Tolerance study and optical optimization of a concentrated photovoltaic module

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Resumo

O crescimento da necessidade energética, estimulada pelos países em crescimento e o consequente decréscimo de fontes de energia, está a tornar o futuro insustentável. Deste modo é necessário utilizar energias renováveis pois elas são inesgotáveis e limpas, em destaque a energia solar. Esta pode produzir calor ou pode ser diretamente convertida em energia elétrica, chamada de energia fotovoltaica (PV). Para chegar à paridade com a rede, o custo dos componentes usados para construir sistemas PV tem que baixar, particularmente o uso do silício. Concentrando a luz em células solares mais pequenas, substitui-se as células solares por elementos mais baratos (fotovoltaico concentrado (CPV)). Associado ao CPV está associada a teoria da Ótica Anidólica (NIO). Desde os primeiros estudos feitos por Roland Winston aos estudos mais recentes, alguns importantes resultados foram obtidos e usados para melhorar sistemas CPV.

A WS Energia SA é uma empresa portuguesa que desenha e produz sistemas CPV. O último sistema CPV desenvolvido foi o HSUN. Este consiste numa espelho em forma de calha parabólica, que reflete a luz para um recetor e usa dois elementos óticos secundários (SOE) formados por espelhos planos que aumentam o ângulo que os raios podem entrar na abertura do sistema CPV e serem refletidos para o recetor (aceitância ou ângulo de aceitação).

No início desta tese, o HSUN estava numa fase intermédia tendo sido o primeiro protótipo recentemente construído. Assim foi definido como principal objetivo, o estudar o HSUN e tentar explicar os resultados obtidos e a proposta de melhoramentos.

Palavras-chave: concentração fotovoltaica, ótica anidólica, desenho ótico, tolerância, aceitância
Abstract

The increase of demand for energy, stimulated by developing countries and consequent decrease of power sources, is leading to an unsustainable future. These way renewable and clean energies are necessary to be used, particularly solar energy. It can produce heat or be directly converted into electricity, called photovoltaic (PV) energy. To achieve the grid parity the cost of components necessary to build a PV system has to decrease, specially the price of silicon. Focusing the sunlight into smaller cells, the expensive cells are substituted by cheaper elements (Concentrated Photovoltaic (CPV)). Associated to CPV there is the theory of the Nonimaging Optics (NIO).

WS Energia S.A. is a Portuguese company that designs and produces CPV systems. The latest CPV system built was HSUN. The main objectives of this thesis were to study the HSUN and obtain the tolerances of the optical components of HSUN, design a new secondary optics in order to improve the performance of the first version of HSUN, and to better study the parabolic trough mirrors, a model and an experimental prototype were developed to study the profile of the mirror, assure that it was well defined and evaluate the performance of the mirror.

The work done to fulfill this goal was highly successful resulting in a tool for both WS Energia and manufacturers of parabolic mirrors to evaluate the mirrors and locate systematic errors and being able to correct them.

Keywords: Concentrated Photovoltaic, Nonimaging optics, Optics Design, tolerance, acceptance
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List of Abbreviations

Acronyms
CAP - Concentration-Acceptance Product
CCD - Charged Coupled Device
CEC - Compound Elliptical Concentrator
CPC - Compound Parabolic Concentrator
CPV - Concentrated Photovoltaics
LED - Light Emitting Diode
LCOE - Levelized Cost Of Electricity
MF - Merit Function
NIO - Non-imaging optics
NREL - National Renewable Energy Laboratory
PMMA - Poly(methyl methacrylate)
PV - Photovoltaics
RMS - Root Mean Square
RSS - Root Sum Square
R.U.I.- Radiation Uniformity Index
SOE - Secondary Optic Element
VSHOT - Visual Scanning Hartmann Optical Tester

\(W_p\) - Watt peak (measure of nominal power of a photovoltaic module under 1000 W/m\(^2\) light intensity

Variables
\(\alpha\) - Second reflection angle
\(\beta_i\) - Angle between of an acceptance edge-ray\((i=1)\) and a 0° edge-ray \((i=2)\) (in °)
\(\Delta \epsilon_{\text{total}}\) - Sum of all error contributions to the slope error
\(\Delta \beta\) - Half angular difference between an acceptance edge-ray\((i=1)\) and a 0° edge-ray \((i=2)\) (in °)
\(\Delta l\) - Minimum measured variation of height attained with the laser during the calibration
\(\epsilon_{\alpha}(x)\) - Slope error of the reflection point of the parabola mirror with coordinates \((x,p(x))\)
\(\eta\) - Efficiency
\(\theta_a\) - Acceptance angle (°)
\( \theta_i \) - Incidence angle
\( \theta_r \) - Reflected angle

2 - D - Two Dimensional
3 - D - Three Dimensional

Average\(_{C_l}\) - Average local concentration (over the entire solar cell surface)

\( a \) - Entry aperture (m)
\( a' \) - Exit aperture (m)

\( C_g \) - Geometrical Concentration Ratio (also defined as \( C \))

\( C_l \) - Local Concentration

\( C_{max} \) - Maximum concentration of a concentrator

\( d \) - Measured distance from the focus and the incidence point

\( e(x) \) - Equation of top secondary optic element mirror

FF - Fill Factor

\( f \) - Distance between the vertex and the focus of the parabola (mm)

\( h \) - Height of the center of the infinitesimal mirror (mm)

\( I_{SC} \) - Short-Circuit Current

\( l \) - Length of the receiver (m)

\( Max_{C_l} \) - Maximum local concentration

\( Min_{C_l} \) - Minimum local concentration

\( n \) - Refractive index

\( P_L \) - Solar power

\( p(x) \) - Function that defines the parabola

\( T_{ASM} \) - Tolerance of the assembly \( T_i \) - Individual tolerance \( V_{OC} \) - Open-circuit voltage

\( w \) - Wall distance

\( x \) - Spatial variable (m)

\( x_e \) - Spatial variable defined for the secondary optics mirror construction (mm)

\( X_i \) - Random variable of an individual tolerance with an assumed distribution

\( x_{min}, x_{max} \) - Extremes of the parabola when only perfect alignment is considered (mm)

\( Y \) - Sum dimension of the tolerances
Chapter 1

Introduction

1.1 Context of the thesis

The increasing demand for energy all over the world is increasing every year, at a tremendous speed, as can be see in Figure 1.1(a). The analysis done by U.S. Energy Information Administration predicts that in 2035 the energy consumption in the world will be 739 Quad. Btu (approximately 24.7 TW). This value represents an increase of almost 50% from the energy consumption of 2007 [2]. Motivated by the fast growing of China, the demand for energy increased as well. Looking to Figure 1.1(b) it is possible to see the evolution and prediction for the energy consumption of U.S.A., China and India. Comparing from 1990 to nowadays, consume share of China is almost twice the actual value, with predictions to increase even more, becoming the most energy consumption country in the world.

