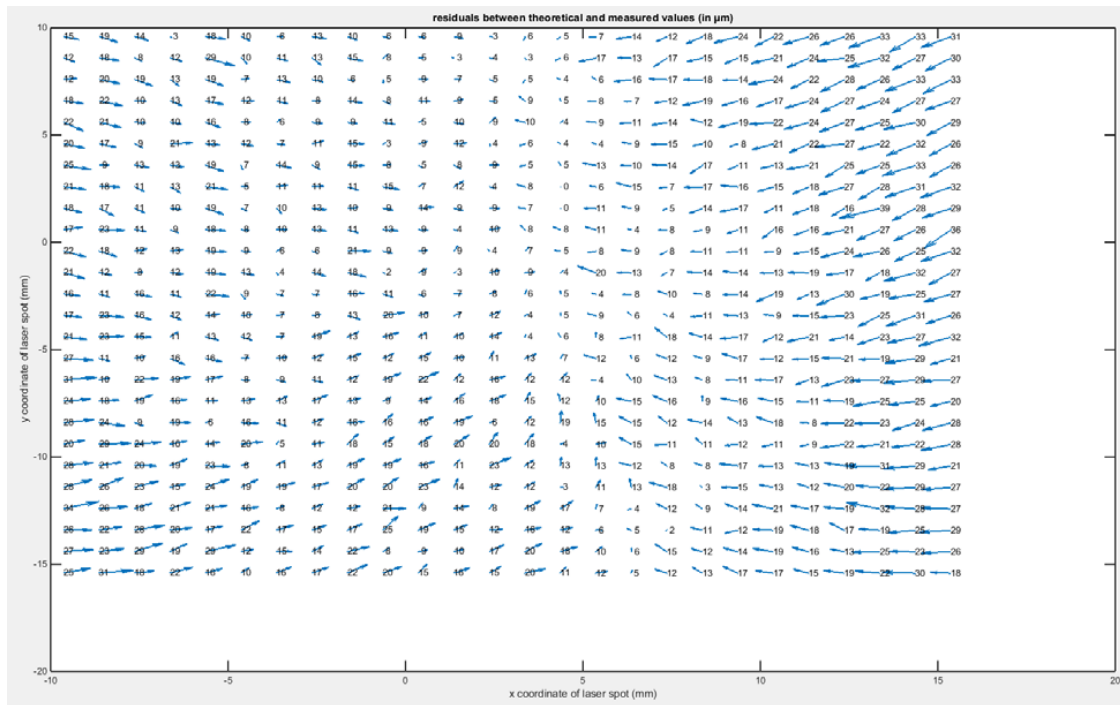
Method

We take results from the experiment on May 6 and we add corrections to the positions of the table.

We adjust corrected micrometre table positions with measured positions of the laser spot and we display residuals.

Results

Total residuals (standard deviation = $7.3\ \mu\text{m}$)



Conclusion

The corrections due to imperfection of the motorised micrometre table do not have a significant impact on the residuals. However, we will keep the corrections for future experiments.

13. Repeatability test over 25 mm

History

2015-05-07: captured pictures

2015-05-08: started report, wrote MATLAB code

2015-05-08: finished report

Context

Previous experiments over 25 mm were done only once, without repeatability test.

Objective

We want to check repeatability, which means doing several tests and estimating the standard deviations of the laser spot on the shutter over these tests.

Method

We apply 5 times the same procedure:

- ➔ We move the sensor over 25 mm in x and y in steps of 1 mm (676 positions in total).
- ➔ For each position, we capture 3 pictures and we keep only the third one in order to have the laser spot stable. Time between pictures is 100 ms.
- ➔ We process pictures with the usual step and we reconstruct the laser spot centres in the shutter plane.
- ➔ We adjust laser spot coordinates with theoretical values given by the micrometre table and we show residuals.

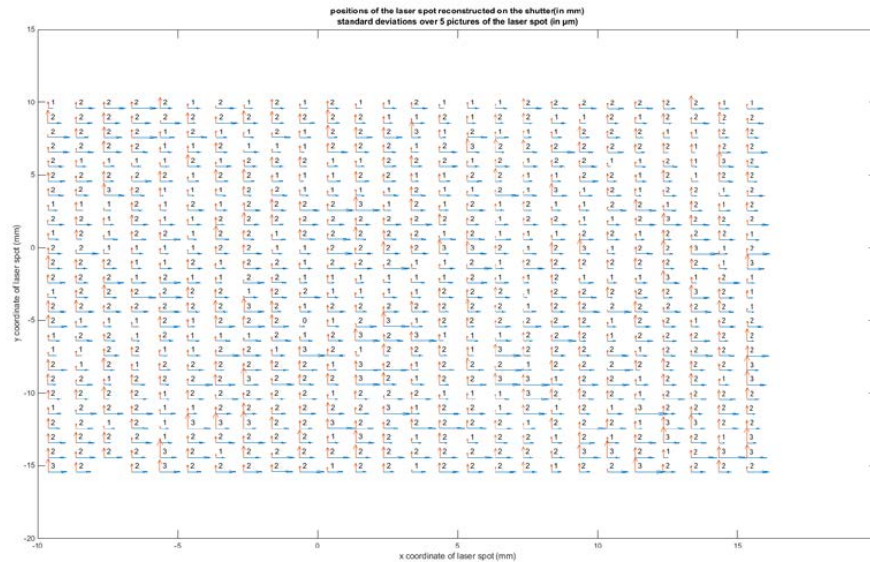
In addition, in order to check repeatability, we compute standard deviations over 5 pictures of the laser spot coordinates in the 676 different positions.

(Parameters used for the camera: pixel clock 10, time exposure 160, frame rate 6.25)

Results

Results are similar for the 5 series of pictures. Residuals look like the previous test (measurement accuracy over 25mm).

Repeatability test: Standard deviations over 5 series of pictures for each position of the laser spot reconstructed (in μm)



Conclusion

The residuals for the first series of pictures show scale factors in x and y. This issue has not been solved yet.

The standard deviations over the 5 series of pictures show in average standard deviations of $1.1 \mu\text{m}$ for x and $1.3 \mu\text{m}$ for y, probably related to laser spot instability. Since we captured pictures during approximately 2h30, this repeatability test is quite satisfying.

14. Measurement accuracy w.r.t. angle

History

2015-05-10: captured pictures, started report

2015-05-11: wrote MATLAB code, added results to report

2015-05-13: finished report

Context

Previous experiments showed scale factors between expected and measured values, especially in radial direction. The angles between laser beam and shutter plane, as well as between shutter plane and table displacement plane can be the reasons for these scale factors. In order to understand better the impact of the angle around the vertical axis on measurement accuracy, we will perform an experiment.

Objective

We want to estimate measurement accuracy with respect to the angle around the vertical axis.

Method

We test 17 different angles : -4° to $+4^\circ$ in steps of 0.5° .

For each angle, we apply the same procedure:

- ➔ We move the sensor over 25 mm in x and y in steps of 5 mm (36 positions in total).
- ➔ For each position, we capture 3 pictures and we keep only the third one in order to have the laser spot stable. Time between pictures is 100 ms.
- ➔ We process pictures with the usual step and we reconstruct the laser spot centres in the shutter plane.
- ➔ We adjust laser spot coordinates with theoretical values given by the micrometre table and we show residuals.

(Parameters used for the camera: pixel clock 10, time exposure 160, frame rate 6.25)

Results

The residuals are minimised for the angles -3.5° and 3.5° . The graphs present scale factors smaller than 1 for angles between -3° and 3° , and larger than 1 for the angles -4° and 4° . In addition, results look symmetrical with respect to angle 0° .

Conclusion

If the angles between laser beam and shutter plane, as well as between shutter plane and table displacement plane were responsible for the scale factors, the results should not be symmetric around 0° . Subsequently, we have to look for another reason.

15. Target reconstruction and measurement accuracy with 3D correction

History

2015-05-13: started report, wrote MATLAB code

2015-05-15: completed MATLAB code, added results to report, finished report

Context

Previous experiments showed scale factors between expected and measured values, which might be related to shutter flatness and a wrong reconstruction of points from ccd to shutter. We want to take into account shutter flatness measured by metrology lab and see its impact on target reconstruction and measurement accuracy.

Objective

We want to estimate residuals of target reconstruction and measurement accuracy with and without 3D correction.

Method

We use target centres measured in the previous experiment (20150510_measurement_accuracy_wrt_angle). We take the MATLAB class "ProjectiveGeometry" from the folder "20150510_measurement_accuracy_wrt_angle" and the MATLAB class "ProjectiveGeometry3D" from the folder "20150331_comparison_grayscale_or_red_component" and we modify them. We perform target reconstruction in both cases and we compare residuals.

In addition, we reconstruct laser spot with and without 3D correction, we perform an adjustment with expected values and we compare residuals.

Results

Target reconstruction is slightly improved. In average over all pictures, the standard deviations of the residuals is 5.6 μm without 3D correction and 4.4 μm with 3D correction.

However, laser spot reconstruction does not improve. For instance, for an angle of 0° , the standard deviations of the residuals between measured and expected values are:

	Total	X	Y
Without 3D correction	6.7 μm	6.6 μm	4.7 μm
With 3D correction	6.6 μm	6.5 μm	4.9 μm

Results are similar for other angles.

Conclusion

3D correction does not improve laser spot reconstruction. Scale factors are still observed.

16. Reconstruction pixel by pixel

History

2015-05-15: started report, wrote MATLAB code, added results to report, finished report

Context

Previous experiments showed scale factors between expected and measured values, which might be related to the fact that Sébastien's algorithm is applied on distorted images. We want to invert the process: reconstruct first pixel by pixel the image in the shutter plane and then apply Gaussian fitting.

Objective

We want to estimate measurement accuracy when reconstructing pixel by pixel and compare it to previous results.

Method

We use target centres measured in a previous experiment (20150510_measurement_accuracy_wrt_angle). We compute parameters of projective geometry with the usual method and reconstruct the images pixel by pixel. We apply Gaussian fitting on these reconstructed images.

Finally, we perform an adjustment with expected values and we compare residuals.

Results

Residuals look similar to the previous experiments and standard deviations are of the same order of magnitude.

Conclusion

Reconstructing pixel by pixel before Gaussian fitting does not improve measurement accuracy in this case. Maybe reconstructing pixel by pixel before ellipse fitting would be more effective but this would require an iterative process, since reconstructing implies knowing parameters of projective geometry.

17. Measurement accuracy with respect to laser spot size

History

2015-05-16: started report, wrote MATLAB code, added results to report, finished report

Context

Previous experiments showed scale factors between expected and measured values, which might be related to laser spot size. Indeed, removing the beam expander had already improved measurement accuracy. We want to see if further reducing the spot size keeps on improving measurement accuracy.

Objective

We want to estimate measurement accuracy with respect to two different spot sizes.

Method

We set laser voltage on two different values (0.02 V and 0.04 V), which results in two different spot sizes. We capture series of 121 pictures in both configurations (x and y between 0 and 25 mm in steps of 2.5 mm). Finally, we perform an adjustment with expected values and we compare residuals.

Results

Residuals look similar for both spot sizes.

Conclusion

Changing laser voltage did not make better or worse measurement accuracy. However, we computed same orders of magnitude for the diameters, so the laser spot size was more or less the same for both tests. If possible, we should try another way of decreasing the laser spot size.

18. Measurement accuracy with respect to shutter type

History

2015-05-18: started report, captured pictures for paper plate, wrote MATLAB code

2015-05-19: completed MATLAB code, added results to report, finished report

Context

Previous experiments showed scale factors between expected and measured values, which might be related to the shutter itself. We want to see if changing the shutter improves measurement accuracy.

Objective

We want to estimate measurement accuracy with respect to two different shutters.

Method

We take two different shutters: in paper (shutter n°6) and in ceramic (shutter n°33). We capture series of 121 pictures in both configurations (x and y between 0 and 25 mm in steps of 2.5 mm). Finally, we perform an adjustment with expected values and we compare residuals.

For the ceramic plate, we take the results from the previous test (measurement accuracy w.r.t. spot size, voltage 0.04 V).

Results

The ceramic plate (residuals st. dev. $6.7 \mu\text{m}$) gave better results than paper plate (residuals st. dev. $22 \mu\text{m}$).

Based on the arrow graphs, the scale factors seem to be still present for paper plate, especially for the x direction, but the residuals are too large to draw a final conclusion.

Conclusion

For future experiments on measurement accuracy, we will keep the ceramic plate.

19. Measurement accuracy of a thin ceramic plate

History

2015-05-21: started report

2015-05-21: wrote MATLAB code

2015-05-24: completed MATLAB code, finished report

Context

The previous experiment showed that ceramic gives better results than paper and glass in terms of measurement accuracy. A quick test with another ceramic plate (thinner than the one used for the previous experiment) seems to give even better results. We want to confirm this with a more detailed experiment.

Objective

We want to estimate measurement accuracy on the thin ceramic plate (n°27). In a first iteration, we reconstruct the laser spot coordinates by means of projective geometry (using targets). In a second iteration, we reconstruct the laser spot coordinates directly from the camera plane to the theoretical positions given by the motorised micrometre machine (without targets). We also do a repeatability test.

Method

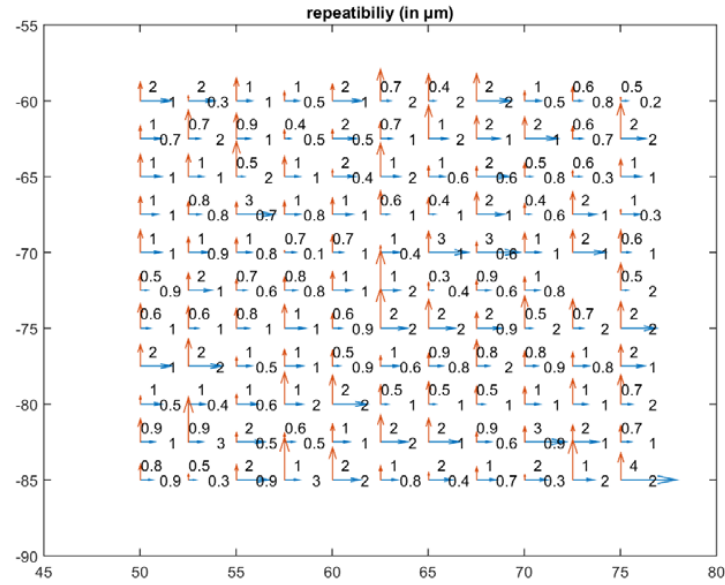
We set the ceramic plate on the sensor. We capture series of 121 pictures (x and y between 0 and 25 mm in steps of 2.5 mm). We process data with and without target reconstruction. Finally, we perform an adjustment with expected values and we show residuals.

We repeat the test 3 times in order to have an idea of repeatability.

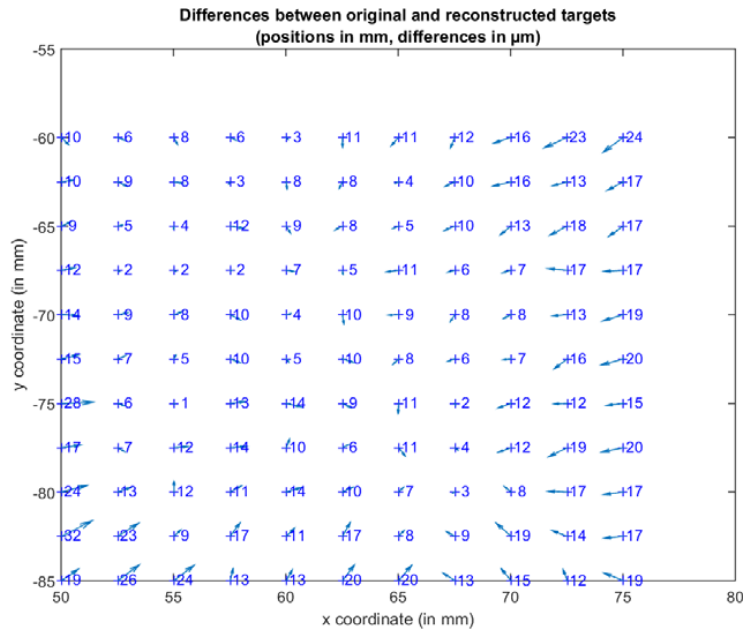
Results

The standard deviation of the residuals (reconstruction without targets) is slightly better with the thin ceramic plate (around 4.5 μm) than with the thick one (around 5.5 μm).

Repeatability – reconstruction with targets



Residuals (series of pictures 3) – reconstruction with targets



Conclusion

The repeatability test shows good repeatability ($< 2\mu\text{m}$).

The residuals of the last series of pictures (with target reconstruction) show that the scale factors are still present for the thin ceramic plates (around $50\mu\text{m}$ for a total course of 2.5 mm). Thus, these scale factors don't seem to be related to the shutter.

However, without target reconstruction, the residuals of the thin ceramic plate (around $4.5\mu\text{m}$) have a smaller standard deviation than the ones of the thick ceramic plate (around $5.5\mu\text{m}$).

20. Measurement accuracy with camera behind shutter

History

2015-05-28: started report, captured pictures, wrote MATLAB code, finished report

Context

Previous experiments showed scale factors between expected and theoretical laser spot positions. Such a phenomenon might be observed because of internal reflection. We want to know if observing the laser spot from behind the shutter (transmitted beam) gives better result than from the front (reflected beam).

Objective

We want to estimate measurement accuracy and repeatability on the thin ceramic plate (n°27), when the camera is placed behind the shutter.

Method

We unscrew the sensor from the micrometre machine, rotate it by 180° in order to have the camera behind the shutter and we screw it again.

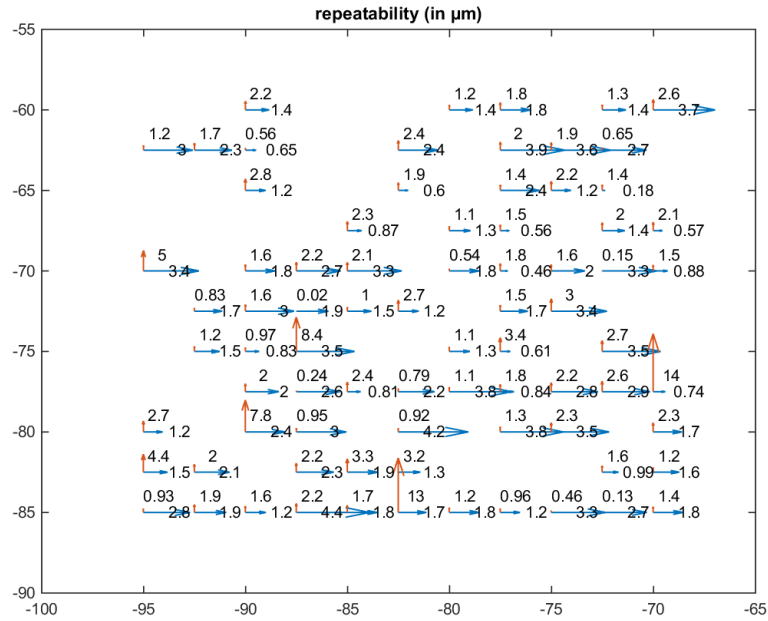
We capture series of 121 pictures (x and y between 0 and 25 mm in steps of 2.5 mm). We process data with and without target reconstruction. Finally, we perform an adjustment with expected values and we show residuals.