The energy necessary to keep up with the demand cannot come only from fossil fuels, as they are reaching a limit in production (as shown in Figure 1.1(c)), and they are one of the major causes for the rise in CO$_2$ emissions, which is the number 1 believed cause for global warming. The solution is to turn to clean and renewable energy sources, capable of supplying large amounts of energy. Despite the actual global economic crisis, in 2010 it were invested US$211 billion in renewable power and fuels, representing an increase of 32%.

Figure 1.1: Fig. a) Evolution of world energy consumption, 1990-2035 (predictions). Fig. b) Share in energy consumption from U.S.A., China and India, 1990-2035. Fig. c) Evolution of production of oil (black curve) and the evolution of finding of oil (red bars for the past, green bars for future prediction). Source: see references [2],[3]
from the investment made in 2009 [8]. PV Industry is rising at an astonishing compound annual rate of 65% [8], showing that the interest in this technologies is increasing and it is believed that photovoltaic (PV) technologies can really supply the growing energy demand, and even be the basis of grid supply around the world [4]. Some estimations indicate that concentrated photovoltaics (CPV) can grow almost 200% per year by 2015. Considering that in 2010 there were only 28 MW of CPV installed capacity (comparing to the 33000 MW of total PV installed capacity), and this year it is currently being constructed 689 MW, with the possibility to grow even more, the estimations are very well supported, revealing a bright and increasing future for CPV market [8]. To reach the Holy Grail of PV world [3], the famous grid-parity, the CPV technologies have being studied for many years to improve their efficiency and reduce the price per watt of energy. To reach this point, the optics of the CPV systems need to be properly designed, the lenses and mirrors used must be well defined and resistant, to be able to withstand the climate, in order to the CPV system be functioning at top efficiency along the entire lifetime.

1.2 Motivation

This master thesis was developed in the R&D Department of WS Energia S.A., and was integrated in the project of the conception and production of a new CPV system, HSUN. With a first version of the design done, and after several prototypes were built, some errors appeared and were not being able to be corrected. The main objective of this thesis was to study and analyze those errors and propose methods and tools to measure them, and finally propose a solution. The major goal to this thesis was the study and improvement of the new CPV system, HSUN. To satisfy this goal, several tools and methods were necessary to be developed in order to properly evaluate, analyze and improve HSUN. The improvement of HSUN is particularly beneficial to WS Energia, but also for the industry associated with the manufacturing of components to the CPV module. The development of a new concentrator requires many different fields of study, stimulating the creation of knowledge, and competition between companies, necessary to farther improve their CPV systems. With more competitive and efficient CPV systems, more clean and renewable energy is produced, which all the whole World benefits. For the scientific community, the methods and models developed during this work represent another step towards the development of scientific tools to analyze and measure meaningful parameters in the study of CPV systems. The main goal of this thesis was divided into three parts:

- Development of a method to analyze the positioning tolerances of a CPV module, and the posterior application of that method to HSUN.

- Proposal of a new design for the secondary optics for HSUN optical system.

- Development of a model to evaluate parabolic troughs, and manufacturing of a functioning prototype to test and validate the model.
1.2.1 Contributions

The results obtained in the work done, fully achieved the objectives outlined in the beginning of this thesis. The main contributions to WS Energia, and particularly to HSUN project were:

- The method used to tolerance HSUN was the first of the kind in WS Energia. With this method, it is now possible to analyze all positioning tolerances of any CPV system;

- The study of tolerances brought new knowledge about the HSUN system, revealing the relatively high tolerances for some pieces, which helped understand the effect of errors in HSUN. These tests also showed that the secondary optics could be improved, as a single change in their angle, increased the acceptance angle;

- The results for the new SOE design where very promising, resulting in two new options for HSUN. The most beneficial to HSUN represents an increase of acceptance, which increases the tolerance of the module to errors in the primary optic and even allows the increase of HSUN concentration, turning this system a more competitive product in PV market.

- The methods used to design the new secondary optics result in the publication of a poster and a paper (*Development of model and software for optimization of primary and secondary optical components for photovoltaic concentration*) in one of the most important PV conferences in the world, the 26th European Photovoltaic Solar Energy Conference and Exhibition.

- The method developed to experimentally evaluate parabolic troughs was successfully tested and validated by the prototype built. The information provided by the results were a major contribution to HSUN, as this model is able to obtain the efficiency of the primary optic to properly reflect the sunlight to the receiver and secondary optics.

- The experimental model can also be a valuable aid to manufacturing companies to test their production line and locate and eliminate some systematic errors (such as a shift in a certain position can be quantified and corrected). To WS Energia, is a major advantage as it gives a form to evaluate the manufacturers, and the manufacturing errors of parabolic troughs, telling if a certain manufactured parabolic trough is precise enough to be used in HSUN.

1.3 Structure of the thesis

This thesis is organized in 7 chapters. In Chapter 1 an introduction of the main theme of the thesis is done, and motivation and major contributions of this thesis are explained. Chapter 2 introduces the theory and fundamental concepts of concentrated photovoltaics, nonimaging optics and tolerancing methods. Chapter 3 explains the HSUN system, the main object of study of this thesis. It is presented a general description, the main characteristics, components and optical parameters. It is also shown the analysis made to HSUN
prototype, identifying the major errors to be studied and solved by the work done in this thesis. Chapter 4 presents the procedure adapted to model HSUN, and the tests done to evaluate the positioning tolerances of HSUN module, along with the respective results. In Chapter 5 it is described the work done to design the new secondary optics. The methods developed and applied are detailed, and a final comparison is made to choose the best result. Chapter 3 describes the new model developed to evaluate parabolic troughs. It is also showed the experimental setup of a prototype to test and validate the model. Finally, in Chapter 4 it is presented the main conclusion of this thesis and some suggestions for future improvements related to the work done are made. In Chapter 8 are the appendices of this thesis, where some secondary graphics and data are located.
Chapter 2

Theory and fundamental concepts

This chapter covers the fundamental concepts of Concentrated Photovoltaics (CPV), the fundamentals of optics applied to concentration, and the main tolerancing methods. In Section 2.1, a resumed description of the conventional photovoltaic technologies is presented. Section 2.2 describes the concepts of CPV, referring also the main technical areas, an overview over the most known technologies, and state of the art products is made. Finally, Section 2.4 presents the tolerancing methods more commonly used in CPV systems.

2.1 Fundamentals of Concentrated photovoltaics

2.1.1 Review of photovoltaic energy

A definition of a photovoltaic (PV) system is a system that converts directly solar radiation into electricity [4]. Since it was first found, in 1839 by Edmond Becquerel, and after improvements made in the almost 100 following years, the photovoltaic energy has raised a constantly growing interest all over the world. The possibility to generate electrical energy in practically any place in the world was extremely appealing. With the major drawback of the high cost of solar cells, the almost exclusive use of PV energy was made by space industry to fuel satellites, where no budget constraints were applied. The efficiency of solar cells more than double from 6% in 1954 to 13.5% [7], but still too expensive. Today the top efficiency of silicon cells is around 27.6% [2].

Only in the early 70s, Dr. Elliot Berman built a PV system, using a silicon cell less efficient, and cheaper packaging materials, lowering the price of watt from $100 to just $20 per watt peak. This value was still high compared to the price per watt from fossil fuels, but it was starting to be interesting to places located far from the electric grid. Ironically, it was in offshore oilrigs and isolated on-shore gas and oil fields, among others, where PV systems were used, replacing the toxic and short-lived batteries [6]. Nowadays, total PV installed capacity is estimated to reach 50.9 GWp, representing a growth of 62.1% comparing to 2010 [8]. The continuously increasing price of oil, the global warming, the Kyoto Protocol, and the recent nuclear disaster that occurred in Fukushima, Japan, turns the attention of the world to renewable energies [2]. Nowadays, the price per watt is already under 1$ per watt peak, at 0.98$ reached by FirstSolar.
2.2 Concentrated photovoltaics

A concentrated photovoltaics (CPV) system consists in a technology in which mirrors and lenses are used to concentrate sunlight onto PV cells. This way, the solar cell can be significantly reduced, which is the most expensive component in a PV system. Concentrating the light, the collected sunlight is the same, hence maintaining (and even increasing) the power output [9]. The main advantages of CPV are the decrease of PV system costs, as less area of solar cell is necessary, silicon cells can still be used (usually only in low or medium concentrations) and a higher efficiency. The major disadvantage of CPV systems is the necessity to have a sun tracking system to keep the CPV module focused to the sun throughout the day. This extra cost, compared to conventional PV, is attenuated with the higher power output. CPV systems are usually divided into three categories depending on the concentration level: low (lower than 10 Suns); medium (up to around 150 Suns); high (higher than 200 Suns) [9]. Small concentrations try to ally the advantages of conventional PV models (high acceptance angle) with the advantage of CPV (lower costs related to solar cells, higher efficiency). Higher levels of concentration drastically reduce the solar cell area (sometimes to a few square millimeters) but usually require high efficiency solar cells (which are expensive), a very high sun tracking precision, and usually require active cooling systems, as the efficiency of solar cells, decrease with increasing temperatures. Medium concentration was the most popular choice as it combines the best features of both low and high concentration. With the recent entering in conventional PV market by Chinese companies, which build cheaper PV modules, and the advent of thin-film PV cells, the PV modules price dropped significantly. These factors decrease the main advantage that CPV systems had over conventional PV that is the price reduction. This fact will force the CPV market to increase the concentration to much higher values [9].

A CPV system is mainly formed by three different components: optics, solar cells, and the Sun tracking system. Next, it is provided a concise description of each component.

Figure 2.1: Schematic of a PV solar cell. The sunlight creates electron-hole pairs, $e^-$ and $h^+$ respectively. Source: see reference [7]
2.2.1 Solar cells

Conventional solar cells are made of silicon, a semiconductor capable of absorbing light and deliver a portion of that energy, to carriers of electric current, electrons and holes. This phenomenon, generates a DC current in a preferential specific direction, working like a silicon diode \([7]\). A typical solar cell scheme is shown in Figure 2.1. A solar cell is usually formed by several layers, each one with a specific function. The top layer, is an anti-reflective material that decreases the reflection of light, hence increasing the amount of light that reaches the silicon. Usually located right under this layer, is the metal grid that with the bottom contact, form the electrical contacts to where the current carriers will pass. The silicon is divided to form two layers: one n-type, thinner and negatively doped with phosphorus, and the other p-type, thicker and positively doped with boron \([7]\). Several types of PV cells exist, depending on the semiconductor used. The most common is the silicon, but even using just silicon, there are different configurations. Actually, there are four major types of PV cells on the market, just based in silicon \([10]\):

- **Single crystalline** Consist on a single silicon crystal per cell. The atoms are ordered in a well defined structure, the material has a good conducting behavior. The process to fabricate a large single silicon crystal is hard and requires high energy related to the high temperatures necessary. The silicon has to be molten and then it passes through a time consuming cooling that needs to be slowly made, in order to permit the atoms to be arranged according to the crystal. This configuration makes these cells the most efficient, among silicon-based cells, to efficiencies varying between 15-20\% \([10]\).

- **Multi crystalline** In this type of cells, the silicon layers have ordered crystals in localized regions. These cells are less efficient, as in the frontiers between two crystals with different orientations, the electric conduction is affected. The fabrication process is faster and cheaper than the single crystalline cells. In this case, the cooling of the molten silicon is done much faster. The conversion efficiency is between 12-14\% \([10]\).

- **String ribbons** Less used in the PV market, string ribbons consist in strips of multi crystalline silicon. Compared to multi crystalline cells, this type require less silicon, and the efficiency is located between 11-13\% \([10]\).

- **Thin films** Thin film cells are the least expensive of the referred cells. Formed by highly disordered silicon structures, and easily made by deposition in glass or plastic, are faster and cheaper to produce. With recent developments in this field, the efficiency of thin films already reached 20.9\% \([1]\).

Another type of cells, are the multijunction cells, also known as III-V cells, very expensive to produce, but with much higher efficiencies. The structure of these cells are similar to a common PV cell, having several (2 to 3 typically) and each one absorbs the radiation in a certain wavelength range, of the electromagnetic spectrum. The materials used are Gallium arsenide, Germanium, Indium Phosphide, elements of III and V column in the Periodic Table (hence the name III-V cells), which are very expensive and hard to combine in
a solar cell. First being used exclusively in spatial projects, with the advent of HCPV (high concentration CPV), the use of these cells began to increase [7]. Figure 2.2 shows one of the most famous graphic in PV world, representing the evolution of efficiency of solar cells. One fact worth of notice, is the evolution tendency of every technology to stagnate at an efficiency level. The technology with most promising and with the most growth potential are the multijunction cells.

In CPV systems, the type of solar cell used depends on the concentration level. For low and medium concentrations, the silicon cells are usually a good choice, as the efficiency increases with the increase of incident light, to a certain level [8]. For higher levels, the solar cells used are usually multijunction cells, or silicon cells modified specially to concentration.

Due to the light concentration in CPV systems, depending on the concentration level, the temperature of solar cells can increase, thus decreasing the efficiency [12], [13]. For low and medium concentration levels, the cooling of the cells is usually made passively, dispersing the heat using high thermal-conductive elements. For higher concentrations, the cooling has to be very efficient and fast so an active cooling system is placed near the solar cells. Usually this systems use water to remove the heat from the cells. This solutions can be adapted to form a hybrid solar panel, producing electric energy directly from the PV cell, and heat water by absorbing the heat on the PV cell.