We repeat the test 3 times in order to have an idea of repeatability.

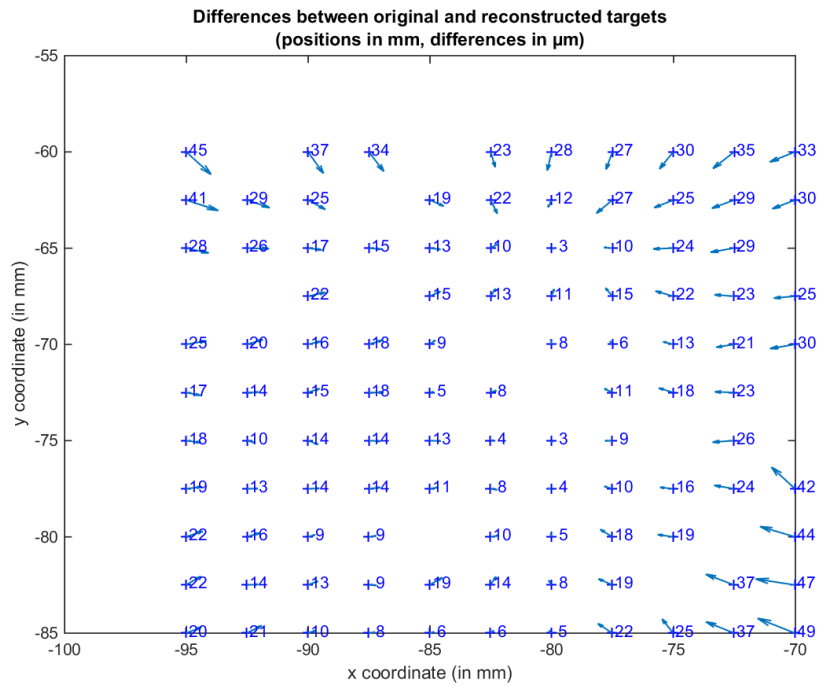
Results

Many outliers were detected (>10%). From the remaining points, results are similar when the camera is behind or in front of the shutter.

Repeatability



Residuals (series of pictures 3)



Conclusion

When the camera is located behind the shutter, many outliers are detected.

Repeatability is good (mainly $< 3\mu\text{m}$). The residuals of the last series of pictures show that the scale factors are still present (almost $70\mu\text{m}$ for a total course of 2.5 mm).

21. Measurement accuracy with respect to camera position

History

2015-05-29: started report, captured pictures, started MATLAB code

2015-06-01: completed MATLAB code, finished report

Context

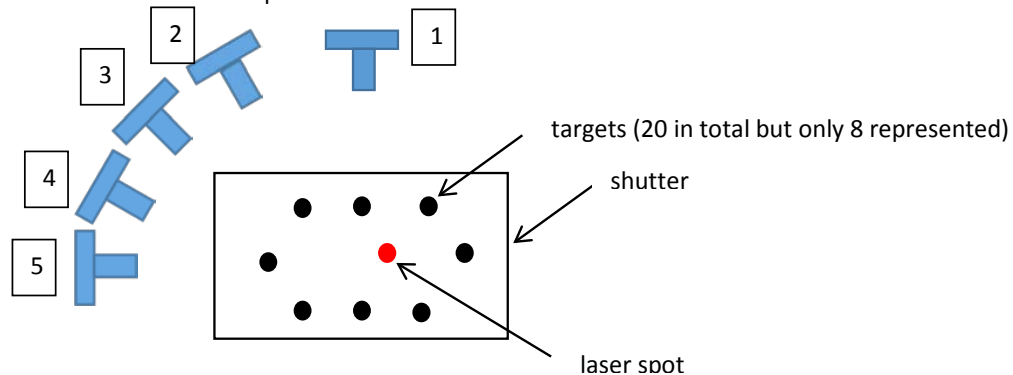
Previous experiments showed scale factors between expected and theoretical laser spot positions. Such a phenomenon might be observed because of the angle between camera axis and laser beam.

Objective

We want to estimate measurement accuracy and repeatability on the thin ceramic plate (n°27) when the camera is placed at different positions.

Method

We set the camera at 5 different positions:



For each camera position, we capture a series of 121 pictures (x and y between 0 and 25 mm in steps of 2.5 mm). We process data with the usual steps. Finally, we perform an adjustment with expected values and we show residuals.

For each camera position, we repeat the test 3 times in order to have an idea of repeatability.

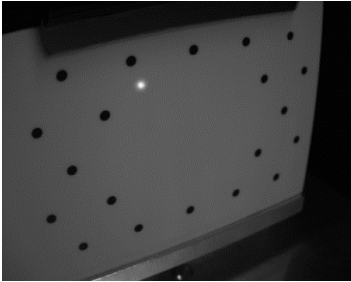
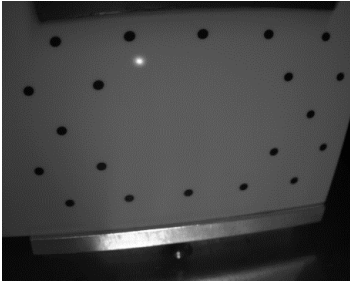
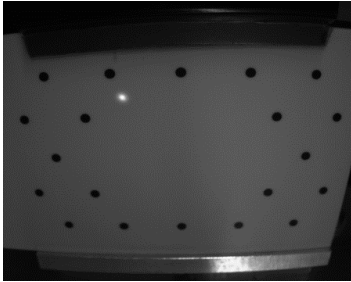
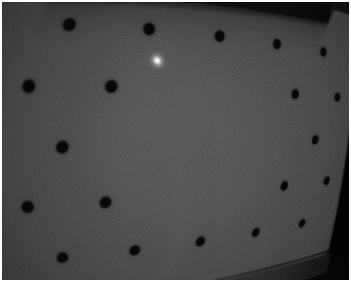
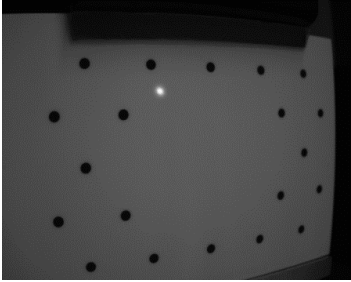
Results

Standard deviations of residuals

For each camera position, results are similar for the 3 series of pictures. The following table gives the standard deviations of the residuals for series of pictures 3.

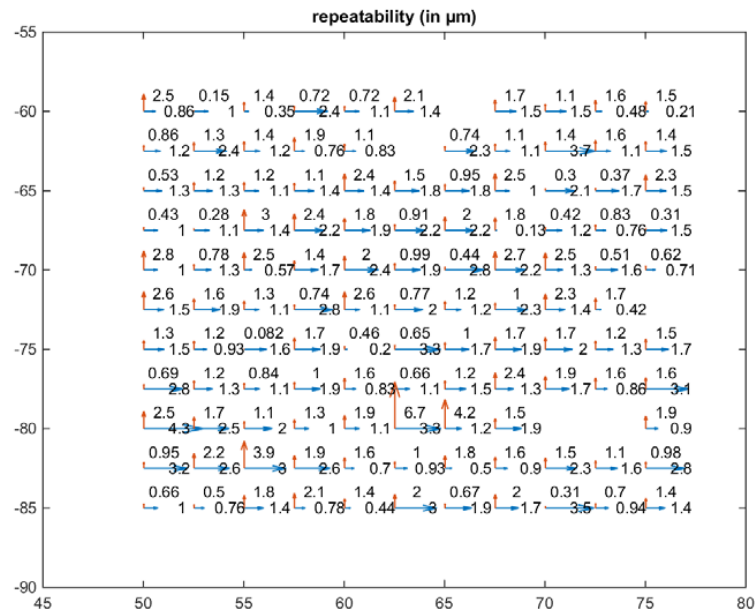
Camera position	1	2	3	4	5
St. dev. residuals reconstructed (in μm)	8.4	7.8	7.8	5.9	7.8

Examples of pictures

Camera position 3 	Camera position 2 	Camera position 1 
Camera position 4 		
Camera position 5 		

Results are similar for all positions, thus only graphs of camera position 1 are presented.

Camera position 1 - Repeatability



Conclusion

The repeatability is good for all positions (mainly $<3\text{ }\mu\text{m}$).

The residuals of the last series of pictures show that the scale factors are still present for all angles.
Camera position 4 shows smaller residuals than other positions, so far unexplained.

22. Measurement accuracy with depth correction

History

2015-06-04: started report, completed MATLAB code

2015-06-05: completed MATLAB code, finished report

Context

Previous experiments showed scale factors between expected and theoretical laser spot positions. Such a phenomenon might be observed because of the angle between camera axis and laser beam.

Objective

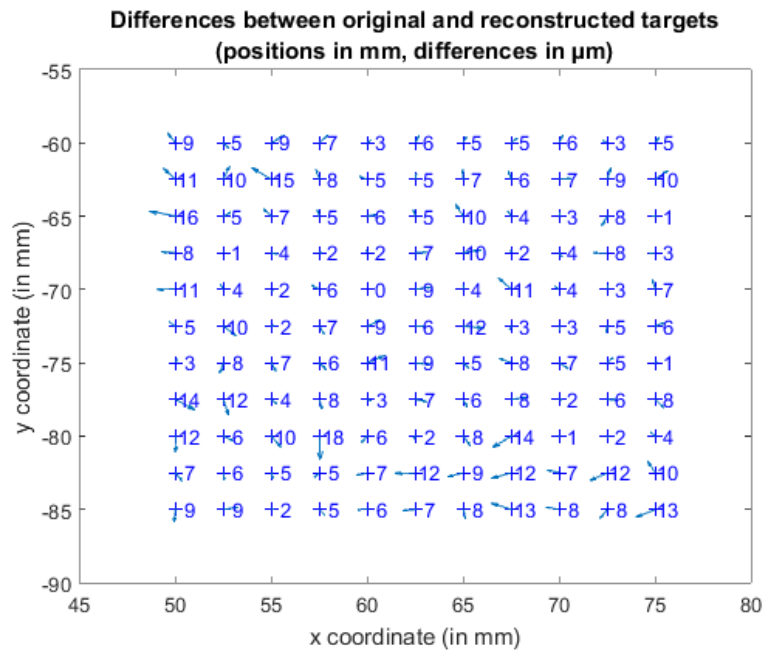
We want to estimate measurement accuracy with depth correction.

Method

We use pictures and MATLAB code of experiment “Measurement accuracy with respect to camera position” from May 29, 2015. We write a new function taking a depth of 100 μm into account and we apply it on the output coordinates. We compute standard deviations of residuals and compare them without depth correction.

Results

Residuals



Standard deviations of residuals

Camera positions	1	2	3	4	5
Estimated angles (around x)	30°	30°	30°	15°	0°
Estimated angles (around y)	0°	10°	20°	20°	20°
St. dev. residuals reconstructed (in μm)	8.4	7.8	7.8	5.9	7.8
St. dev. residuals reconstructed and depth correction (in μm)	5.4	5.1	5.6	7.2	5.2

Conclusion

The standard deviation of the residuals decrease when depth is corrected. Except camera position 4, all standard deviations are below 5.6 μm (instead of being below 8.4 μm). In addition, the scale factors have disappeared.

However, with corrections due to depth reflection, we have to determine the angles between camera plane and shutter accurately.

23. Determining angle between shutter plane and camera plane

History

2015-06-09: started report, started MATLAB code

2015-06-10: completed MATLAB code, finished report

Context

In the previous experiments (depth correction), the angles between shutter and camera were roughly estimated. However, if we know the 8 parameters of projective geometry, we should be able to calculate the angles between shutter plane and camera plane. I found an interesting paper dealing with this problem (Horn 1999, *Projective Geometry Considered Harmful*).

Objective

We want to compute the rotation matrix from the shutter coordinate system to the camera coordinate system.

Method

We use a vector of 8 parameters coming from the previous test (depth correction, camera position n°5). We apply the procedure described in the paragraph "Recovery of Orientation" of the paper mentioned above and we retrieve angles based on Slabaugh's paper *Computing Euler angles from a rotation matrix*.

Results

We find following rotation matrix:

$$R = \begin{bmatrix} 0.8941 & -0.0141 & 0.4475 \\ 0.0440 & 0.9975 & -0.0553 \\ -0.4456 & 0.0689 & 0.8925 \end{bmatrix}$$

And following rotation angles:

Rotation around x axis: 4.4°

Rotation around y axis: 26.5°

Rotation around z axis: 2.8°

These results correspond to what was expected. However, one problem appears: the rotation matrix is not orthonormal. Based on B. Horn's paper, this result is not surprising because projective geometry is not a perfect camera model. Thus, the rotation matrix cannot be reconstructed accurately.

Conclusion

We managed to compute angle values that are close to reality but we don't know their uncertainties.

24. Angles computed from parameters of projective geometry

History

2015-06-12: started report, wrote MATLAB code, finished report

Context

The previous study enabled the calculation of the angles between shutter and camera. It was done for one picture in the configuration where the camera was set on the left of the shutter (camera position n°5).

Objective

We want to estimate the angles from all camera positions (n°1 to n°5) and compare them to guessed values.

Method

We use the vectors of 8 parameters coming from the previous test (depth correction). We apply the procedure described in the paragraph "Recovery of Orientation" of the paper mentioned above and we retrieve angles based on Slabaugh's paper *Computing Euler angles from a rotation matrix*.

Results

Computed angles over 363 pictures

Series of 363 pictures	Angle around x			Angle around y		
	Guessed value	Computed value	Standard deviation	Guessed value	Computed value	Standard deviation
1	30°	31.5°	0.009°	0°	-1.7°	0.007°
2	30°	35.8°	0.008°	10°	10.2°	0.009°
3	30°	32.1°	0.008°	20°	25.7°	0.006°
4	15°	13.1°	0.006°	20°	26.4°	0.004°
5	0°	4.4°	0.010°	20°	26.7°	0.006°

In the previous study, I guessed with the eye some values for the angles around x and y. Now, I can check whether these guesses were right or not. For the angle around x, the errors were about 5°. For the angle around y, the errors were about 6°.

Conclusion

With the correct angle values, we can now estimate more precisely the depth that minimises the residuals of the reconstructed laser spot positions.

25. Comparison between projective geometry and perspective projection

History

2015-06-24: started report, wrote MATLAB code

2015-06-29 -> 2015-07-03: modified MATLAB code, finished report

Context

B. Horn points out in his paper *Projective Geometry Considered Harmful* that projective geometry is not the most appropriate model for picture capture by a camera. On the contrary, he recommends perspective projection.

Objective

We want to compare projective geometry and perspective projection in terms of target reconstruction and parameter estimation.

Method

We use target centres computed for pictures captured on May 29 (Measurement accuracy with respect to camera position), camera position 5.

For *projective geometry*, we use the usual process and the usual equations.

$$x_s = \frac{u h_{11} + v h_{12} + h_{13}}{u h_{31} + v h_{32} + 1}$$

$$y_s = \frac{u h_{21} + v h_{22} + h_{23}}{u h_{31} + v h_{32} + 1}$$

(x_s, y_s) are coordinates in the shutter system, (u, v) are coordinates on the camera chip (in the principal point coordinate system) and the h_{ij} are the 8 parameters to be estimated.

For *perspective projection*, our calculations are based on two relationships:

(1) Rigid body transformation between camera and shutter:

$$\begin{pmatrix} x_s \\ y_s \\ z_s \end{pmatrix} = \begin{pmatrix} r_{11} & r_{12} & r_{13} \\ r_{21} & r_{22} & r_{23} \\ r_{31} & r_{32} & r_{33} \end{pmatrix} \begin{pmatrix} x_c \\ y_c \\ z_c \end{pmatrix} + \begin{pmatrix} x_0 \\ y_0 \\ z_0 \end{pmatrix}$$

The vector (x_c, y_c, z_c) represents a point in the coordinate system of the camera. The vector (x_s, y_s, z_s) represents the same point in the coordinate system of the shutter. The r_{ij} are the elements of the rotation matrix and (x_0, y_0, z_0) is the translation vector from shutter system to camera system.

(2) Perspective projection:

$$\frac{x_c}{z_c} = \frac{u - u_0}{f}$$

$$\frac{y_c}{z_c} = \frac{v - v_0}{f}$$

The parameter f is the principal distance of the camera, the vector (u_0, v_0) is the principal point of the camera. These parameters are known.