PV cells are the most important component in any solar system. For this reason, certain conditions need to be met to assure the proper function. The major factors that affect the efficiency of a solar cell are the uniformity of radiation and the temperature of the cell [12], [13]. The distribution of radiation over the surface of the cell is very important. The distribution should preferentially be the most uniform possible. A nonuniform distribution of light over a PV cell may produce a very accentuated decrease in efficiency. This fact occurs due to the Joule effect power losses due to resistance in the cell series [11]. The efficiency of a PV
cell (\(\eta\)) is defined by
\[
\eta = \frac{V_{OC} \times I_{SC} \times FF}{P_L},
\]
(2.1)
where \(V_{OC}\) is the open-circuit voltage, \(I_{SC}\) is the short-circuit current, \(FF\) is the cell fill-factor and \(P_L\) is the solar power. The fill-factor parameter is highly affected by the radiation uniformity. One unknown factor is how the variation of the light distribution affects the FF \cite{11}. The nonuniformity might have several different forms. It can be a peak of higher concentration, called hot-spot, a shaded area, and even this forms can be located at different areas in the cell. There are some recent studies and experiments studying this effects but no general model was yet obtained \cite{12}. The radiation distribution in a solar cell is usually shown a graphic revealing the radiation intensity at each point of the surface of the cell. To compare different radiation distributions between different designs, it is used the radiation uniformity index. In PV world, there is not a consensual and generally accepted formula. In this thesis, the formula considered to the radiation uniformity index (\(R.U.I.\)) calculus is
\[
R.U.I. = \frac{Max_{C_1} + Min_{C_1}}{2 \times Average_{C_1}}
\]
(2.2)
A perfect uniform distribution, \(Max_{C_1} = Min_{C_1} = Average_{C_1}\), hence the R.U.I.=100%.

2.2.2 Optics

CPV system use reflective and/or refractive materials, mirrors or lenses, to concentrate the light. The most common lenses used are Fresnel lenses, either point-focus or linear focus, depending on the type of focus shape that each one forms. The material chosen to manufacture the lenses is usually PMMA, an acrylic plastic with special characteristics that make it suitable to this projects. It is molded relatively easy, it has a good weatherability, important to guarantee a large warranty of the module (usually up to 15-20 years). A factor that decrease the long-term durability of the lenses, is the fact that they tend to gain a yellow color, result of the effect of ultraviolet radiation that deteriorates the PMMA \cite{7}. Some tests have been done to produce lenses using glass, but so far, they have not been successful \cite{11}. Alternatively to lenses, are mirrors, which instead of refracting the light, reflect it. Made of aluminum or a special reflective coating, mirrors can have different shapes (some easier to obtain than others), have a large longevity as the aluminum does not deteriorate and can even be recycled. The most common shapes are the parabolic mirrors, that concentrate light parallel to their axis in one point, or parabolic troughs that form a focus line \cite{11}.

2.2.3 Sun Tracking system

The tracking system is a component with a major importance, as with the increase of concentration, lower is the angle that the sunlight can enter in the CPV. To guarantee that the CPV module is always facing the Sun, in order to the sunlight enter the aperture of the module within the acceptance angle, a mechanical system needs to track the position of Sun in the sky, and align the CPV module. Sun tracking systems are usually divided into 1 or 2 axis trackers, depending on the configuration of the optics. Usually in low concentration levels, only tracking in 1 axis is required, while in medium to high concentration, 2-axis trackers
are used. Trackers are an extra cost in CPV systems compared to conventional PV modules, being the price proportional to the tracking precision (usually measured in degrees). The tracking precision necessary is imposed by the acceptance angle, which is the tolerance that the optical system have to a deviation in the angle of sunlight rays [14].

### 2.2.4 State of the art of concentrated photovoltaic technologies

Despite increasing market of PV systems, in 2010, there are just 28 MW of CPV capacity installed, out of more than 33000 MW of PV installed capacity [9]. The low penetration in the market is mainly related to the areas that where the market increased, were developing countries, where CPV systems are not that advantageous as they require more maintenance, comparing to conventional PV modules. Despite these facts, the future perspective is of growth for CPV systems. Actually, there are around 689 MW of new CPV capacity under construction, that may increase with potential large scale projects to be constructed India and South Africa [9].

![Figure 2.3: Fig. a) Low concentration (2 Suns) DoubleSun, from W.S. Energia. Fig. b) Low concentration (2.25 Suns) from Zytech](image)

Source: WS Energia S.A., Zytech

Figure 2.3: Fig. a) Low concentration (2 Suns) DoubleSun, from W.S. Energia. Fig. b) Low concentration (2.25 Suns) from Zytech

![Figure 2.4: Fig. a) Medium concentration (20 Suns) HSUN, from W.S. Energia. Fig. b) Medium concentration (120 Suns) from Zytech](image)

Source: WS Energia S.A., Zytech

Figure 2.4: Fig. a) Medium concentration (20 Suns) HSUN, from W.S. Energia. Fig. b) Medium concentration (120 Suns) from Zytech

In Figure 2.3 some low concentration CPV systems are presented. Both systems, either Double Sun from WS Energia or the one from Zytech, use flat mirrors to concentrate light into a conventional PV system. Two
medium CPV systems are shown in Figure 2.4. The first system, HSUN, from WS Energia, uses parabolic trough mirrors to concentrate light into PV cells located in the back of the next parabolic trough. The second system, from Zytech, uses prismatic lenses to concentrate the sunlight. Figure 2.5 shows three high concentration CPV systems. The first system, from Emcore, uses point-focus Fresnel lenses, while the third CPV, from Solergy, concentrates the light with a cone lens made of glass. The second concentrator uses parabolic dishes mirrors to concentrate in a single PV cell, while the previous seen systems use smaller modules, but greater number of modules per CPV system.

2.3 Fundamentals of optics applied to solar concentration

The theory of optics is usually associated with the creation of an image from an initial object. Therefore, in imaging optical systems the light emitted by a point in the object, is captured by the optical system and is concentrated onto a specific point in the image, in order to the image be proportional to the object [11]. In CPV systems, it is not necessary to form an image of the Sun in the receiver, as the main goal is to transfer the maximum energy from a source into a receiver. In nonimaging optical systems, the optical system have to take the light from the light source, instead of an object, and concentrate it in any point at the surface of the receiver, instead of an image. The nonimaging optical theory is called Nonimaging or Anidolic Optics [11].