With these two relationships, we can derive following equations for perspective projection:

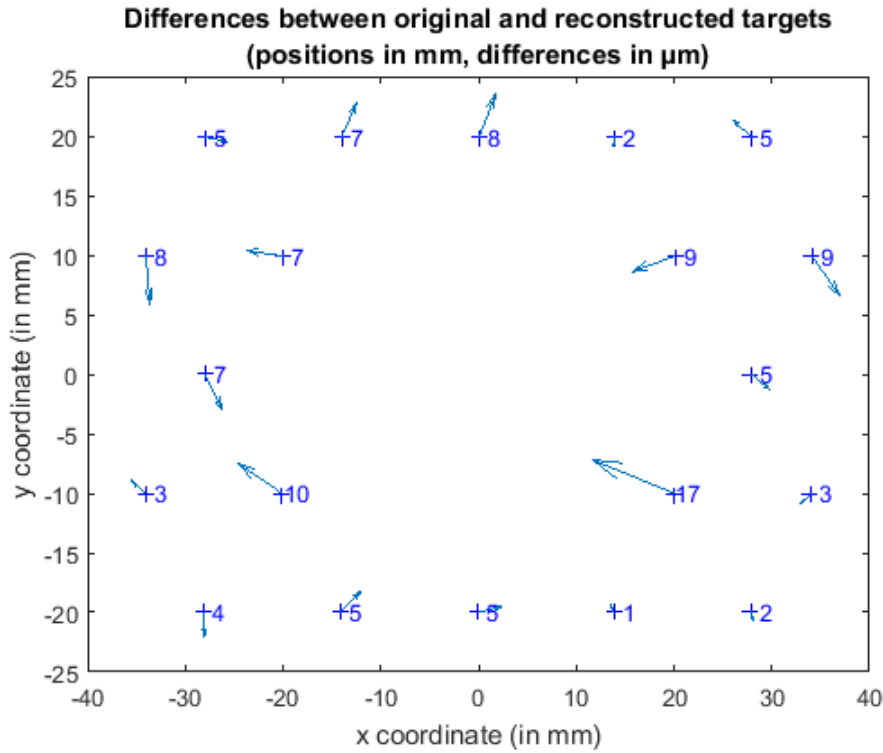
$$x_s = x_0 + (z_s - z_0) \frac{(u - u_0) r_{11} + (v - v_0) r_{12} + f r_{13}}{(u - u_0) r_{31} + (v - v_0) r_{32} + f r_{33}}$$

$$y_s = y_0 + (z_s - z_0) \frac{(u - u_0) r_{21} + (v - v_0) r_{22} + f r_{23}}{(u - u_0) r_{31} + (v - v_0) r_{32} + f r_{33}}$$

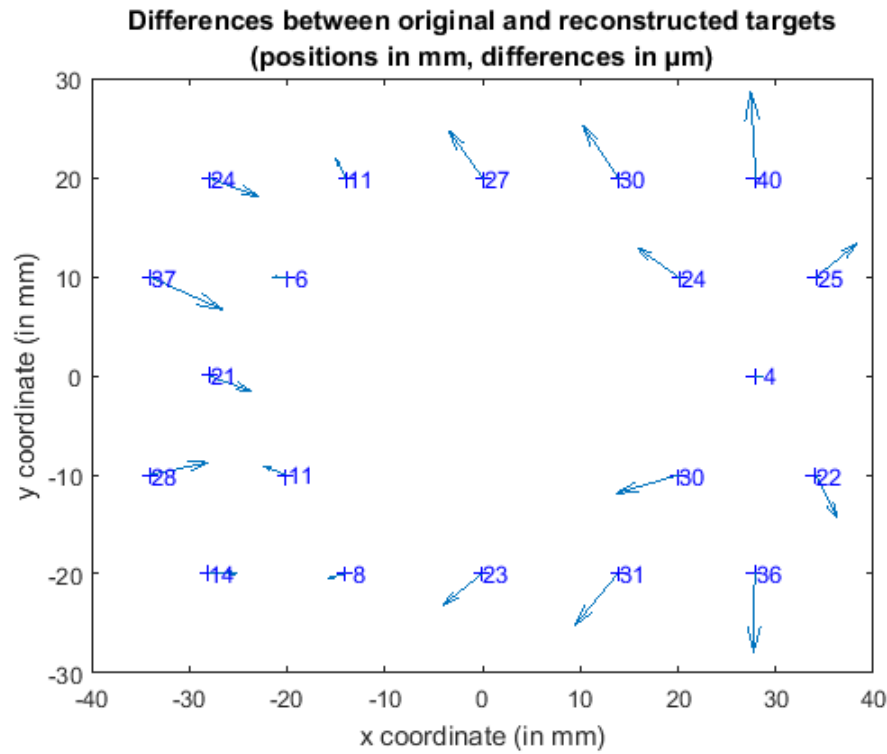
The parameters to be estimated are the 3 angles (a_x, a_y, a_z) of the rotation matrix with elements r_{ij} and the 3 coordinates of the translation vector (x_0, y_0, z_0) .

Results

Target reconstruction for projective geometry



Target reconstruction for perspective projection



Parameter estimation

	x_0	y_0	z_0	α_x	α_y	α_z
Projective geometry	-52.43 mm	10.24 mm	-84.66 mm	4.4°	26.5°	-2.8°
Perspective projection	-52.74 mm	10.27 mm	-84.51 mm	3.5°	26.8°	-0.9°

Conclusion

We can see that target reconstruction does not work well with perspective projection. Maybe the equations for perspective projection mentioned above are not correct?

However, the estimations of the translation vector and the rotation angles are of the same order of magnitude.

26. Comparison between projective geometry and perspective projection for different camera positions

History

2015-07-06: started report, wrote MATLAB code

2015-07-07: finished report

Context

In the previous experiment, projective geometry surprisingly gave better results than perspective projection when the camera was positioned on the left side of the shutter. So far, we don't have any explanation. Maybe the used formulas are not correct.

Objective

In order to better understand the phenomenon, we want to compare projective geometry and perspective projection in terms of target reconstruction and parameter estimation for different camera positions.

Method

We use target centres computed for pictures captured on May 29 (Measurement accuracy with respect to camera position), camera position 1 to 5.

We use the same formula as the previous report (comparison projective geometry / perspective projection, June 24, 2015)

Results

We observe similar residuals for all camera positions: random behaviour in case of projective geometry, scale factor behaviour for perspective projection. Parameters are of the same order of magnitude with both methods but residuals are not satisfying for perspective projection (st. dev. around $20\mu\text{m}$).

Conclusion

We have still not understood why perspective projection presents this scale factor behaviour.

27. Comparison with other software

History

2015-07-08: started report, sent data to Bertrand Cannelle (HEIG-VD)

2015-07-29: received report from B. Cannelle

2015-08-03: finished report

Context

Since perspective projection does not give satisfying results in terms of target reconstruction, I contacted Bertrand Cannelle, a colleague of Thomas Touzé at HEIG-VD, who can check target reconstruction with his photogrammetry software (working with perspective projection).

Objective

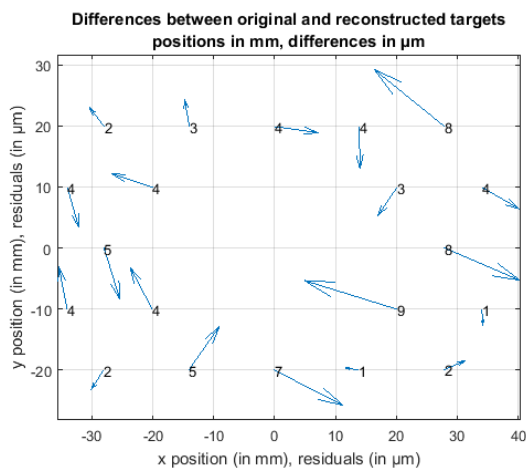
We want to check residuals after target reconstruction with another photogrammetry software.

Method

We use target centres computed for pictures captured on May 29 (Measurement accuracy with respect to camera position), camera position 1 to 5.

Results

Target reconstruction after adjustment with 5 pictures



Conclusion

It is possible to find a standard deviation of residuals of $5 \mu\text{m}$ when all parameters (distortion and perspective projection) are estimated together.

28. Comparison between projective geometry and perspective projection when fitting done with half of the targets

History

2015-07-15: started report, wrote MATLAB code, finished report

Context

In the previous experiments, projective geometry gave better results than perspective projection. We want to check if this is due to the fact that projective geometry has more parameters than perspective projection, and thus, compensates for errors in the data.

Objective

We want to compare projective geometry and perspective projection in terms of target reconstruction when half of the targets are used for the fit.

Method

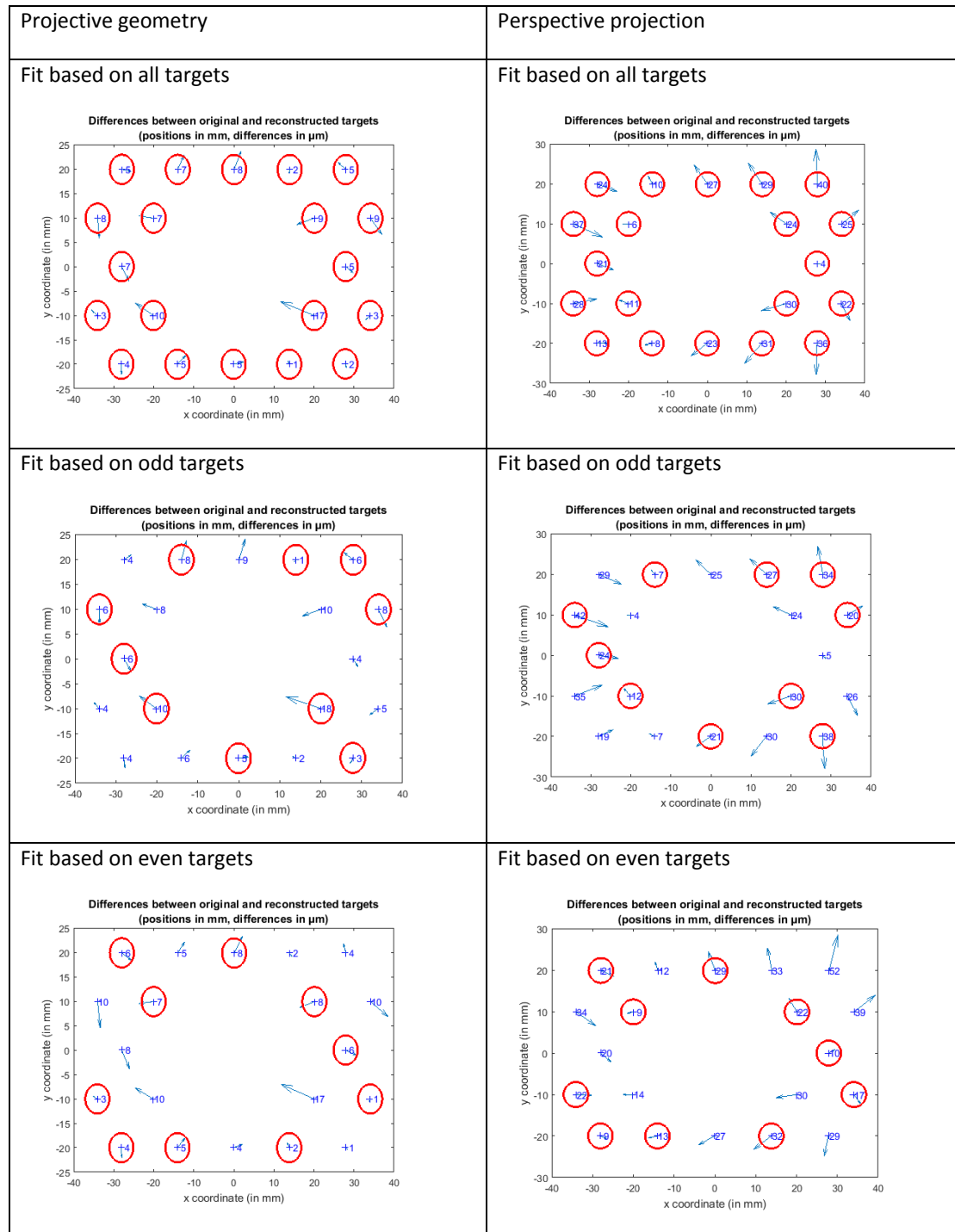
We use target centres computed for pictures captured on May 29 (Measurement accuracy with respect to camera position), camera position 5.

We use the same formulas of projective geometry and perspective projection as in the previous report (comparison projective geometry / perspective projection, July 6, 2015).

For the adjustment, half of the targets are used.

Results

Target reconstruction (red circles indicate targets used for fitting)



Parameter estimation

All targets	x_0 (mm)	y_0 (mm)	z_0 (mm)	a_x (°)	a_y (°)	a_z (°)
Projective geometry	-52.428	10.243	-84.658	4.4	26.5	-2.8
Perspective projection	-52.739	10.261	-84.514	3.5	26.8	-0.9

Odd targets	x_0	y_0	z_0	a_x	a_y	a_z
Projective geometry	-52.424	10.232	-84.666	4.4	26.5	-2.8
Perspective projection	-52.745	10.291	-84.479	3.5	26.8	-0.9

Even targets	x_0	y_0	z_0	a_x	a_y	a_z
Projective geometry	-52.436	10.234	-84.652	4.4	26.5	-2.8
Perspective projection	-52.746	10.192	-84.537	3.5	26.8	-0.9

Conclusion

Taking odd targets or even targets do not change significantly the outcome of target reconstruction.

29. Comparison between projective geometry and perspective projection in terms of noise gain

History

2015-07-15: started report, wrote MATLAB code, finished report

Context

In the previous experiment, projective geometry gave better results than perspective projection. We want to check if this is due to the fact that projective geometry has more parameters than perspective projection, and thus, compensates for errors in the data.

Objective

We want to compare projective geometry and perspective projection in terms of noise gain.

Method

We use target centres computed for pictures captured on May 29 (Measurement accuracy with respect to camera position), camera position 5.

We use the same formulas of projective geometry and perspective projection as in the previous report (comparison projective geometry / perspective projection, July 6, 2015).

We perform a Monte Carlo simulation by repeating 100 times the following actions: (1) add Gaussian noise (with standard deviation $1\mu\text{m}$) to the target positions in the image plane, (2) adjust these corrupted positions with target positions measured in metrology lab. Finally, after 100 simulations, we compute the standard deviations of the parameters of projective geometry and perspective projection.

Results

Mean - Projective geometry

Noise (μm)	x_0 (mm)	y_0 (mm)	z_0 (mm)	a_x (mrad)	a_y (mrad)	a_z (mrad)
0	-52.429	10.243	-84.658	76.918	461.877	-49.175
0.1	-52.427	10.247	-84.658	76.958	461.867	-49.176
0.2	-52.432	10.243	-84.656	76.920	461.917	-49.173
0.5	-52.433	10.264	-84.652	77.160	461.938	-49.160

Mean - Perspective projection

Noise (μm)	x_0 (mm)	y_0 (mm)	z_0 (mm)	a_x (mrad)	a_y (mrad)	a_z (mrad)
0	-52.737	10.262	-84.514	61.811	467.198	-15.951
0.1	-52.737	10.261	-84.514	61.809	467.203	-15.951
0.2	-52.738	10.262	-84.513	61.813	467.212	-15.949
0.5	-52.738	10.260	-84.515	61.802	467.202	-15.939

Standard deviation - Projective geometry

Noise (μm)	x_0 (μm)	y_0 (μm)	z_0 (μm)	a_x (μrad)	a_y (μrad)	a_z (μrad)
0	0	0	0	0	0	0
0.1	8	14	4	157	76	16
0.2	16	27	10	296	162	42
0.5	51	93	30	1018	512	129

Standard deviation - Perspective projection

Noise (μm)	x_0 (μm)	y_0 (μm)	z_0 (μm)	a_x (μrad)	a_y (μrad)	a_z (μrad)
0	0	0	0	0	0	0
0.1	3	5	3	58	41	26
0.2	6	11	8	130	82	55
0.5	15	27	18	312	197	116

x_0 y_0 a_x a_y : the noise on estimated parameters is approximately 2 to 3 times larger for projective geometry than for perspective projection.

z_0 a_z : the noise on estimated parameters is of the same order of magnitude for projective geometry and for perspective projection.

Conclusion

Perspective projection is more robust to noise, which was expected.

30. Comparison between projective geometry and perspective projection

In terms of uncertainty on parameters

History

2015-07-26: started report, wrote MATLAB code

2015-07-26 until 2015-07-30: wrote MATLAB code, finished report

Context

In the previous experiment, we determined the position and the orientation of the camera with respect to the shutter (6 parameters in total) for projective geometry and perspective projection.

Objective

We want to compute the uncertainty associated to these parameters.

Method

We take the results from the experiment on May 29, camera position 5. For perspective projection, the uncertainties can be derived from the covariance matrix K_{xx} almost directly. For projective geometry, a calculation is needed to pass from the uncertainties of the 8 parameters to the uncertainties of the 6 parameters (cf B. Horn's paper).

Results

Parameter estimation and uncertainties

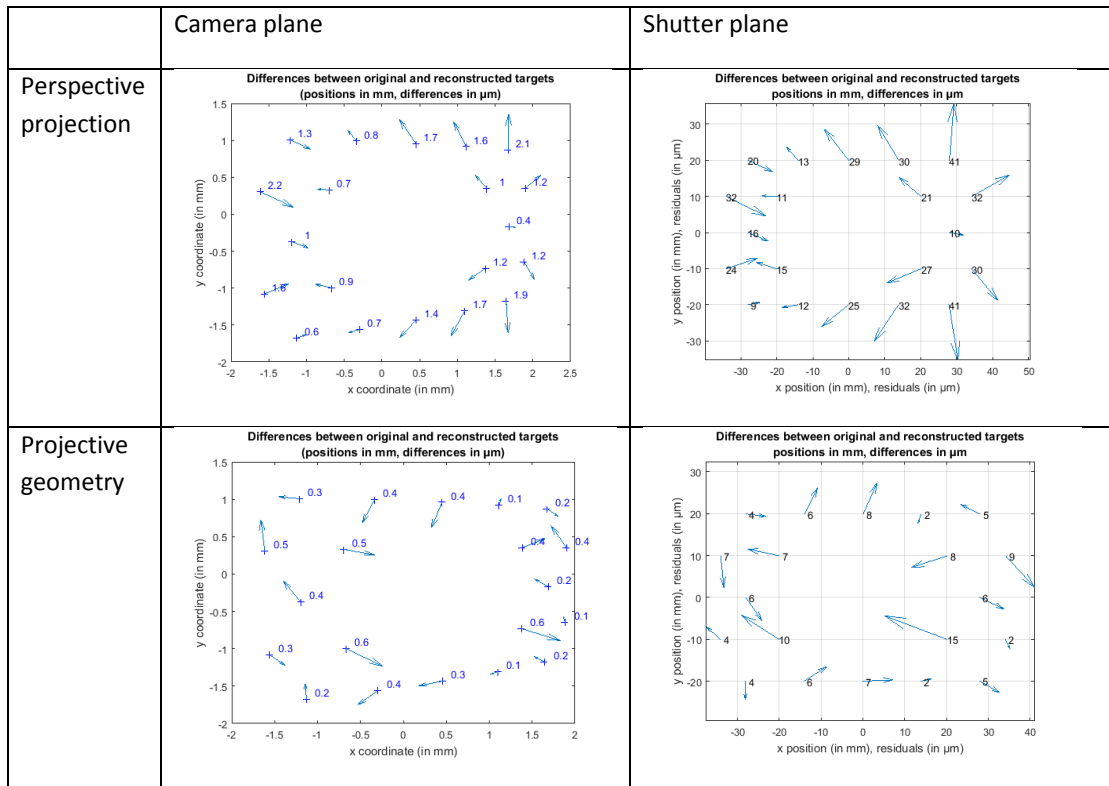
First, we study the parameters describing the position and the orientation of the shutter coordinate system in the camera coordinate system (PP: perspective projection // PG: projective geometry)

	$x_0(mm)$	$y_0(mm)$	$z_0(mm)$	$a_x(mrad)$	$a_y(mrad)$	$a_z(mrad)$
PP values	9.163	-3.269	-99.677	77.29	465.32	48.99
PP uncert.	0.004	0.004	0.021	0.61	0.44	0.18
PG values	9.138	-3.268	-99.621	77.12	461.88	49.20
PG uncert.	0.002	0.001	0.007	0.38	0.21	0.05

Second, we study the parameters describing the position and the orientation of the camera coordinate system in the shutter coordinate system

	$x_0(mm)$	$y_0(mm)$	$z_0(mm)$	$a_x(mrad)$	$a_y(mrad)$	$a_z(mrad)$
PP values	-52.762	10.269	84.504	-61.89	-467.45	-15.93
PP uncert.	0.032	0.052	0.039	0.63	0.44	0.26
PG values	-52.421	10.266	84.648	-61.654	-464.03	-16.48
PG uncert.	0.020	0.033	0.013	0.42	0.21	0.20

Residuals



Conclusion

Uncertainties are smaller for projective geometry than for perspective projection. This is in adequation with the better residuals obtained for projective geometry than perspective projection

31. Study of the most appropriate distortion model

History

2015-08-04: started report, wrote MATLAB code

2015-08-08: finished report

Context

B. Cannelle showed that we can have residuals with a standard deviation of 5 μm when all parameters are estimated at the same time (distortion parameters as well as exterior and interior orientation). I tried to write a similar program but it did not converge. I want to try again with a modified algorithm (Levenberg-Marquardt) and less distortion parameters.

Objective

We want to slightly change the algorithm (add parameter of Levenberg-Marquardt) and compare residuals on target reconstruction in 4 different configurations:

- distortion corrected with 1 parameter (radial distortion)
- distortion corrected with 2 parameters (radial distortion)
- distortion corrected with 4 parameters (radial distortion + tangential distortion)
- distortion corrected with 6 parameters (radial distortion + tangential distortion + affinity and shear)

Method

We take the results from the experiment on May 29, camera position 5.

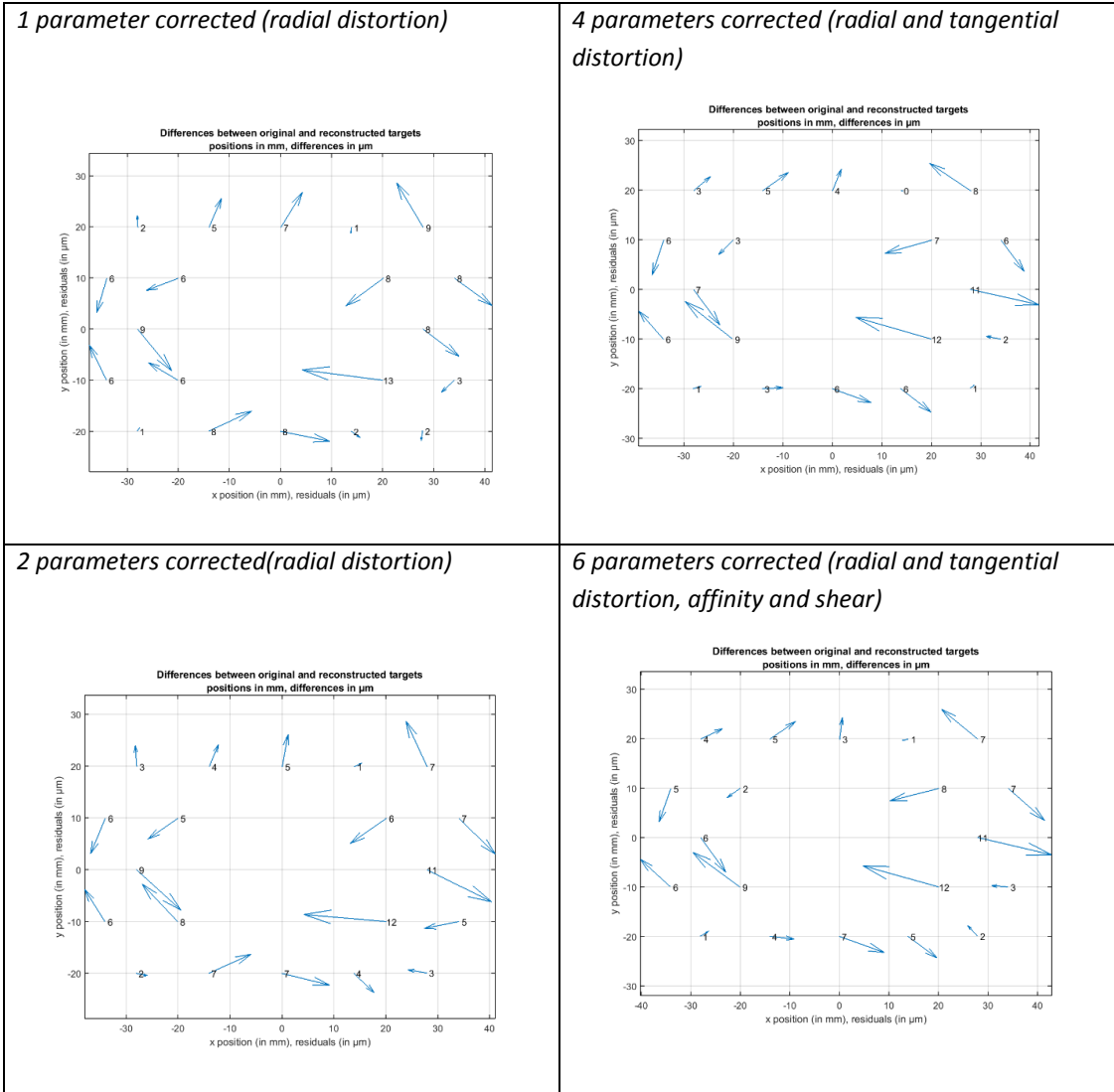
We use the formulas of perspective projection.

Results

Standard deviations of residuals in shutter plane

Nb of parameters corrected	Residuals in x (μm)	Residuals in y (μm)
1	5.3	4.1
2	5.3	3.9
4	5.3	3.4
6	5.5	3.2

Residuals In shutter plane



Parameter estimation and uncertainties

Nb of param. corrected	X0 (mm)	Uncertainty X0 (mm)	Y0 (mm)	Uncertainty Y0 (mm)	Z0 (mm)	Uncertainty Z0 (mm)
1	8.9806	0.095664	-3.1083	0.083821	-101.0572	0.077152
2	9.0768	0.11408	-3.1328	0.08456	-101.0438	0.076408
4	8.0829	0.75297	-2.9566	0.11949	-103.1354	1.4726
6	8.0017	0.88914	-3.126	0.28047	-102.9747	2.3381

Nb of param. corrected	ax (mrad)	Uncertainty ax (mrad)	ay (mrad)	Uncertainty ay (mrad)	az (mrad)	Uncertainty az (mrad)
1	79.8517	1.0314	469.3738	1.0418	50.1043	0.45845
2	79.4750	1.0479	468.3605	1.2322	49.9514	0.46383
4	81.7119	1.6371	478.284	7.6057	51.0675	0.76373
6	81.6203	2.3824	477.6514	11.9783	50.1801	1.54470

Conclusion

The algorithm converges with Levenberg-Marquardt parameter.

The standard deviations of residuals get slightly smaller when the distortion model is changed from 1 to 2 parameters and from 2 to 4 parameters. But they do not decrease from 4 to 6 parameters.

The estimated parameter values are acceptable but their uncertainties are really large. However, according to Sébastien, this is not a problem because the reconstruction of the targets is done with small uncertainty. Thus, the reconstruction of the laser spot will be also done with small uncertainty.

32. Camera calibration on the same plate as the future measurements

History

2015-08-11: started report

2015-08-11 to 2015-08-14: modified MATLAB code

2015-08-15: wrote report

Context

Previous experiments showed that:

- (1) Calibrating the camera with a different plate than the shutter does not give accurate results
- (2) Principal vector and distortion parameters are not estimated correctly with only one picture.

Objective

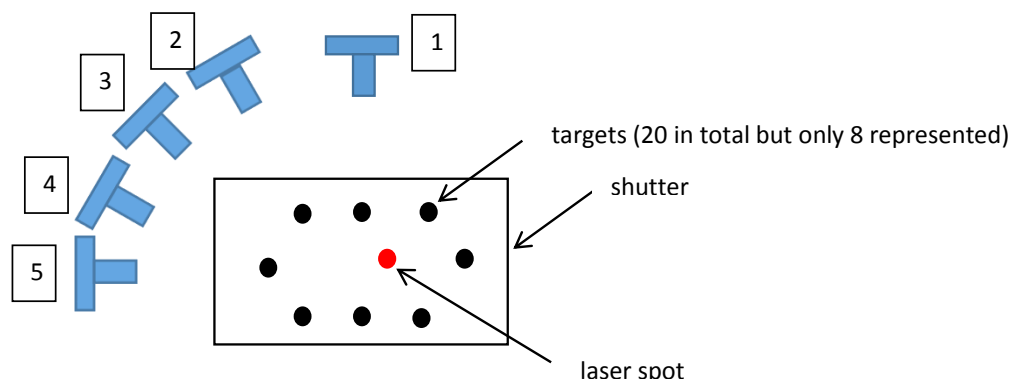
We want to write a program for camera calibration, that:

- (1) Is based on pictures of the shutter
- (2) Estimates parameters with several pictures

With this program, we want to check residuals on reconstructed targets, uncertainties on parameters, uncertainties on reconstructed targets, uncertainties on simulated laser spots.

Method

We use pictures captured on May 29 (measurement accuracy with respect to camera position). We write a program processing target values from 5 different camera positions. For the distortion model, we use only two parameters of radial distortion because the algorithm does not converge with more parameters.



Results

Parameters of exterior orientation - values

Camera positions used for the adjustment	X0 (mm)	Y0 (mm)	Z0 (mm)	Ax (mrad)	Ay (mrad)	Az (mrad)
1	2.187	-2.360	-101.582	557.695	-24.152	8.124
1, 5	2.305	-2.367	-101.662	557.722	-25.391	8.108
1, 3, 5	2.312	-2.395	-101.594	557.363	-25.476	8.111
1, 2, 3, 4, 5	2.346	-2.383	-101.624	557.526	-25.847	8.103

Parameters of exterior orientation - uncertainties

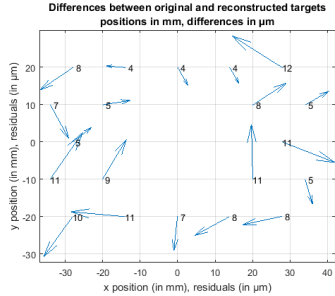
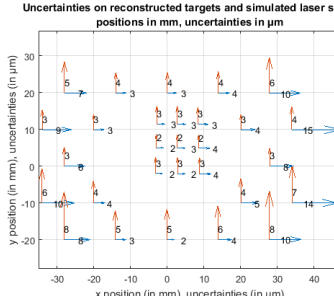
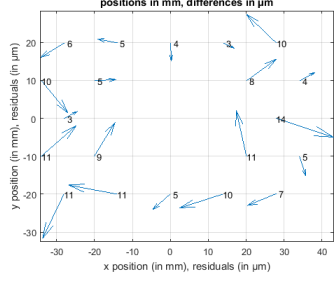
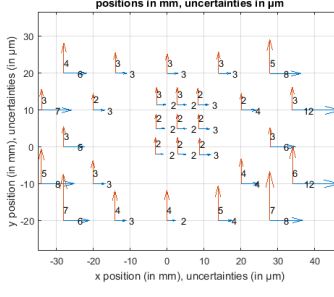
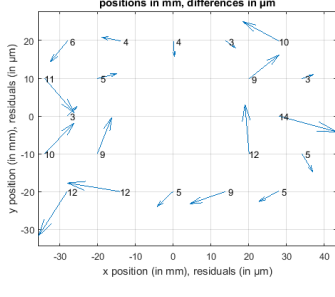
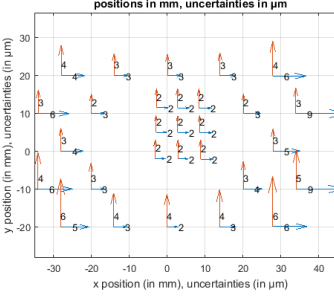
Camera positions used for the adjustment	X0 (mm)	Y0 (mm)	Z0 (mm)	Ax (mrad)	Ay (mrad)	Az (mrad)
1	0.087	0.076	0.089	0.754	0.938	0.052
1, 5	0.069	0.055	0.056	0.557	0.750	0.048
1, 3, 5	0.053	0.044	0.038	0.451	0.578	0.046
1, 2, 3, 4, 5	0.038	0.035	0.031	0.376	0.436	0.050

Parameters of interior orientation (principal vector, distortion parameters) - values

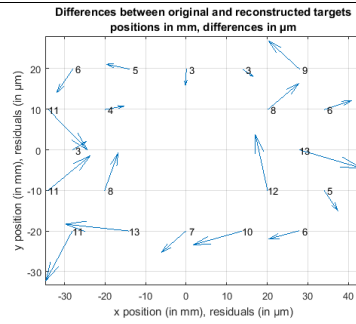
Camera positions used for the adjustment	Xp (pixel)	Yp (pixel)	Zp (pixel)	A1	A2
1	615.13	531.38	1652.38	-0.0441	0.0015
1, 5	613.18	531.25	1653.66	-0.0450	0.0019
1, 3, 5	613.06	530.80	1652.54	-0.0449	0.0019
1, 2, 3, 4, 5	612.50	530.99	1653.11	-0.0447	0.0018

Parameters of interior orientation (principal vector, distortion parameters) - uncertainties

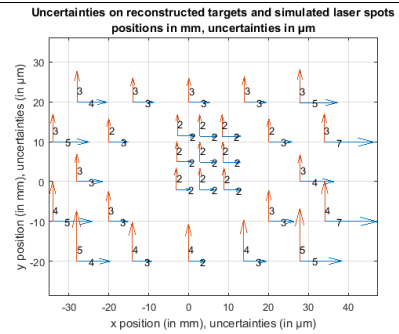
Camera positions used for the adjustment	Xp (pixel)	Yp (pixel)	Zp (pixel)	A1	A2
1	1.44	1.24	1.46	0.0008	0.0004
1, 5	1.14	0.90	0.94	0.0005	0.0003
1, 3, 5	0.87	0.72	0.64	0.0004	0.0002
1, 2, 3, 4, 5	0.62	0.57	0.51	0.0001	0.0001

Camera positions used for the adjustment	Residuals between targets measured in metrology lab and reconstructed with the algorithm	Uncertainties on reconstructed targets and reconstructed laser spots (for camera position 1)
1	Differences between original and reconstructed targets positions in mm, differences in μm  st. dev. x = $6.1 \mu\text{m}$ st. dev. y = $5.5 \mu\text{m}$	Uncertainties on reconstructed targets and simulated laser spots positions in mm, uncertainties in μm 
1, 5	Differences between original and reconstructed targets positions in mm, differences in μm  st. dev. x = $6.5 \mu\text{m}$ st. dev. y = $5.4 \mu\text{m}$	Uncertainties on reconstructed targets and simulated laser spots positions in mm, uncertainties in μm 
1, 3, 5	Differences between original and reconstructed targets positions in mm, differences in μm  st. dev. x = $6.4 \mu\text{m}$ st. dev. y = $5.6 \mu\text{m}$	Uncertainties on reconstructed targets and simulated laser spots positions in mm, uncertainties in μm 

1, 2, 3, 4, 5



st. dev. $x = 6.6 \mu\text{m}$
st. dev. $y = 5.5 \mu\text{m}$



Conclusion

We can see that the number of camera positions does not change significantly the standard deviations of residuals between targets measured in metrology lab and targets reconstructed by the algorithm (always in the range 5 and 7 μm).

The more camera positions, the smaller the uncertainties on reconstructed targets and laser spots.

However, even for 1 camera position, the uncertainties on reconstructed laser spots remain smaller than 4 μm .

33. Estimation of the depth minimising residuals

History

2015-09-08: started report

2015-09-09 to 2015-09-22: wrote MATLAB code

2015-09-22: finished report

Context

In a previous experiment, we corrected laser spot coordinates by taking into account depth reflection. To do this, we had to estimate the angles between camera and shutter. In a first iteration, we estimated them with naked eye. In the meantime, we worked on the camera model, in particular we used perspective projection as the transformation between camera and shutter. Such a transformation allows us to have more accurate estimates for the angles between camera and shutter.

Objective

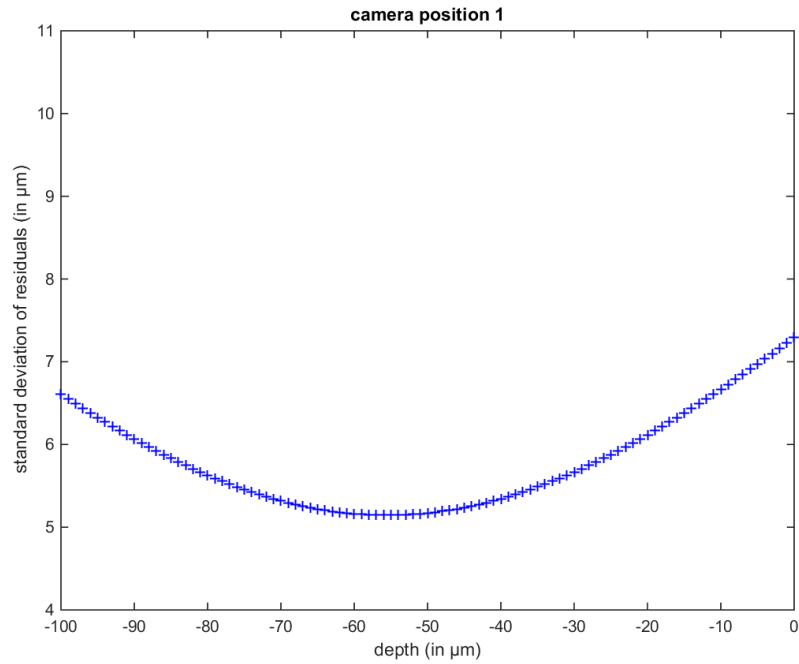
We want to estimate the depth values minimising residuals for different camera positions.

Method

We take the results from the experiment on May 29. To determine the parameters of the transformation between camera and shutter, we use projective geometry for the first estimate and perspective projection for the final (more accurate) estimate.