2.3.1 Concentration Ratio

A central concept in Nonimaging Optics applied to solar concentration is the geometric concentration ratio, concentration for short. The geometrical concentration ($C_g$) of a given optical system is defined by the ratio between the entry aperture ($a$) and the exit aperture ($a'$):

\[ C_g = \frac{a}{a'}. \]  

(2.3)
Higher the entry aperture relative to the exit aperture, i.e., the area where the light is focused (in CPVs it is usually the receiver), higher is the concentration of light of that optical system. One of the most important results that had a great impact, was the calculus of the maximum concentration level related with the maximum incident angle for which the light is accepted. Considering the second law of thermodynamics, it can be proven that the maximum concentration of a 2-D concentrator, filled with a material with refractive index $n$, is related with the maximum incident angle (also known as acceptance angle $\theta_a$) by the following equation:

$$C_{max} = \frac{n}{\sin(\theta_a)} \quad (2.4)$$

or for 3-D concentrators, $C_{max}$ becomes

$$C_{max} = \frac{n^2}{\sin^2(\theta_a)} \quad (2.5)$$

Considering equations 2.4 and 2.5 one can see that if the concentration is set too high, the acceptance angle decreases. This results in a higher precision of the Sun tracking system to maintain the CPV module facing Sun with an error within the acceptance angle limit. It is also possible to conclude that increasing the refraction index of the filling material, increases the concentration proportionally. 3-D concentrators have a greater potential to higher concentrations as with the increase of acceptance angle, the concentration decreases slowly, and the effect of the refractive index is squared.

Using the two equations 2.4 and 2.5 it is possible to tell how well projected is a concentrator. The parameter that measures that quality is the $CAP$, Concentration-Acceptance Product bound, and is defined for a 2-D concentrator by

$$CAP = C \times \sin(\theta_a), \quad (2.6)$$

and for a 3-D concentrator, the previous expression becomes

$$CAP = C \times \sin^2(\theta_a), \quad (2.7)$$

where $C$ is the concentration and $\theta_a$ is the acceptance angle.

If the multiplication of the concentration value of a CPV by the respective acceptance angle is closer to 1, it means that the design is at the thermodynamic limit, hence it cannot be optimized. If the $CAP$ value is far from it, the optical design is far and some improvements might be done.

Another very important information can be learned by studying the $CAP$ value of a concentrator. If the receiver and secondary optics (if there is) are maintained the same, and the primary optics size is changed, the $CAP$ value is conserved. Rearranging equation 2.6 and 2.7 to

$$C = \frac{CAP}{\sin(\theta_a)}, \quad (2.8)$$

and

$$C = \frac{CAP}{\sin^2(\theta_a)}, \quad (2.9)$$
it is obtained the relation between the concentration and the acceptance angle of a CPV optical system. Considering a typical CPV system, the tracker has a precision to follow the Sun. If the concentration of the considered CPV system is desired to be the highest possible that has an acceptance angle equal to the precision of the tracker, one just have to substitute the desired acceptance angle in equation 2.8 or 2.9 depending on the type of concentrator (2-D or 3-D), and calculate the maximum concentration possible. Per example, considering two similar 2-D concentrators with $C = 20$ Suns, one with $\theta_a = 1.5^\circ$ and the other $\theta_a = 2.5^\circ$, and a tracker having a precision of $1^\circ$. The $\text{CAP}$ values are and 0.872 and 0.524, respectively. Equaling the acceptance angle to the precision of the tracker, the maximum concentration level are approximately 30 and 50 Suns, respectively. This represent a very large difference, and shows the importance of a well designed optical system in order to utilize the full potential of a CPV system.

2.3.2 Nonimaging concentrators design

Figure 2.6: Scheme of a CPC, formed by two parabolic arcs $AC$ and $BD$. The CPC accepts light entering the entry aperture $CD$, making a maximum angle of $\pm \theta$ with the vertical, and concentrates it into the exit aperture (usually the receiver) $AB$. [11]

One of the most important tools to design concentrators is the edge-ray principle. Fermat stated a principle in imaging optics which states that the optical path length between an object and the respective image, is constant for all the rays [19]. Transposing that principle to Nonimaging Optics, the rays are changed to strings. This design tool has been used since the 1960s, although it was only proven in 1985 by Miñano [19]. Considering Figure 2.6, it is possible to visualize the edge-ray principle. Miñano proved that for a ray at the edge ($p$) of the entry aperture ($a$), incident at the extreme angle of acceptance, incident at the opposite edge ($p'$) of the exit aperture ($a'$), any ray leaving the entry aperture, with an entry angle smaller or equal to the acceptance angle, will be incident within the exit aperture ($a'$) [19]. With this principle, it was obtained the first 2-D ideal concentrator: the Compound Parabolic Concentrator - CPC for short. In Figure 2.6, a scheme of a CPC is represented. The CPC is designed considering a parallel light source, located at an infinite distance. The walls of the concentrator, are formed by two parabolas, with their axis parallel to the light (vertical) and focus placed at the opposite edges of the receiver. This way, using the edge-ray theory, considering two rays, incident with an incidence angle equal to the acceptance angle of the CPC, will be reflected to the edges of the receiver. This way, every ray incident with an angle lower than
the acceptance angle will be reflected to the receiver area, and all the rays with higher incidence angles are rejected \[19\]. If instead of a single parallel ray source, there are two sources with different inclinations, as

![Diagram of Asymmetrical CPC](image1)

Figure 2.7: Asymmetrical CPC. Similarly to the CPC, the asymmetrical CPC is composed by two parabolic arcs \(AC\) and \(BD\), each reflecting the rays \(r_2\) and \(r_1\), respectively. As the source \(A_2\) is larger than \(A_1\), parabola \(AC\) is longer than \(BD\). Source: see reference [11]

represented at Figure 2.7, the ideal solution have a form of an asymmetrical CPC. The light coming from \(A_1\) is reflected by the parabola \(BD\), and the light from \(A_2\) is reflected by parabola \(AC\). As source \(A_2\) is larger than \(A_1\), parabola \(AC\) is longer than parabola \(BD\).

Considering now a sources, with finite length and located at a finite distance from the receiver, and a receiver

![Diagram of Asymmetrical CEC](image2)

Figure 2.8: Asymmetrical CEC. Similarly to the CPC, the asymmetrical CPC is composed by two parabolic arcs \(AC\) and \(BD\), each reflecting the rays \(r_2\) and \(r_1\), respectively. As the source \(A_2\) is larger than \(A_1\), parabola \(AC\) is longer than \(BD\). Source: see reference [11]

placed at asymmetrical positions relative to each other, the ideal solution is an asymmetrical Compound Elliptic Concentrator, CEC for short. Figure 2.8 shows the scheme of an asymmetrical CEC [11]. An important characteristic of ellipses to optical design methods, is the existence of two foci. Any ray leaving one focus, will be reflected in the ellipse, and be reflected to the other focus. With this knowledge, the design of an optical system for the considering case becomes trivial. The elliptical arc \(BD\) is formed by drawing an elliptical arc, with foci located at points \(E\) and \(A\). This way, every ray leaving Point \(E\), is reflected in the elliptical arc \(BD\) and focused at point \(A\). The process to draw elliptical arc \(AC\) is the same, but considering as foci, point \(F\) and \(B\). If the distance of the source tend to infinity, the elliptical arcs will tend to parabolic
arcs, forming the already shown asymmetrical CPC [11].