Results

Standard deviation of residuals with respect to depth (camera position 1, series of pictures 1)

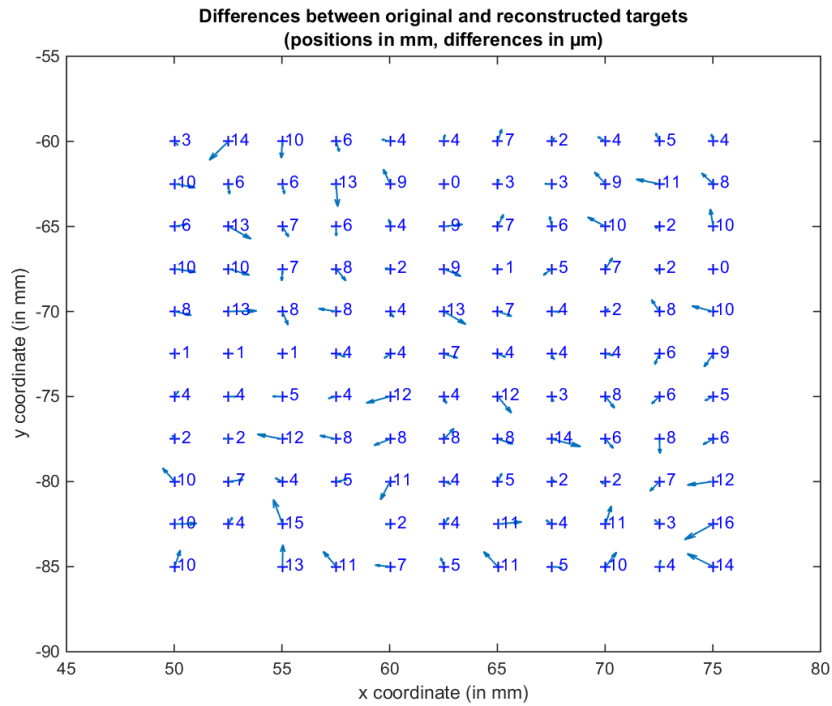


For camera positions 2 to 5, we obtained similar graphs.

Minimum standard deviation for each camera position and corresponding depth

Camera position	Minimum standard deviation (μm)	Corresponding depth (μm)
1	5.1	-56
2	4.9	-54
3	5.4	-44
4	5.2	-22
5	5.0	-45

Residuals for a depth of $-50\text{ }\mu\text{m}$ (camera position 1, series of pictures 1)



Standard deviations of residuals for a depth of $-50\text{ }\mu\text{m}$

Camera position	Standard deviation (in μm)
1	5.4
2	5.3
3	5.1
4	5.8
5	4.9

Conclusion

The optimal depth value depends on camera position. It was computed to be in the range $[-56\text{ }\mu\text{m} \dots -44\text{ }\mu\text{m}]$ for all camera positions except the 4th one ($-22\text{ }\mu\text{m}$). This outlier is so far unexplained.

If we correct laser spot coordinates with a depth of $-50\text{ }\mu\text{m}$, we find standard deviations of residuals smaller than $6\text{ }\mu\text{m}$ for all camera positions.

A collateral result of this test deals with the algorithm of least-squares used to compute the parameters of the transformation between shutter and camera. The algorithm converges faster if we use first projective geometry (to have a good first approximation) and then perspective projection.

Appendix F

Material used for experiments

F.1 Measurement benches



Figure F.1: Measurement bench used during 2011-2012 in the optical lab .



Figure F.2: Measurement bench used during 2013-2015 in the optical lab. Compared to the previous measurement bench (F.1), it is located in a closed room, which is better in terms of stability.

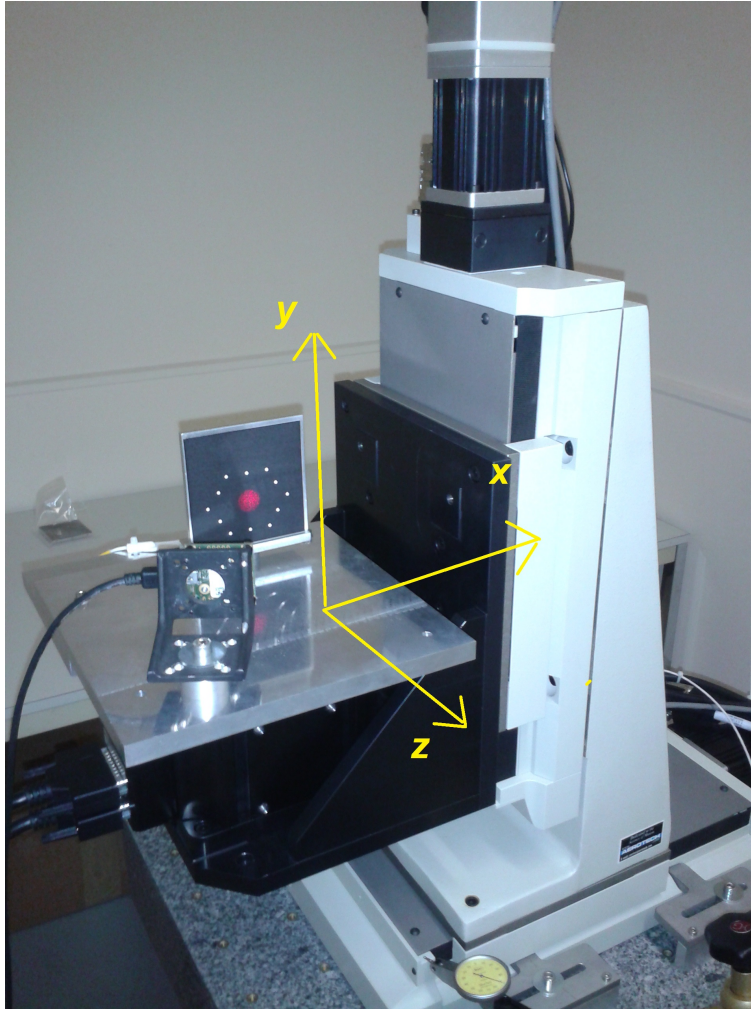


Figure F.3: Motorised micrometre table located on the second measurement bench F.2 of the optical lab. The motorised micrometre table can move the LAMBDA sensor in x and y directions and can also rotate it around y .



Figure F.4: Measurement bench in the optical lab and theodolites used for experiments of repositioning.



Figure F.5: Measurement bench used for long distance measurement in the geodetic base. The LAMBDA sensor can be manually displaced along a 50 m rail.

F.2 Lasers



- Output power to 35 mW
- $M^2 < 1.1$
- >90% TEM₀₀ mode
- Complete systems, including power supply
- CE compliant (230-Vac version only)

The CVI Melles Griot family of high-power helium neon lasers exhibit the long life, excellent stability, and field-proven performances that have made Melles Griot the undisputed worldwide leader in helium neon laser technology.

The 25 LHR/P 925, 828, and 928 lasers have guaranteed performances of 17, 25, and 35 mW, respectively, making them ideal for Raman spectroscopy, holography, fast scanning, and test and measurement applications. Most are available either in randomly or linearly polarized (with >500:1 extinction ratio) configurations, and they can be mounted in a variety of orientations without sacrificing power or performance. Systems are convection cooled and operate from standard 100 Vac, 115 Vac, or 230 Vac outlets.

Lasers

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HEM

High-Power Helium Neon Laser Systems

SPECIFICATIONS: High-Power Helium Neon Laser Systems

Beam Characteristics	Output Wavelength M^2 Transverse Mode	633 nm <1.1 TEM ₀₀ (>90%)
Stability Characteristics	Long-Term Power Drift Pointing Stability Amplitude Noise rms	±2% per hour <0.03 mrad after 30 minutes <1.0% (30 Hz to 10 MHz)
Operating Characteristics	Warm-up Time	<60 min (25 mW, 35 mW) to 95% of max power <15 min (17 mW) to 95% of max power
Environmental Requirements	Operating Temperature Nonoperating Temperature Operating Humidity Nonoperating Humidity Shock	–20°C to +40°C –40°C to +80°C 0% to 90%, noncondensing 0% to 100% 25 G for 11 msec
Electrical Characteristics	Input Voltage Input Frequency	100 Vac, 115 Vac, or 230 Vac ±10% (specify) 50–60 Hz
Safety and Regulatory Compliance	CDRH Class IEC Class Regulatory Compliance	IIIB 3B CE Compliant (230-Vac only)

High-Power Helium Neon Laser Systems

cw Output Power (mW)	Beam Diameter (1/e ²) (mm)	Beam Divergence (1/e ²) (mrad)	Maximum Mode Sweeping (%)	Polarization	Longitudinal Mode Spacing (MHz)	Noise (rms)	PART NUMBER*
17.0	0.96	0.84	1	Random	257	<0.5%	25 LHR 925
17.0	0.96	0.84	1	Linear, >500:1	257	<0.5%	25 LHP 925
25.0	1.23	0.66	5	Linear, >500:1	165	<1.0%	25 LHP 828
35.0	1.23	0.66	5	Linear, >500:1	165	<1.0%	25 LHP 928

*Add the appropriate suffix to the product number to indicate input voltage: -249 for 115 Vac, -230 for 230 Vac.



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Helium Neon Lasers 35.9

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Diode Pumped Solid-State Lasers

Air-Cooled Ion Lasers

Helium-Cadmium Lasers

Helium Neon Lasers

Diode Laser Assemblies

Figure F.6: Technical data sheet (page 1) of the laser used during 2011–2014 in the optical lab (propagation over 2 m) and in the geodetic base (propagation over 200 m). It died in December 2014 and was replaced by F.10.

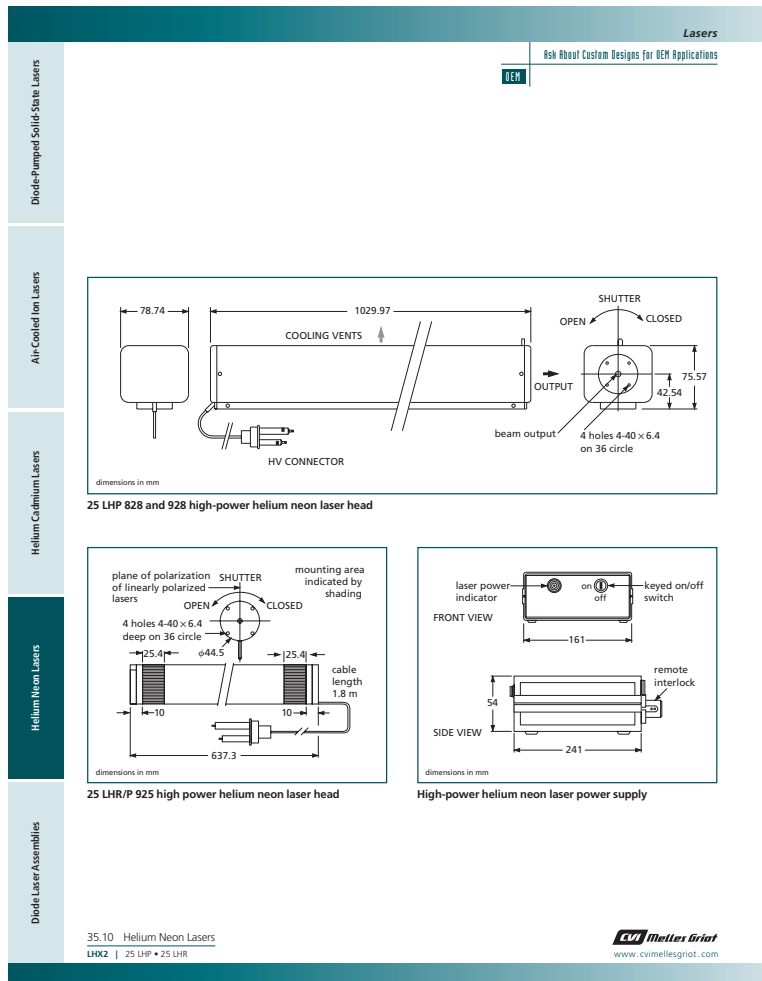
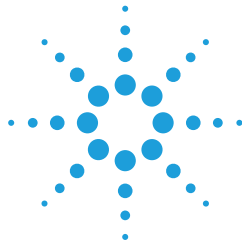


Figure F.7: Technical data sheet (page 2) of the laser used during 2011-2014 in the optical lab (propagation over 2 m) and in the geodetic base (propagation over 200 m). It died in December 2014 and was replaced by F.10.



Agilent 5530 Dynamic Calibrator Data Sheet



Power Requirements

Laser Head:

100 – 240 Vac, 50/60 Hz
50W (during warmup), 33W (after warmup)

Calibrator Electronics (all +5V via USB):

E1735A 280 mA max (plus 55290B if used)
E1736A 120 mA (plus sensors)
E1737A 6 mA maximum, 0.3 mA typical
E1738A 6 mA maximum, 0.6 mA typical
55290B 250 mA maximum

System Requirements

Environmental

Operating Temperature: 0 – 40°C (32 – 104°F)
Optics temperature must be stabilized to $\pm 2^\circ\text{C}$ to achieve accuracy specifications.

PC Requirements

Compatible with any portable computer with Windows® XP, Windows Vista (32-bit), Windows 7 (32-/64-bit) or Windows 8 (32-/64-bit) and two USB 2.0 ports and a CD drive

*Windows® is a registered trademark of Microsoft, Inc.

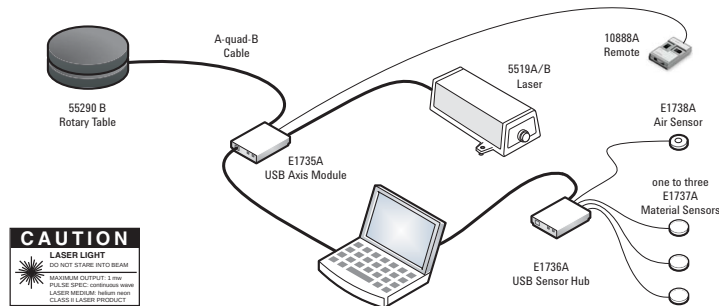


Figure F.8: Technical data sheet of the laser used for experiments in vacuum (page 1)

Laser Characteristics

Type: Helium-Neon with automatically tuned Zeeman-split two-frequency output

Output Power: ≥180 μW (<1 mW per Class II Laser Product)

Safety Classification: Class II Laser Product conforming to U.S. National CDRH Regulations 21CFR 1040.10 and 1040.11.

Warm-up Time: Less than 10 minutes (4 minutes typical)

Vacuum Wavelength: 632.991354 nm

Wavelength Accuracy: ±0.1 ppm (±0.02 ppm of measured wavelength with factory calibration, Option UK6)

Wavelength Stability (typical): short term (1 hour): ±0.002 ppm long term (lifetime): ±0.02 ppm

Beam Diameter: 6 mm (0.24 in)

Beam Centerline Spacing: 11.0 mm (0.44 in) (input to output aperture)

Linear Distance, Diagonal, and Velocity Measurement Specifications



Measurement Range

Up to 40 m (130 ft) with Linear Optics;
Up to 80 m (260 ft) with Long Range Option

Linear Distance and Diagonal Measurement Performance

Linear Distance and Diagonal Measurement Accuracy

Temperature Range, °C [°F]	E1738A	
	Air Sensor	In Vacuum †
0 – 40° [32° – 104°]	±0.4 ppm	±0.1 (±0.02) ppm

† Vacuum accuracy is ±0.02 ppm if the laser head is calibrated to MIL-STD 45862A.

OPTICS	RESOLUTION	MAXIMUM AXIS VELOCITY	
		5519A	5519B
Linear Optics (10766A)	1 nm (0.04 μin)	±0.7 m/s (±28 in/s)	±1 m/s (±40 in/s)
Plane Mirror Optics (10706A/B) *	0.5 nm (0.02 μin)	±0.35 m/s (±14 in/s)	±0.5 m/s (±20 in/s)
High Resolution Plane Mirror Optics (10716A) ‡	0.25 nm (0.01 μin)	±0.18 m/s (±7 in/s)	±0.25 m/s (±10 in/s)

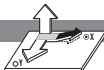
* Requires the 10724A Plane Mirror Reflector. Since alignment of these optics is much more sensitive than for linear optics, linear optics are recommended for general use.

‡ Aperture distance of 10716A is 12.7 mm, whereas 5519A is 11 mm.

Velocity Measurement Accuracy

$$\left[\frac{2 \mu\text{m/s}}{\text{Velocity}} + 0.01 \right] \% \text{ of displayed value}$$

Angular Measurement Specifications



Angle Measurement Accuracy

±0.2% of displayed value
±0.05 arc-seconds per meter of distance traveled by the linearly moving optic.

Maximum Distance Between Laser Head and Reflector

Up to 15 m (50 ft)

Angle Measurement Resolution

0.005 arc-seconds

Measurement Range

±10° (rotated about base of optic)
±20° (rotated about center of optic)

Measurement Type

Pitch and yaw

Figure F.9: Technical data sheet of the laser used for experiments in vacuum (page 2)



Figure F.10: Technical data sheet of the laser used during 2015 in the optical lab (page 1)

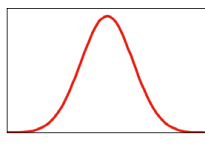
ZFSM

Mechanical specifications	
Dimensions	PCB 70mm x 60mm Housing 105,25 x 82,5 x 36,6mm PCB or housing with FC / PC connector 1000mm standard fiber length (others on request)
Connection	M12 plug 4-pin, D-Sub plug 9-pin; USB, Ethernet optionally
Electrical specifications	
Supply voltage	4.5 to 30VDC
Operation mode	Power stabilized (TEC in housing)
Modulation	Analog and simultaneous TTL modulation up to 200kHz
Protection	Reverse polarity and transient protection / ESD, over temperature protection and LED pre-failure indicator
Interfaces	I ² C, RS-232
Optical specifications	
Wavelength	450nm, 520nm, 640nm, 660nm, 785nm, 830nm, others on request
Output power	Up to 50mW
Wavelength vs. temperature	Typ. 0.20 - 0.30nm / °C depending on wavelength
Power stability	< 1% in steady state (1h)
Focus range	20mm up to ∞ (depending on optic head)
Pointing stability	< 3μrad / °C
Boresight error	< 3mrad
Line (Gaussian profile)	3°, 5°, 10°, 15°, 20°, 30°, 90°
Line (homogeneous intensity profile)	1°, 5°, 10°, 20°, 30°, 45°, 60°, 75°, 90°
Dot	Circular
M ²	SM < 1,05
Classification	IEC 60825-1:2007 IEC 60601-2-22 (for laser classes 3R and 3B) Software according to IEC 62304
Environmental conditions	
Case temperature	0°C up to +50°C (PCB version); -20°C up to +50°C (version with housing)
Storage temperature	-20°C up to +80°C
Humidity	Max. 90%, non-condensing (version with housing)
MTTF at 25°C	> 10,000h

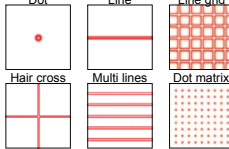
CE-Conformity according to the directives 2004/108/EC and 73/23/EEC.