2.4 Tolerancing Methods

Since the early 1900s, tolerances have been one of the most important issues in engineering process related to a product realization [15]. The objectives of the products determine the tolerance. Tolerance can be defined as the maximum error that a certain quantity (position, inclination, length, etc) can have, according to the design. It is important to understand and know the tolerance values to a certain assembly of components as the price to manufacture the components is inversely proportional to the tolerance value. To obtain a very precise and well defined piece, hence a low tolerance, the methods to manufacture it has to be very precise and controlled, being naturally more expensive [15]. In optical systems, errors in the components can affect directly the efficiency and well-functioning of an optical system. The optical surfaces have microscopic roughness that causes the scattering of light, and the surface profiles have contour errors that change the theoretical reflection angle of the light. Another type of error is the positioning of the elements. An error in the relative positions and inclinations of the optical elements (optics, receiver, orientation relative to the source). It is crucial to know the effect of those errors to correctly design and predict the performance of the optical system [17]. One of the most accepted models is the tolerance chain technique [15]. This models, determines the propagation of conventional (plus/minus) tolerances assigned to each arc, forming a chain. The methods based on this model are classified according to the following three approaches:

- **Linear/linearized tolerance accumulation;** This type of models are based in worst case and statistical (root sum square (RSS)). The tolerance operators are respectively defined by

\[
T_{ASM} = \sum_{i=1}^{n} T_i,
\]

and

\[
T_{ASM} = \sqrt{\sum_{i=1}^{n} T_i^2},
\]

where \(T_{ASM}\) is the tolerance of the assembly, i.e., the result of the chain of individual tolerances of the components, and \(T_i\) is the individual tolerance. This models base their analysis in the linearization of the sum of the effects of each individual tolerance to the final assembly tolerance (considering the tolerances to be independent from each other). (Chase et al. from 1195 to 1998, Gao et al. 1998). [15]

- **Statistical tolerance analysis;** this analysis method aims to characterize the sum dimension (\(Y\)) of the design equation

\[
Y = f(X_1, X_2, ..., X_N),
\]

where \(X_i\) have an assumed distribution. Despite used in by some authors, these methods implies the analytical determination of the statistical moments of random variables \(X_i\)\'s. This procedure is usually a challenge, and as a statistical method, it has a fierce competition from the Monte Carlo simulation method [15].
Monte Carlo simulation; this largely used simulation method, in many different fields of physics, mechanics, and overall real-world statistical studies. This method operates by defining random values (within a certain range and/or according to a certain distribution) to the variables $X_i$'s. This method is usually used to test the effect of several individual tolerances in the final performance, being hard to obtain the individual tolerances from this technique [15].

Nowadays, with the almost exclusive use of CAD software, a large number of those softwares already include one or several tolerancing routines. In optics, the most known software are based in ray tracing, which use a large number of rays, to perform a statistical study of the behavior of the optical system. The most famous ray-tracing softwares are ZEMAX, Oslo, Code V, among others. ZEMAX has several tolerancing procedures built-in, being one of the most complete and reputed of his kind. One mathematical tool used in almost every ray tracing software to perform a tolerance is the Merit Function ($MF$) [16]. The merit function is the user-defined function that measures the performance of the system in study. In NIO, it is most commonly used the total incident irradiation, and the RMS spot radius to certain optical configurations [16]. The tolerances routines in ZEMAX are the following:

- **Sensitivity analysis** - The sensitivity analysis test the individual effect of a single tolerance value in the $MF$ value. As the test is done for individual tolerances, it is not considered the stacking effect of tolerances. The computation of the sensitivity, i.e., the effect that a certain tolerance has to the performance of the optical system, begins with the evaluation of $MF$ value. Then, it is individually changed the defined parameters according to the tolerance values imposed and is recalculated the new $MF$ value. The difference between the initial and the new $MF$ value represent the variation of performance [16].

- **Inverse tolerancing method** - This method performs the opposite function of the sensitivity analysis. In this routine, it is provided the change in the $MF$ value desired, and the software computes the individual maximum tolerances that perform that change. The inverse tolerancing routine is very handy to the determination of the components tolerances that result in a controlled change of performance [16].

- **Monte-Carlo simulation** - The Monte-Carlo simulation in ZEMAX has the same basis of all simulations of this kind. It randomly changes a parameter within a user-defined tolerance limit, and according to a distribution (normal, uniform, parabolic, or user-defined) and evaluates the $MF$ function of all tolerances at the same time. Finally it presents the statistical results with the proper mean and deviation values.

The inverse tolerancing method is complemented by the Monte-Carlo simulation has the first allows to obtain the tolerances, and the second studies the global effect of them in the performance of the optical system. A complete and thorough study of the tolerances of any optical system can be done using this software [16].
Chapter 3

Experimental model to evaluate parabolic troughs

This chapter presents the experimental model developed to evaluate parabolic troughs. As seen in the tolerance results, the parabolic trough is the optical element in HSUN that most losses can inflict, within reasonable values. The errors in the contour, specially those where parts of the parabola are rectilinear, can make the total incident power drop drastically. To be able to evaluate and measure quantitatively those errors, an experimental model to evaluate parabolic troughs was developed. This evaluation model had to satisfy these three objectives:

1. Measure slope (hence position) errors and their direction, along a parabola;
2. Tell if the errors of a given parabolic trough, are tolerable by the SOE;
3. Measure the efficiency of a parabolic trough to reflect correctly all incident light;

This Chapter is organized by sections: in Section 3.1 where the evaluation model is explained; in Section 3.2 are referenced the materials used and the experimental setup of the model prototype. In the same section it is presented the software used to implement the evaluation model and the calibrations necessary to perform it. Section 3.3 describes the existing errors and limitations of the built prototype; in Section 3.4 is explained the experimental procedure adapted to evaluate the parabolic troughs. In Section 3.5 the results obtained are analyzed and discussed. Finally, in Section 3.6 a summary of this chapter is presented and some future improvements are suggested to enhance the model prototype.

3.1 Parabolic trough evaluation model

The parabolic evaluation model consists in a mathematical model that is able to measure the errors of slope along a section in a parabolic trough. The laser light scanning the parabola trough, forms a section that has a form of a parabola. To avoid confusions and ease the description, in this chapter the line drawn by the laser scanning along the parabolic trough is referred as a parabola. Later, a prototype was built to experimentally apply the model to real parabolic troughs. To begin the model, it was defined that, to evaluate a parabolic
trough, it was divided into several parabolas, and then each one of those parabolas was individually studied. Then, it is possible to evaluate a parabolic trough in different sections. In HSUN this study is particularly important because of the manufactured structure used to support the parabolic trough. As it has only two supports, located in the ends, the contour of the parabolic trough have different characteristics and defects, depending on the position analyzed. As seen in the prototype, the primary mirror has a more perfect curvature where is supported than in the middle section.