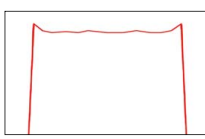
Gaussian profile



Optics



Homogeneous profile



Order code

Z X FSM - X - X

Power | Wavelength

Product family name



© Z-LASER / Merzhauser Str. 134, 79100 Freiburg / Germany / Tel: +49 761 2964444 / info@z-laser.de / www.Z-LASER.com
May 2015 / Subject to change

Figure F.11: Technical data sheet of the laser used during 2015 in the optical lab (page 2)

F.3 Collimators and beam expanders



Figure F.12: Collimator and optical fibre used in combination with the lasers (F.6 and F.10) in order to have parallel beams over 3 m.

TECHSPEC® 15X Complete Beam Expander



Stock No. #58-209
\$495.00
1 - 2 for \$495.00 each.
3 or more for \$439.00.

Availability: **IN STOCK**

SPECIFICATIONS

Expansion Power	15X
Maximum Entrance Aperture (mm)	2.0 (Optimized for 1.0mm 1/e ²)
Maximum Exit Aperture (mm)	27
Coating	MgF ₂
Coating Specification	λ/2 MgF ₂ @ 632.8 nm
Transmitted Wavefront, P-V	λ/4
Total Length (mm)	120.5
Housing Diameter (mm)	50
Construction	Black Anodized Aluminum
Focus Range	1.2 m - ∞
Mount	C-Mount
Type	Beam Expander
Style	Fixed Magnification
RoHS	N

TECHNICAL INFORMATION

Beam Expander Mounting Configurations.

Click on an item below to be brought to that item's product page.

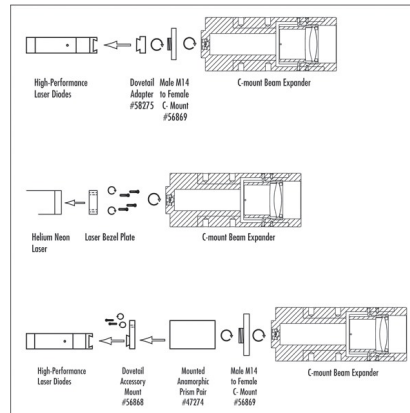


Figure F.13: Technical data sheet of the beam expander ($\times 15$) used for experiments mainly over long distance (up to 200 m) but also over short distance (up to 3 m). (Page 1)

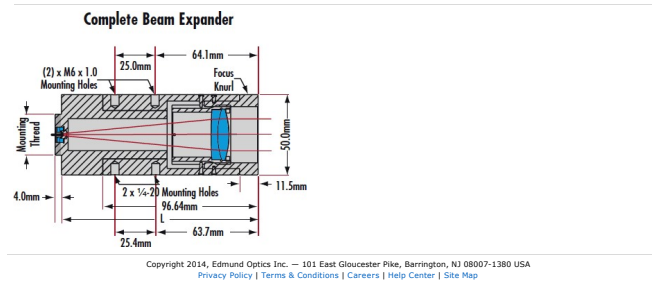


Figure F.14: Technical data sheet of the beam expander ($\times 15$) used for experiments mainly over long distance (up to 200 m) but also over short distance (up to 3 m). (Page 2)

F.4 Mirrors

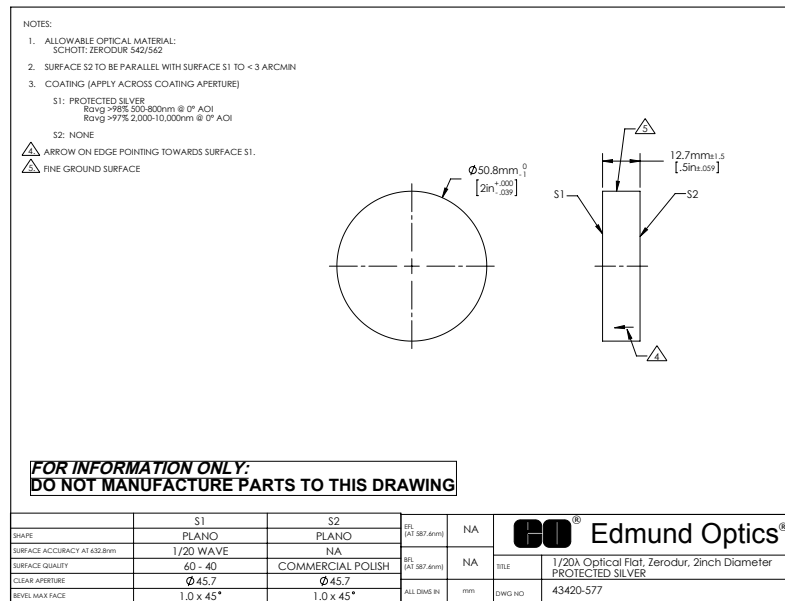
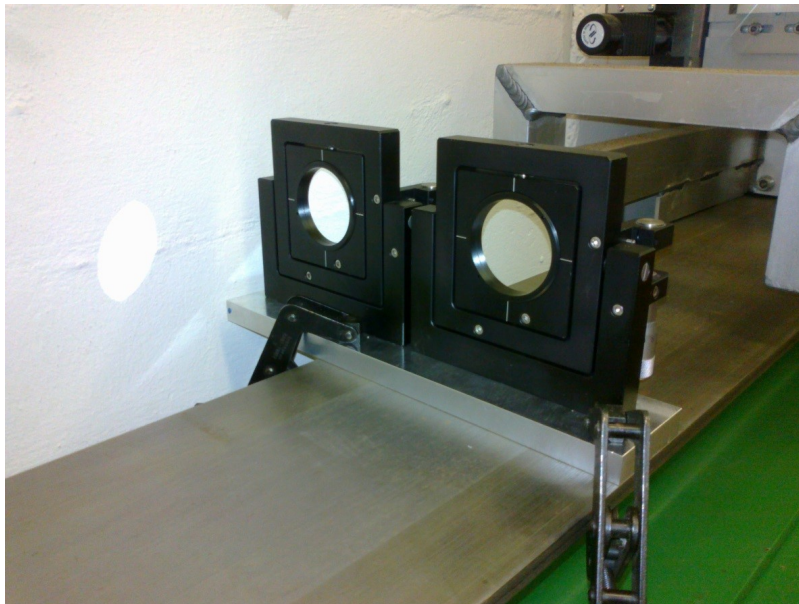


Figure F.15: Technical data sheet of the mirrors used for long distance experiments.



(a) One mirror (left) and beam expander (right) at one end of the rail.



(b) Two mirrors at the other end of the rail.

Figure F.16: Mirrors used for experiments over long distance.

F.5 Camera chips and lenses

XC-77 (EIA), XC-77CE (CCIR)

Monochrome machine vision video camera modules.

1. Outline

The XC-77/77CE is a monochrome video camera module designed for the industrial market. The camera is equipped with 2/3-inch IT CCD and provides a high resolution video signal according to EIA (60 field)/CCIR (50 field) standard. Camera XC-77 works in accordance with EIA, the XC-77CE with CCIR video norm.

- Square pixels, 11×11 μm (XC-77CE only)
- High resolution: 768×493 (EIA), 756×581 (CCIR)
- High sensitivity: 400 lux F4 (min 3 lux F1.4)
- High S/N ratio (>50 dB)
- Frame and field integration
- Restart Reset function
- Compact, lightweight: 44×29×107 mm, 190 g

2. Main features

Internal/External synchronization

Except the internal sync (provided by internal electronics), the camera can accept external sync information as well. Three types of sync signals are possible:

HD/VD (horizontal drive/vertical drive) signals

The camera determines whether to operate in interlaced or noninterlaced modes from the phase relation between HD and VD (see Scanning system).

VBS (composite video signal)

The camera is synchronized by supplying a composite video signal (for example from another image sensor).

SYNC (composite sync signal)

Synchronization is performed by means of composite sync input signal.

The unit switches automatically between all sync types mentioned above. If no sync signal is input, it operates with internal sync and 2:1 interlace mode.

Restart Reset function

The Restart Reset function enables to start new image integration at any time (specified by external trigger pulse). While HD signal must be supplied all the time, V reset pulses are generated from the trigger signal. Meaningful video signal (being stored after the trigger) is output since the second (in the field integration mode) or the third (in the frame integration mode) field.

The other kind of the restart reset function (which requires further internal setting in the camera) assures the slow speed shutter operation. The image data, integrated

Figure F.17: Technical data sheet of the first camera used in the optical lab. It was abandoned because it was too large for the LAMBDA project.

USB UI-1646LE

The UI-1646LE is an extremely compact board-level camera with modern Aptina CMOS sensor in 1.3 Megapixel resolution (1280x1024 pixels). Through the use of the widespread USB 2.0 technology the camera can be interfaced with a vast variety of systems without problems. The UI-1646LE features an S-mount lens holder with M12 thread and integrated filter glass.



Specification

The characteristics at a glance

Interface	USB
Lens Mount	S-Mount
Sensor Technology	CMOS (Aptina)
Model Description (color)	UI-1646LE-C
Model Description (mono)	---
Resolution (h x v)	1280 x 1024
Resolution Depth	8bit (10bit ADC)
Resolution Category / Pixel Class	1.3 Megapixel
Sensor Size	1/3"
Shutter	Rolling
max. fps in Freerun Mode	25 fps
Exposure Time in Freerun Mode	37µs-10s
Exposure Time in Trigger Mode	37µs-10s
AOI Modes	horizontal + vertical
Binning Modes	---
Subsampling Modes	horizontal + vertical
I/O - Strobe	1
I/O - Trigger	1
I/O - RS-232	-
I/O - GPIO	2
I/O - I2C	✓
HDR (High Dynamic Range)	-
Sensor Model (m/c)	- / MT9M131STC
Pixelpitch in µm	3.60
Optical Size	4.608 x 3.686 mm
Dimensions H/W/L	36.00 mm, 36.00 mm, 20.00 mm
Mass	12.00 g
Power Supply	USB

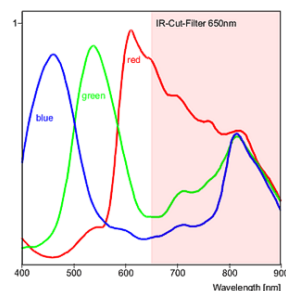


Figure F.18: Technical data sheet of the camera chip used for experiments in the optical lab and in the geodetic base



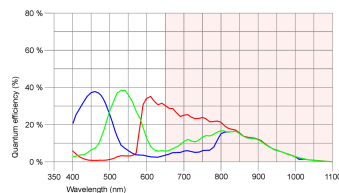
UI-5251LE-C



Specification

Sensor

Sensor Technology	CMOS Color
Manufacturer	e2v
Resolution (h x v)	1600 x 1200
Color depth (sensor)	10 bit
Color depth (camera)	12 bit
Pixel Class	2 MP
Sensor Size	1/1.8"
Shutter	Rolling shutter/Global shutter/Global start shutter
max. fps in Freerun Mode	35.6
Binning Modes	M/C automatic
Subsampling Modes	-
Sensor Model	EV76C570ACT
Pixel size	4.5 μ m
Optical Size	5.400 mm x 7.200 mm



Design

Interface	GigE
Lens Mount	M12-long
I/O In	1 x TTL
I/O Out	1 x TTL
I/O RS-232	-
I/O GPIO	2
I/O I2C	1
Protection Class	-
Dimensions H/W/L	45.0 mm x 45.0 mm x 26.4 mm
Mass	24 g
Power supply	12V - 24V

Subject to technical modifications

Page 1 of 1

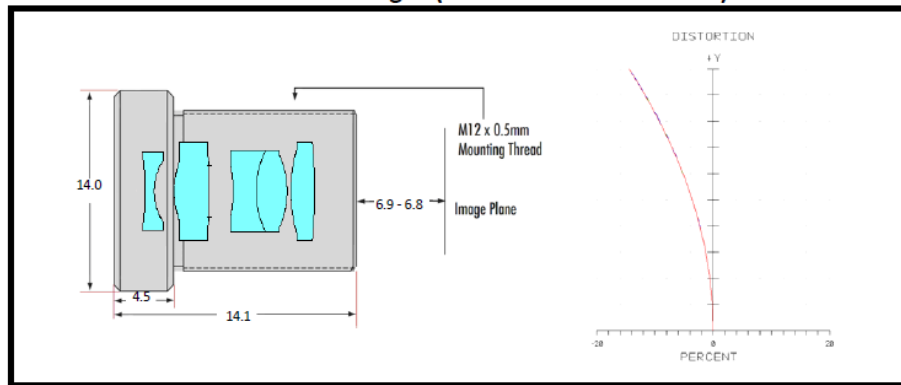
<http://www.ids-imaging.com>

IDS Imaging Development Systems GmbH

Dimbacher Straße 6 - 8 · 74182 Obersulm · Phone +49 7134/96196-0 · Fax +49 7134/96196-99 · E-Mail info@ids-imaging.de

Figure F.19: Technical data sheet of the camera chip used for tests in the vacuum pipe

**Megapixel Finite Conjugate μ -Video™ Imaging Lens
8.0 mm Focal Length (Stock Number: #58-202)**



Optical Parameters	
Focal Length (F')	6.00 (mm)
F/#	2.52
Max Sensor Format (2 γ)	1/3in (4.8 mm H/6.0 mm D)
Number Of Lenses	5
Working Distance (From Lens) (s)	150 - 250 (mm)
Field Of View (H) (2 γ)	132 - 220 (mm)
Angular Field Of View (@ longer WD) (H) (2 σ)	47.12 (°)
Image Distance (From Lens) (s')	9.68 - 9.68 (mm)
Housing To Front Element	0.92 (mm)
Housing To Back Element	3.78 (mm)
Object - Image Distance (OO')	169.99 - 270.08 (mm)
Entrance Pupil Distance From Front Element (h)	2.02 (mm)
Diameter Of Entrance Pupil	2.38 (mm)
Exit Pupil Distance From Back Element (h')	-11.95 (mm)
Diameter Of Exit Pupil	8.57 (mm)
Distortion (D)	-14.24 - -14.42 (%)
Range Of Wavelength (λ)	400 - 700 (nm)
Transmission Average (t)	96.05 (%)
Lens Diameter x Length	14.0 D x 14.1 L

* (H) measured on horizontal chip size/(D) measured on diagonal chip size

Figure F.20: Technical data sheet of the camera lens (focal length 6 mm) used for experiments in the optical lab and in the geodetic base

TECHSPEC 8mm FL f/2.5, MegaPixel Finite Conjugate Micro Video Lens



Stock No. #58-203

Availability: [CONTACT US](#)

\$95.00

1 - 10 for \$95.00 each.
11 - 24 for \$80.75 each.

SPECIFICATIONS

Primary Magnification PMAG	0.053X - 0.032X
Focal Length FL (mm)	8.0
Maximum Camera Sensor Format	1/3"
Working Distance (mm)	150 - 400
Aperture (f/#)	f/2.5
Field of View, 1/3" Sensor	92 - 154 mm
Distortion (%)	-6.5 Diagonal, -4.0 Horizontal
Outer Diameter (mm)	14.0
Length (mm)	12.3
Mount	M12 x 0.5 (S-Mount)
Type	Fixed Focal Length Lens
Note	Optimized Working Distance 150-250 mm Specifications are given for optimized range
Resolution, Full Field	145 lp/mm @ 20% Contrast
RoHS	C

TECHNICAL INFORMATION

Dimensions				
Focal Length	A	B	C*	D
3.0mm	14.0mm	17.1mm	4.8 - 4.7mm	5.8mm
4.0mm	14.0mm	19.7mm	6.1 - 6.0mm	4.4mm
5.0mm	14.0mm	14.6mm	4.0 - 3.9mm	3.7mm
6.0mm	14.0mm	14.1mm	6.9 - 6.8mm	4.5mm
8.0mm	14.0mm	12.3mm	8.8 - 8.6mm	3.7mm
10.0mm	14.0mm	17.0mm	6.6 - 6.3mm	3.7mm
12.5mm	15.0mm	22.9mm	10.1 - 9.7mm	4.8mm
17.5mm	14.0mm	20.7mm	5.8 - 4.9mm	7.6mm
25.0mm	18.0mm	30.0mm	8.5 - 6.5mm	11.5mm

Megapixel Finite Conjugate MVO® μ -Video™ Imaging Lenses

*Specified for Optimized Working Distance of 150 - 250mm.

Figure F.21: Technical data sheet of the camera lens (focal length 8 mm) used for experiments in the vacuum pipe

F.6 Shutters

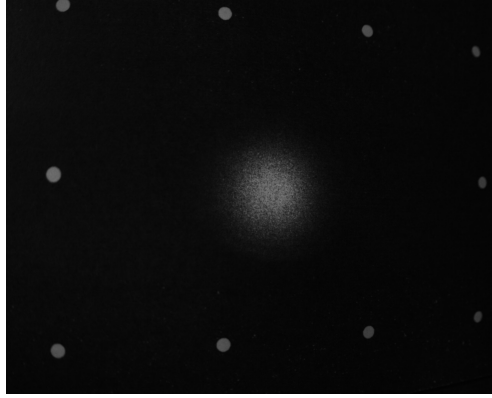


Figure F.22: Shutter used for experiments in the optical lab with laser spot in the middle. The shutter is made of an aluminium plate and a sheet of paper glued on it. The black background is printed on the sheet of paper in order to let white disks (targets) appear.

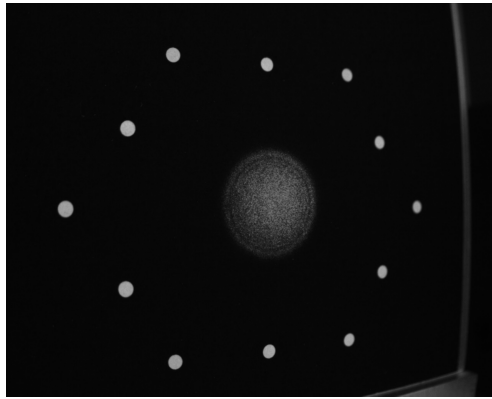


Figure F.23: Shutter used for experiments in the optical lab and in the geodetic base with laser spot in the middle. The fabrication process is the same as F.22.