This model was developed based in an existing system: VSHOT, which is a laser ray-trace system, that scans the surface of parabolic type mirrors, used in solar concentration \[20,21\]. This system was developed in NREL, a major R&D company in CPV systems. The operating method of VSHOT is represented in Figure 3.1 and can be described by the following steps:

1. a rotating laser is fixed in a target plan, is pointed to the parabolic mirror;
2. the light is reflected in the mirror back to the target plan;
3. that ray angle is compared with the theoretical ray (considering a parabola with no contour error);
4. using a Zernike polynomial, the mirror is reconstructed and afterward the results are analyzed;

The model developed in this thesis, aimed to obtain similar results and information from the parabolic troughs used in HSUN, but using a different configuration and operation model for the laser ray-trace system. The operating method of the developed laser ray-trace is shown in Figure 3.2. The procedure can be described as a sequence of the following steps:

1. a laser is placed above the aperture of the parabola, parallel to the axis of the parabola;
2. if the parabola has a perfect contour, the light coming from the laser, will be reflected to the focus;
3. an opaque vertical target plan is placed in the focus plan;

4. the reflected ray will be incident in the target in at a certain distance from the focus;

5. measuring that distance and knowing the position of the parabola where the ray was reflected, the reflecting angle is measured and compared to the theoretical angle (considering a perfect parabola);

6. that angle deviation can be related to an error in the slope of that point of the mirror;

7. using the slope error to trace infinitesimal mirrors, the mirror contour is traced;

To obtain more information considering now all of the optical system (in this case HSUN optical system) and not just the primary optics, a complementary model to measure the efficiency of the mirror to reflect correctly the rays into the aperture of the SOEs was also developed. By calculating the positive and negative maximum angle deviation that each point of the parabola can have and comparing the angle deviation with that maximum value, it is possible to tell if a ray will be reflected into the SOEs aperture or not. Making the ratio of the mirror points that have a slope error within the positive and negative limits with all the scanned points, the efficiency of the parabola is measured.

### 3.1.1 Mathematical description of the evaluation model

The principle of the model is that a incident ray of light, parallel to the axis of a parabola, will be reflected to the focus of that parabola. If the parabola has some sort of defect in the surface, the ray will be reflected to a point, other than the focus. Knowing that the reflection angle ($\theta_r$) of a ray of light is changed by a surface with an inclination $\alpha$, by the following equation:

$$\theta_{r'} = \theta_r + 2 \times \alpha,$$  \quad (3.1)
if a reflected ray has a certain angle deviation, \( \Delta \theta_r = \theta_r' - \theta_r \), from the theoretical ray that pass through the focus, the error in slope of the point in the parabola where the ray was reflected, is given by

\[
\epsilon_\alpha = \frac{\Delta \theta_r}{2}
\]  

(3.2)

To obtain the angular deviation \( \Delta \theta_r \), it is considered a vertical target, placed in the vertical plan where the focus of the parabola is. Measuring the distance from focus in target to the point where the reflected ray focuses in target, and knowing the point where the ray was reflected, it is possible to calculate the angular deviation.

Considering a ray reflected in a point in a parabola, with coordinates \((x, p(x))\), where \(x\) the abscissa measured from the focus, and \(p(x)\) is the equation of the parabola. The incidence point in the target has coordinates \((\theta, d)\), where \(d\) is the measured distance from focus to the incidence point. The reflection angle of a ray is given by

\[
\theta_r(x, d) = \tan^{-1}\left(\frac{d - p(x)}{-x}\right)
\]  

(3.3)

Substituting equation 3.2 in equation 3.3 and substituting for the incident point and the focus, the slope error of the reflection point of the parabola mirror is given by

\[
\epsilon_\alpha(x) = \tan^{-1}\left(\frac{p(x) - d}{x}\right) - \tan^{-1}\left(\frac{p(x)}{x}\right)
\]  

(3.4)

With the model presented, it is possible to evaluate a surface of a parabola, point-by-point, using equation 3.4 in which the variables are obtained by measuring the distance from the incidence point in the target to the focus and the reflection point in the parabola.

The efficiency of a parabola to reflect the rays to a certain area, depends on optical system where that parabola is integrated. This dependence can be described as the maximum tolerance for the slope errors of the mirror. Considering the optical system to be HSUN, the maximum tolerance for the slope errors, was defined by calculating the maximum angle deviation that a certain ray could have in order to enter in the SOE aperture. Looking to Figure 3.3 the maximum angle (relative to the top SOE) that the reflection mirror point \((x, p(x))\) can have, is given by Equation

\[
\text{Max} \epsilon_\alpha = 2 \tan^{-1}\left(\frac{y_1 - p(x)}{x_1 - x} - \frac{p(x)}{x}\right)
\]  

(3.5)

To calculate the minimum \(\epsilon_\alpha\), the method is the same, just substituting the top SOE coordinates for the bottom SOE coordinates, \((x_2, y_2)\). Although this calculation is not entirely exact (as the rays must enter in the SOE aperture within a certain angle range to be reflected to the receiver), as a first approximation, it is good enough to perform a first study. With the information of the maximum and minimum slope errors given
Figure 3.3: Schematic of model developed to measure the efficiency. Considering the ideal ray, it has a maximum and minimum possible angle deviation in order to still enter in the SOE aperture. Computing those limit angles for a ray coming from a point of the parabola, and comparing with the angles of the actual rays, it is said if a certain point is or not efficient, i.e., if it reflects the ray into the SOE aperture.

for the previous equations, comparing the slope error with those values, it is possible to tell which points do (or not) have a tolerable slope. This way, the efficiency of the parabola, \( \eta \), can be defined, in percentage, as

\[
\eta = \frac{n^\circ \text{tolerable points}}{total \ n^\circ \text{points}}
\]  

(3.6)

With the previous equation, the efficiency of a given parabola can be determined. Considering a parabolic trough, this efficiency is defined over a parabola, and gives an idea of the quality of a parabolic trough in the analyzed areas. In HSUN the most relevant areas to study are the extremes and the middle section of the parabolic trough, as observed in the HSUN module prototype.

### 3.2 Setup of the model prototype

#### 3.2.1 Materials

To build the experimental model prototype to evaluate parabolic troughs, it were used the main following materials:

1. Laser pointer;
   
   As it is only necessary a visible light source, that creates a small spot in the mirror, and no lenses or refractive material is used, a common laser pointer is sufficient to this study.

2. LEDs;
   
   Common small white light LEDs were used. One LED was used to obtain the laser position in the parabola, and other four LEDs, fixed in a plaque, forming a "L", with known distance between them, were used in the calibration process.
3. Rectangular piece of opaque glass;
   the piece of opaque glass was used as target. The function of the target is to intercept the light in the
   focus vertical plan, but has to let some light pass in order to the CCD camera to capture it, hence the
   opaque glass. A regular glass was tested as target, but a second reflection to the parabola and back to
   the target occurred. This fact was not seen with the use of opaque glass.

4. CCD camera;
   The CCD camera used was a webcam Logitech HD PRO webcam C910. A 2592x1944 pixels resolution
   was used. Some viewing parameters had to be changed in the webcam definitions. The color was
   removed to obtain images in black and white, as the color is not needed to this model. The intensity
   and gain of image are decreased to avoid a possible image saturation, and to obtain a more defined
   spot for the laser and LED points.