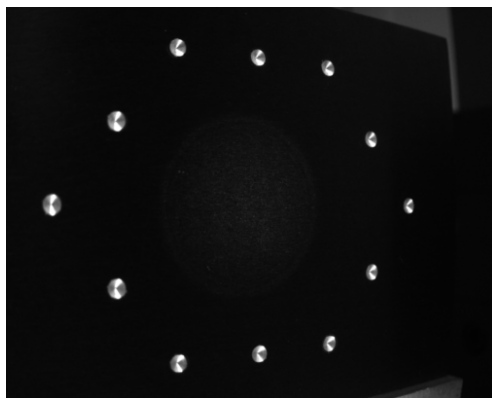


Figure F.24: Shutter used for experiments in the optical lab. It is a black anodised aluminium plate with machined conical grooves of diameter 2 mm and with laser spot in the middle (slightly visible).

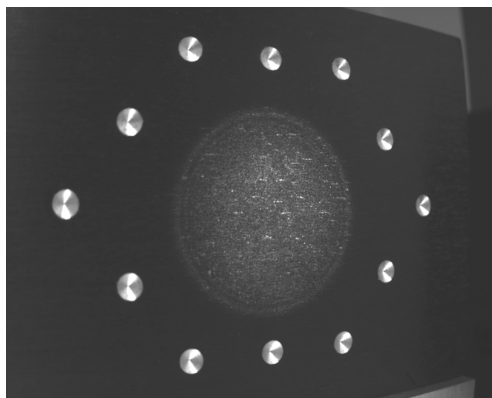


Figure F.25: Shutter used for experiments in the optical lab. It is a black anodised aluminium plate with machined conical grooves of diameter 3 mm and with laser spot in the middle.

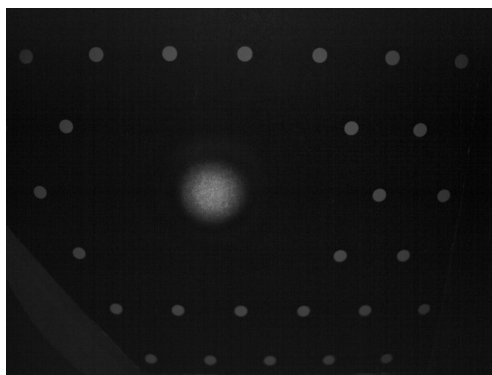


Figure F.26: Shutter used for experiments in the vacuum pipe in the geodetic base (front side). The fabrication process is the same as F.22.

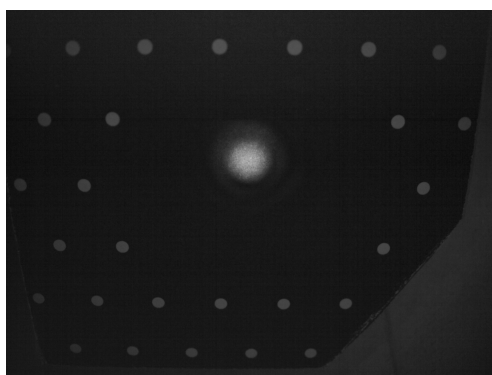


Figure F.27: Shutter used for experiments in the vacuum pipe in the geodetic base (back side). The fabrication process is the same as F.22.

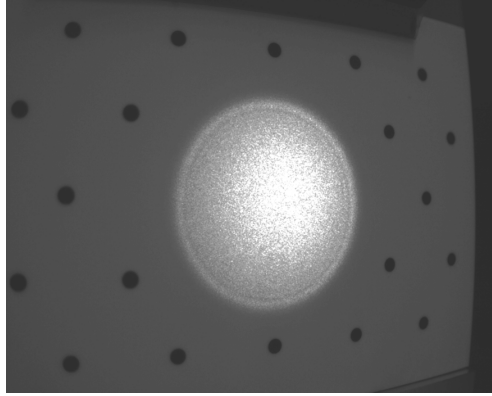


Figure F.28: Shutter used for experiments in the optical lab. It is a white alumina plate. Targets are obtained by laser siltering. In the middle, the laser spot occupies a large area between the targets.

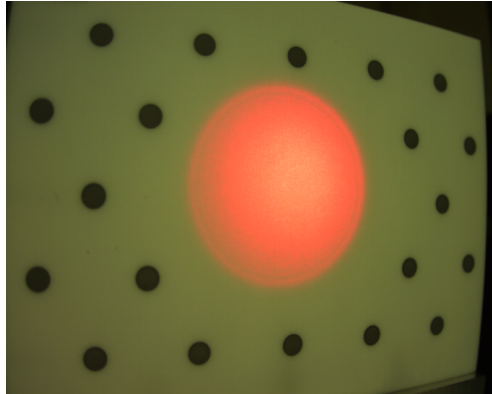
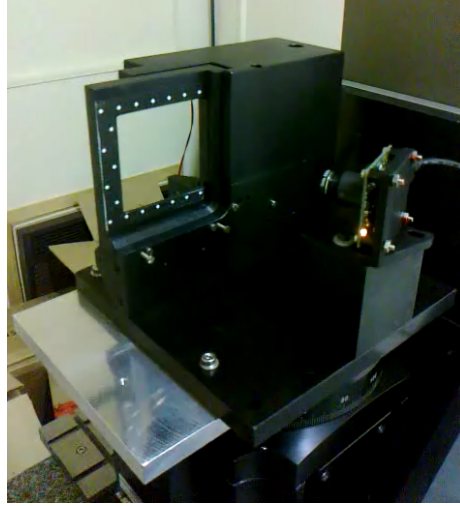
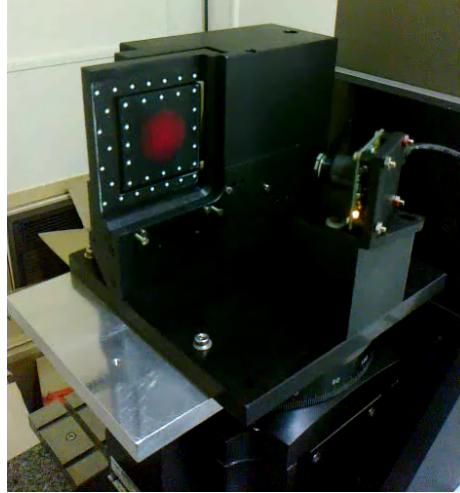


Figure F.29: Shutter used for experiments of measurement accuracy. It is a white macor plate. Targets are obtained by deposit of a thin ($1\text{ }\mu\text{m}$) metal layer. In the middle, the laser spot occupies a large area between the targets.



(a) Shutter open



(b) Shutter closed

Figure F.30: LAMBDA sensor used for experiments of repositioning. It comprises a camera, a shutter and a frame. The shutter and the frame are made of black anticorodal AlMg alloy plates and sheets of paper glued on them. The black backgrounds are printed on the sheets of paper in order to let white disks (targets) appear.

F.7 Vacuum pipe

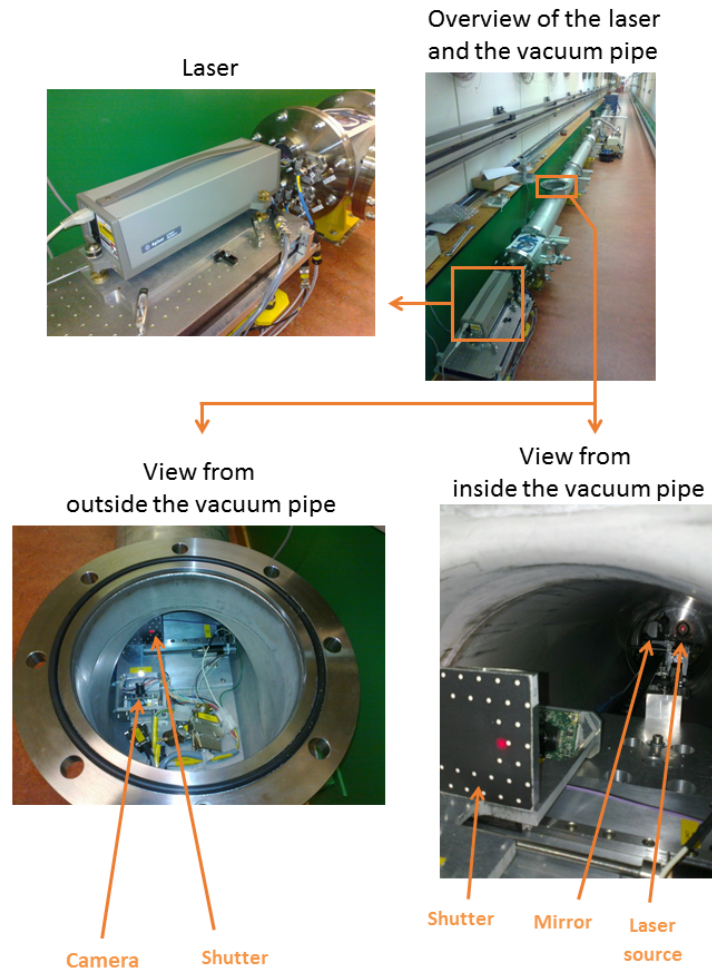


Figure F.31: Vacuum pipe, laser and LAMBDA sensor in the geodetic base used for experiments in vacuum.

F.8 Open/close mechanism

Picard Industries
Specializing in Miniature Smart Motors and Sensors

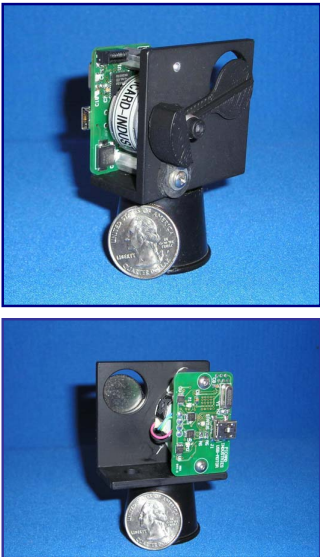
Servo Designs™

USB Shutter

USB Shutter Features

- Small Low cost USB controlled shutter
- Draws power from a standard USB port
- Auto closing shutter (by spring) if power or communications is lost
- Quiet stepper motor operation (no clunk) to open and close
- USB Hot pluggable with Auto-detection
- Mounts on standard optical tables with ¼-20 screws on 1.0" centers
- Clear beam aperture of 0.75 inches or ~ 19.0 Millimeters
- A hard stop defines the closed position
- Easy to use Windows (XP/Vista) based User Interface software included
- LabView Drivers and DLL files provided

(\$ 275.00 single piece price)



Picard Industries

4960 Quaker Hill Road, Albion, New York 14411
(585) 589-0358
info@Picard-Industries.com
www.Picard-Industries.com

Figure F.32: Shutter used for first tests (page 1).

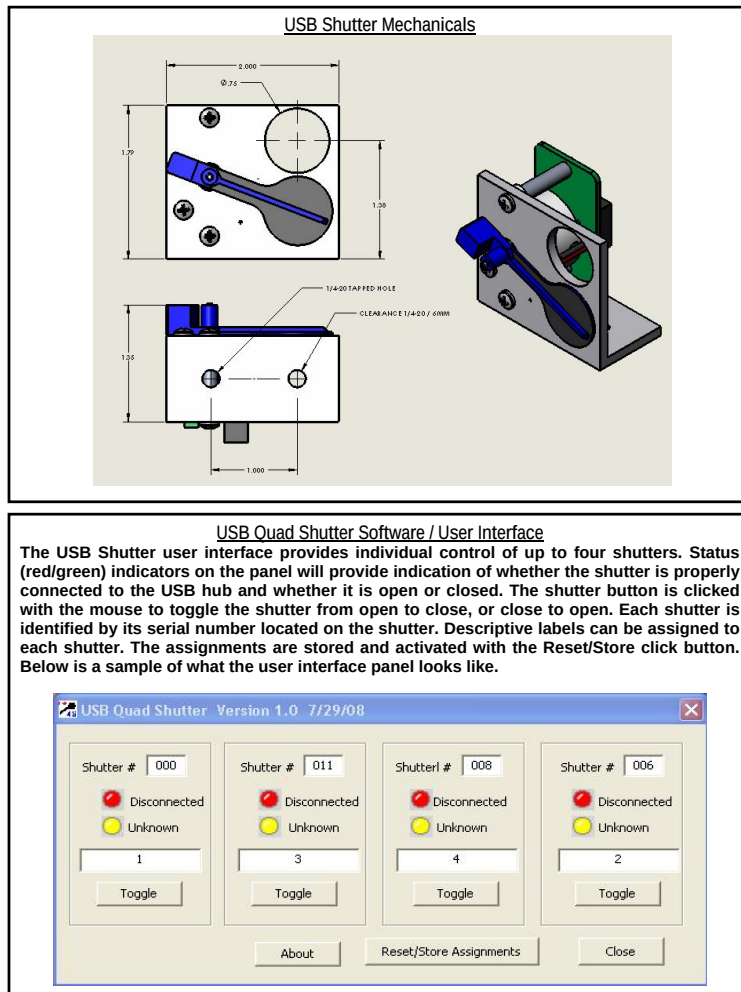


Figure F.33: Shutter used for first tests (page 2).

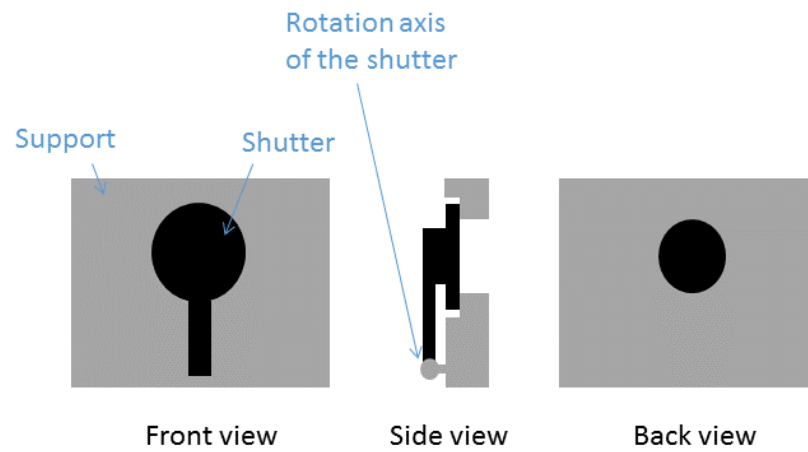


Figure F.34: Solution not developed: shutter as a check valve (closed position)

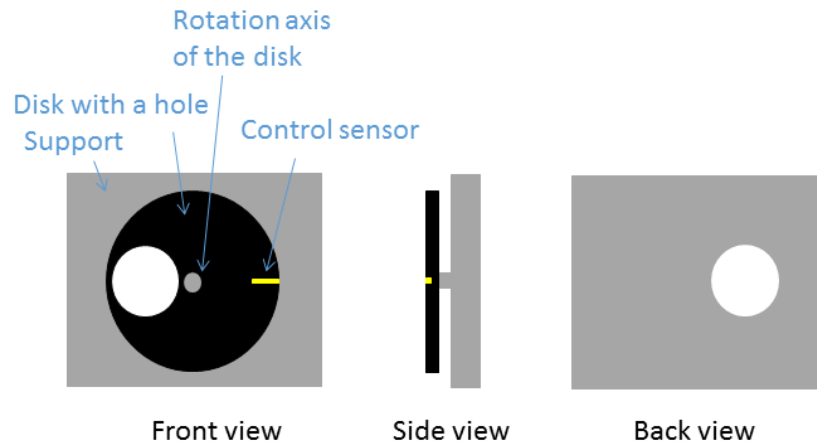


Figure F.35: Solution not developed: shutter as a disk with a hole (open position)

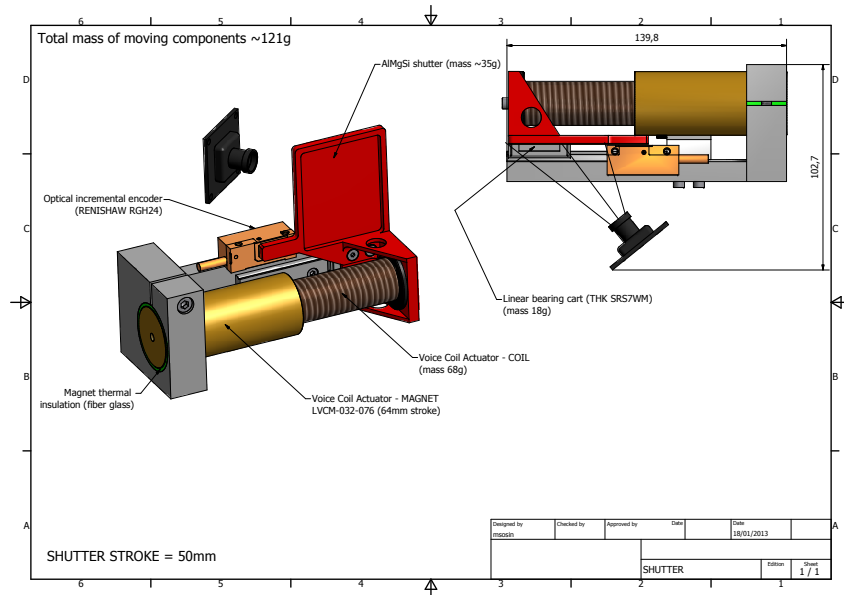


Figure F.36: Solution developed: shutter on a rail moved by voice coil actuator (closed position) - drawing from M. Sosin (CERN, EN-MEF-SU)

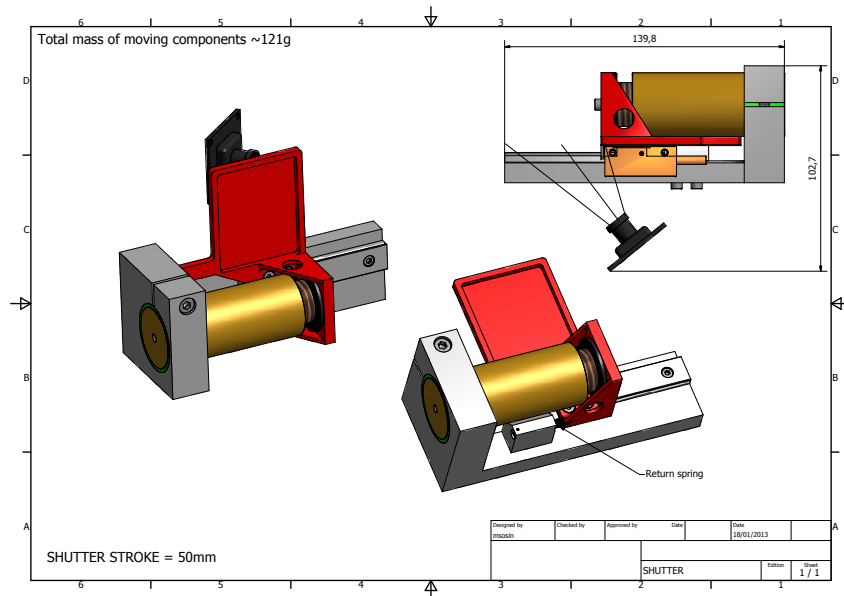
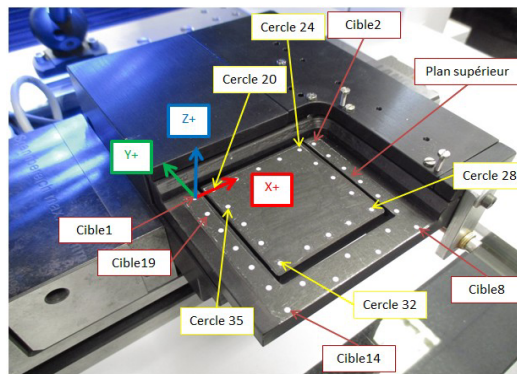


Figure F.37: Solution developed: shutter on a rail moved by voice coil actuator (open position) - drawing from M. Sosin (CERN, EN-MEF-SU)

F.9 Measurements performed by metrology lab

 RAPPORT DE CONTROLE 	
Nom du plan de contrôle:	EDMS 1404793 - MONTAGE CIBLE SHUTTER MOBILE
Nom de la pièce:	MONTAGE CIBLES SHUTTER MOBILE
N° de plan et indice:	/
Date:	13/03/2015 14:13
Contrôleur:	HAERINCK Cyril
Cliant:	STERN Guillaume
N° de pièce:	1
CMM type:	O_Inspect
N°EDMS:	1404793
Incertitude de mesure:	1.9µ + L/250
Fournisseur:	/
Température:	20°C ±1°C

Informations relatives au référentiel de mesure



Construction du référentiel de base:

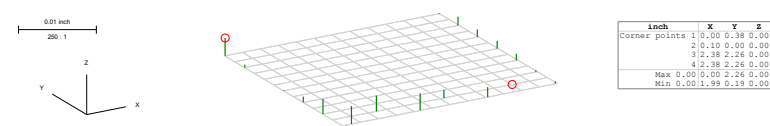
- Orientation primaire: Plan supérieur
- Orientation secondaire: Droite passant par le cercle 1 et le cercle 2
- Origine: X = Cercle 1
Y = Cercle 1
Z = Plan Supérieur

1 / 6

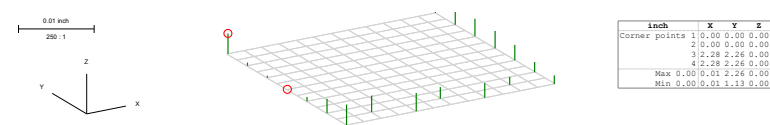
Figure F.38: Measurements performed by the metrology lab on the sensor with open/close shutter (page 1).

	Nom du plan de contrôle: EDMS 1404793 - MONTAGE CIBLE SHUTTER MOBILE			
	Nom de la pièce: MONTAGE CIBLES SHUTTER MOBILE			
	N° de plan et plan: /	Date: 13/03/2015 14:13		
	N° de pièce: 1	Contrôleur: HAERINCK Cyril		

Name	Nom	Act	-Tol	+Tol	Dev.
Planéité Plan U papier noir	0.000	0.058	0.000	0.050	0.058 



Planéité Plan U passant par les cibles	0.000	0.069	0.000	0.050	0.069 
--	-------	-------	-------	-------	---



Planéité Plan carré papier noir	0.000	0.085	0.000	0.050	0.085 
---------------------------------	-------	-------	-------	-------	---

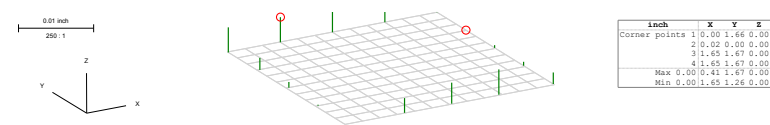
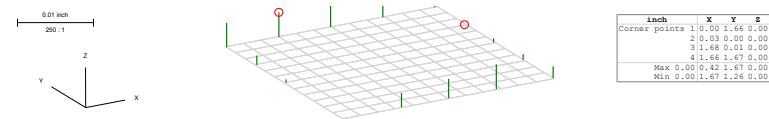


Figure F.39: Measurements performed by the metrology lab on the sensor with open/close shutter (page 2).

	Nom du plan de contrôle: EDMS 1404793 - MONTAGE CIBLE SHUTTER MOBILE			
	Nom de la pièce: MONTAGE CIBLES SHUTTER MOBILE			
	N° de plan et plan: /	Date: 13/03/2015 14:13		
	N° de pièce: 1	Contrôleur: HAERINCK Cyril		

Name	Nom	Act	-Tol	+Tol	Dev.
Planéité Plan carré passant par les cibles	0.000	0.083	0.000	0.050	0.083



X-Valeur_Cible1	0.000	0.000	0.000
Y-Valeur_Cible1	0.000	0.000	0.000
Z-Valeur_Cible1	0.000	0.000	0.000
Diamètre_Cible1	2.000	1.841	-0.159
X-Valeur_Cible2	57.500	57.583	0.083
Y-Valeur_Cible2	0.000	0.000	0.000
Z-Valeur_Cible2	0.000	0.000	0.000
Diamètre_Cible2	2.000	1.834	-0.166
X-Valeur_Cible3	57.500	57.527	0.027
Y-Valeur_Cible3	-9.500	-9.547	-0.047
Z-Valeur_Point3	0.000	-0.043	-0.043
Diamètre_Cible3	2.000	1.827	-0.173
X-Valeur_Cible4	57.500	57.468	-0.032
Y-Valeur_Cible4	-19.000	-19.122	-0.122
Z-Valeur_Point4	0.000	-0.029	-0.029
Diamètre_Cible4	2.000	1.835	-0.165
X-Valeur_Cible5	57.500	57.411	-0.089
Y-Valeur_Cible5	-28.500	-28.698	-0.198
Z-Valeur_Point5	0.000	-0.028	-0.028
Diamètre_Cible5	2.000	1.838	-0.162
X-Valeur_Cible6	57.500	57.353	-0.147
Y-Valeur_Cible6	-38.500	-38.288	0.212
Z-Valeur_Point6	0.000	-0.034	-0.034
Diamètre_Cible6	2.000	1.824	-0.176
X-Valeur_Cible7	57.500	57.290	-0.210
Y-Valeur_Cible7	-48.000	-47.880	0.120
Z-Valeur_Point7	0.000	-0.050	-0.050
Diamètre_Cible7	2.000	1.834	-0.166
X-Valeur_Cible8	57.500	57.273	-0.227

Figure F.40: Measurements performed by the metrology lab on the sensor with open/close shutter (page 3).



Nom du plan de contrôle: EDMS 1404793 - MONTAGE CIBLE SHUTTER MOBILE

Nom de la pièce: MONTAGE CIBLES SHUTTER MOBILE

N° de plan et plan: /

N° de pièce: 1

Date: 13/03/2015 14:13

Contrôleur: HAERINCK Cyril



Name	Nom	Act	-Tol	+Tol	Dev.
Y-Valeur_Cible8	-57.500	-57.451			0.049
Z-Valeur_Point8	0.000	-0.053			-0.053
Diamètre_Cible8	2.000	1.828			-0.172
X-Valeur_Cible9	47.500	47.702			0.202
Y-Valeur_Cible9	-52.500	-52.689			-0.189
Z-Valeur_Point9	0.000	-0.054			-0.054
Diamètre_Cible9	2.000	1.834			-0.166
X-Valeur_Cible10	38.000	38.061			0.061
Y-Valeur_Cible10	-57.500	-57.478			0.022
Z-Valeur_Point10	0.000	-0.027			-0.027
Diamètre_Cible10	2.000	1.836			-0.164
X-Valeur_Cible11	28.500	28.496			-0.004
Y-Valeur_Cible11	-52.500	-52.710			-0.210
Z-Valeur_Point11	0.000	-0.035			-0.035
Diamètre_Cible11	2.000	1.830			-0.170
X-Valeur_Cible12	19.000	18.977			-0.023
Y-Valeur_Cible12	-57.500	-57.489			0.011
Z-Valeur_Point12	0.000	-0.010			-0.010
Diamètre_Cible12	2.000	1.834			-0.166
X-Valeur_Cible13	9.500	9.392			-0.108
Y-Valeur_Cible13	-52.500	-52.706			-0.206
Z-Valeur_Point13	0.000	-0.013			-0.013
Diamètre_Cible13	2.000	1.819			-0.181
X-Valeur_Cible14	0.000	-0.225			-0.225
Y-Valeur_Cible14	-57.500	-57.458			0.042
Z-Valeur_Cible14	0.000	0.000			0.000
Diamètre_Cible14	2.000	1.841			-0.159
X-Valeur_Cible15	0.000	-0.217			-0.217
Y-Valeur_Cible15	-48.000	-47.889			0.111
Z-Valeur_Point15	0.000	-0.019			-0.019
Diamètre_Cible15	2.000	1.844			-0.156
X-Valeur_Cible16	0.000	-0.211			-0.211
Y-Valeur_Cible16	-38.500	-38.304			0.196
Z-Valeur_Point16	0.000	-0.053			-0.053
Diamètre_Cible16	2.000	1.833			-0.167
X-Valeur_Cible17	0.000	-0.173			-0.173
Y-Valeur_Cible17	-28.500	-28.716			-0.216
Z-Valeur_Point17	0.000	-0.070			-0.070
Diamètre_Cible17	2.000	1.846			-0.154
X-Valeur_Cible18	0.000	-0.122			-0.122
Y-Valeur_Cible18	-19.000	-19.134			-0.134

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Figure F.41: Measurements performed by the metrology lab on the sensor with open/close shutter (page 4).



Nom du plan de contrôle: EDMS 1404793 - MONTAGE CIBLE SHUTTER MOBILE

Nom de la pièce: MONTAGE CIBLES SHUTTER MOBILE

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N° de pièce: 1

Date: 13/03/2015 14:13

Contrôleur: HAERINCK Cyril



Name	Nom	Act	-Tol	+Tol	Dev.
Z-Valeur_Point18	0.000	-0.065			-0.065
Diamètre_Cible18	2.000	1.846			-0.154
X-Valeur_Cible19	0.000	-0.061			-0.061
Y-Valeur_Cible19	-9.500	-9.554			-0.054
Z-Valeur_Point19	0.000	-0.062			-0.062
Diamètre_Cible19	2.000	1.835			-0.165
X-Valeur_Cible20 Pièce carrée	8.000	7.917			-0.083
Y-Valeur_Cible20 Pièce carrée	0.000	-0.074			-0.074
Z-Valeur_Point20	0.000	-0.055			-0.055
Diamètre_Cible20 Pièce carrée	2.000	1.847			-0.153
X-Valeur_Cible21 Pièce carrée	18.500	18.445			-0.055
Y-Valeur_Cible21 Pièce carrée	0.000	0.017			0.017
Z-Valeur_Point21	0.000	-0.030			-0.030
Diamètre_Cible21 Pièce carrée	2.000	1.842			-0.158
X-Valeur_Cible22 Pièce carrée	29.000	28.984			-0.016
Y-Valeur_Cible22 Pièce carrée	0.000	0.104			0.104
Z-Valeur_Point22	0.000	-0.019			-0.019
Diamètre_Cible22 Pièce carrée	2.000	1.851			-0.149
X-Valeur_Cible23 Pièce carrée	39.500	39.520			0.020
Y-Valeur_Cible23 Pièce carrée	0.000	0.188			0.188
Z-Valeur_Point23	0.000	-0.025			-0.025
Diamètre_Cible23 Pièce carrée	2.000	1.853			-0.147
X-Valeur_Cible24 Pièce carrée	50.000	50.032			0.032
Y-Valeur_Cible24 Pièce carrée	0.000	0.272			0.272
Z-Valeur_Point24	0.000	-0.029			-0.029
Diamètre_Cible24 Pièce carrée	2.000	1.841			-0.159
X-Valeur_Cible25 Pièce carrée	50.000	50.123			0.123
Y-Valeur_Cible25 Pièce carrée	-10.200	-10.296			-0.096
Z-Valeur_Point25	0.000	-0.099			-0.099
Diamètre_Cible25 Pièce carrée	2.000	1.824			-0.176
X-Valeur_Cible26 Pièce carrée	50.000	50.228			0.228
Y-Valeur_Cible26 Pièce carrée	-20.500	-20.770			-0.270
Z-Valeur_Point26	0.000	-0.142			-0.142
Diamètre_Cible26 Pièce carrée	2.000	1.833			-0.167
X-Valeur_Cible27 Pièce carrée	50.000	50.323			0.323
Y-Valeur_Cible27 Pièce carrée	-31.000	-31.311			-0.311
Z-Valeur_Point27	0.000	-0.191			-0.191
Diamètre_Cible27 Pièce carrée	2.000	1.836			-0.164
X-Valeur_Cible28 Pièce carrée	50.000	50.422			0.422
Y-Valeur_Cible28 Pièce carrée	-42.000	-41.928			0.072
Z-Valeur_Point28	0.000	-0.229			-0.229

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Figure F.42: Measurements performed by the metrology lab on the sensor with open/close shutter (page 5).

	Nom du plan de contrôle: EDMS 1404793 - MONTAGE CIBLE SHUTTER MOBILE					
	Nom de la pièce: MONTAGE CIBLES SHUTTER MOBILE					
	N° de plan et plan: /					
	N° de pièce: 1					
					Date: 13/03/2015 14:13	
					Contrôleur: HAERINCK Cyril	
Name		Nom	Act	-Tol	+Tol	Dev.
Diamètre_Cible28 Pièce carrée		2.000	1.844			-0.156
X-Valeur_Cible29 Pièce carrée		39.000	38.954			-0.046
Y-Valeur_Cible29 Pièce carrée		-42.000	-42.002			-0.002
Z-Valeur_Point29		0.000	-0.211			-0.211
Diamètre_Cible29 Pièce carrée		2.000	1.843			-0.157
X-Valeur_Cible30 Pièce carrée		29.300	29.379			0.079
Y-Valeur_Cible30 Pièce carrée		-42.000	-42.064			-0.064
Z-Valeur_Point30		0.000	-0.250			-0.250
Diamètre_Cible30 Pièce carrée		2.000	1.853			-0.147
X-Valeur_Cible31 Pièce carrée		19.800	19.802			0.002
Y-Valeur_Cible31 Pièce carrée		-42.000	-42.134			-0.134
Z-Valeur_Point31		0.000	-0.288			-0.288
Diamètre_Cible31 Pièce carrée		2.000	1.843			-0.157
X-Valeur_Cible32 Pièce carrée		8.500	8.553			0.053
Y-Valeur_Cible32 Pièce carrée		-42.000	-42.214			-0.214
Z-Valeur_Point32		0.000	-0.361			-0.361
Diamètre_Cible32 Pièce carrée		2.000	1.837			-0.163
X-Valeur_Cible33 Pièce carrée		8.500	8.216			-0.284
Y-Valeur_Cible33 Pièce carrée		-31.500	-31.622			-0.122
Z-Valeur_Point33		0.000	-0.305			-0.305
Diamètre_Cible33 Pièce carrée		2.000	1.850			-0.150
X-Valeur_Cible34 Pièce carrée		8.500	8.118			-0.382
Y-Valeur_Cible34 Pièce carrée		-21.000	-21.095			-0.095
Z-Valeur_Point34		0.000	-0.239			-0.239
Diamètre_Cible34 Pièce carrée		2.000	1.836			-0.164
X-Valeur_Cible35 Pièce carrée		8.500	8.022			-0.478
Y-Valeur_Cible35 Pièce carrée		-10.500	-10.631			-0.131
Z-Valeur_Point35		0.000	-0.162			-0.162
Diamètre_Cible35 Pièce carrée		2.000	1.833			-0.167

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Figure F.43: Measurements performed by the metrology lab on the sensor with open/close shutter (page 6).

Evolution of target positions with respect to time

The metrology lab measured twice the targets on the frame of the open/close sensor, the first time in August 2014 and the second time in March 2015.

	August 2014			March 2015		
	x (in mm)	y (in mm)	z (in mm)	x (in mm)	y (in mm)	z (in mm)
Target01	0	0	0	0	0	0
Target02	57.566	0	0	57.583	0	0
Target03	57.524	-9.567	-0.026	57.527	-9.547	-0.043
Target04	57.456	-19.156	-0.033	57.468	-19.122	-0.029
Target05	57.403	-28.743	-0.035	57.411	-28.698	-0.028
Target06	57.349	-38.339	-0.030	57.353	-38.288	-0.034
Target07	57.307	-47.937	-0.052	57.290	-47.880	-0.050
Target08	57.289	-57.527	-0.047	57.273	-57.451	-0.053
Target09	47.716	-52.738	-0.054	47.702	-52.689	-0.054
Target10	38.068	-57.542	-0.034	38.061	-57.478	-0.027
Target11	28.499	-52.755	-0.039	28.496	-52.710	-0.035
Target12	18.977	-57.551	-0.008	18.977	-57.489	-0.010
Target13	9.383	-52.755	-0.025	9.392	-52.706	-0.013
Target14	-0.242	-57.531	0	-0.225	-57.458	0
Target15	-0.228	-47.945	-0.025	-0.217	-47.889	-0.019
Target16	-0.204	-38.351	-0.029	-0.211	-38.304	-0.053
Target17	-0.162	-28.756	-0.060	-0.173	-28.716	-0.070
Target18	-0.111	-19.167	-0.077	-0.122	-19.134	-0.065
Target19	-0.052	-9.579	-0.060	-0.061	-9.554	-0.062

Between these two dates, significant changes were observed. For example, if we take the targets in the four corners of the frame, following distances changed:

- between Target01 and Target14: -74 μ m
- between Target02 and Target08: -76 μ m
- between Target01 and Target02: +17 μ m
- between Target08 and Target14: -33 μ m

Figure F.44: Distances between targets changed significantly within 6 months for the frame of the open/close LAMBDA sensor.

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