5. Aluminum tubes;
   Due to the relative low density and large amount of aluminum tubes available in WS Energia, it was
   the preferred material to build the overall structure.

6. Aluminum mirror;
   The aluminum mirror is used to build a small rectangular piece to be placed in front of the webcam.  
   The aluminum mirror used here, is the same as used in the manufacturing of the parabolic troughs,
   due to the availability.

7. Engine with extensible arm;
   The engine used was an electric engine, with an extensible arm attached to it that moves linearly. The
   velocity is controlled by the tension applied to the terminals. The functioning of the engine, extends
   or contracts an extensible arm, attached to the engine. One fact worth of noticing is the non-constant
   velocity, besides the constant (within two decimal cases) value of tension applied. Another fact seen
   was the occurrence of some oscillation in the arm, during the engine functioning.

8. Computer with the controlling and acquisition software;
   A laptop was used to control the webcam and store the gathered data.

3.2.2 Prototype setup

Figure 3.4(a) shows the representation of the prototype built to test the new model, and Figure 3.4(b) is a
real photograph of the prototype. The components of the laser ray-tracer are placed in the following manner:

- The laser pointer(4) and the positioning LED(5) were fixed in the support structure(3) and connected
  to the extensible arm(2) connected to the engine(1).
- The laser pointer(4) is fixed to be perfectly vertical, parallel to the axis of the parabolic trough (7),
  and the positioning LED is fixed parallel to the laser, several centimeters apart.
Figure 3.4: Fig a) Prototype of the new model. It is represented a descriptive figure of the prototype made to test the new model. The most important components used are represented. The extensible arm(2) attached to the engine(1) moves the laser pointer(4). The laser light is reflected in the parabolic trough(7) and is reflected to the target(6). The CCD camera(9) field of view is divided in two areas, one captures the target image and the other captures the positioning LED(5) light through a mirror(10). Fig b) Photograph of the built prototype to test the model. The numbers marked correspond to the numbers of the scheme of Fig. a). The engine is not visible in the photograph.

- In the focus vertical plan, is placed the opaque mirror target (6), and the webcam, a CCD camera (9) is placed behind, parallel to the target, in a distance where the field of view captures all of the target.

- A mirror (10) is placed in front of the webcam to divide the field of view in two equal areas. The left side, captures the target image, while the right side, captures the image of the positioning LED, reflected in the mirror. A schematic of the image obtained by the webcam is presented in Figure 3.5

- The webcam is connected to a computer that controls the acquisition of pictures to analyze and after, the algorithm of the model is applied

3.2.3 Description of the new laser ray-tracer software

The goal of this experiment, is to obtain a raw image, captured by the CCD camera, to finally obtain a matrix with data to further analysis. The image acquisition is made using the CCD camera. The digital image is divided into pixels, each one of them providing information about the intensity of radiation. With the values of each pixel, is created a matrix. The CCD camera was controlled by computer. There are several programs on the market that can control the camera, but they are usually expensive and design to a specific webcam model. To obtain the software with the desired features, a custom made controlling software was developed. The software was written in MATLAB and developed for the operative system Windows. To adapt the software to other environments or languages some changes are necessary. The environment was
chosen to be MATLAB due to the easy access to webcam. The description of the functioning of the software viewed by the user is presented in the flowchart diagram of Figure 3.6.

The program begins with the detection of webcam and opens the webcam menu to the user manually change some parameters. The software is based in detection of light that ideally only comes from the laser pointer and the positioning LED. If there were present any other light source, it could create an unwanted light spot in the CCD camera. To decrease this potential error source, the laser ray-tracer is placed in a dark room. The intensity and the gain are adjusted to only the LED and laser light spots appear in the image, and the color is reduced to the image be in black and white (as the color analysis is not necessary).

After all the settings changed, the software asks if the user want to perform a calibration. In the calibration procedure, it is computed the constants that convert the pixels to millimeters, necessary to the analysis. The calibration procedure is explained in more detail in subsection 3.2.4. After this step, the software is ready to start the photo acquisitions. Before the start, it is asked to the user to choose the tension applied to the engine. To start the laser scanning, the engine that moves the laser and the software that controls the webcam are simultaneously started. In the end of this routine, the program applies the equations of the method, described in section 3.1, being the output a matrix, with one column per photo taken, and 4 lines. The lines have, respectively, the position of the positioning LED in millimeters, the distance of the laser to the focus, the slope error of that mirror point and finally the angle deviation between the ideal and real reflected rays.

3.2.4 Calibrations

To use the described apparatus, some calibrations are necessary to obtain absolute values. The image obtained by the webcam, can only give relative distances, in pixels. It is necessary to convert those pixels values to

![Figure 3.5](image)

Figure 3.5: In Figure a, schematic of webcam image. In Figure b, real photo obtained by webcam. With one single photo, the laser light and the position of the LED are obtained, eliminating errors of delay in the capture of this two variables.
Detection of webcam and imposition of resolution and number of acquisitions

Calibration routine

Load previous calibration parameters

Calibrate?

Yes
No

Acquisition of image

Laser and LED maximum coordinates

Angle deviation computation

Values storage to matrix

Positioning calibration LEDs

Pixels to cm conversion

Laser movement

Figure 3.6: Flowchart diagram of operation of the software

millimeters. In the calibration process, two "pixels to mm" constants are necessary, one for the laser light and the other for the LED.

The positioning of the webcam, relative to the target, was purposely chosen to be parallel, in order to facilitate this process. This way, to obtain the conversion constant to the laser light, it is used the LED plaque, placed in the target surface, only with two vertical LEDs. The light spot recognition algorithm is used to detect the maximums coordinates, and knowing the distance between those LEDs, in mm, the conversion constant simply becomes:

\[
\text{Conversion constant} = \frac{\text{real distance (in mm)}}{\text{distance between maximums (in pixels)}}
\] (3.7)

To obtain the distance between the laser spot and the focus position in the target, obtained during in the image acquisition routine, in millimeters, is just necessary to multiply that value in pixels by the result from equation 3.7.

To perform a similar calibration to the positioning LED light spot, the process is not so simple. The mirror placed in front of the webcam, is tilted with a certain angle to make possible to see the positioning LED along the full laser scanning movement. The presence of this tilt, makes the same real distance to have different pixel values, depending on the place of the mirror that it is seen. In this case, to calibrate the pixel
to mm conversion, a different procedure was taken. A ruler was placed in the path where the positioning LED will pass during the laser scan. With the apparatus fully mounted, and the laser placed in the beginning of the parabola, a photo was taken with the webcam, in full light. Using Figure 3.7, it was plotted a function that corresponds the real distance in mm to the pixel distance between the scale marked in the ruler. Finally it was fitted a polynomial function of third order, and the resulting function adapted almost perfectly ($R^2=0.9995$). This way, the calibration is done by substituting the pixel value of the positioning LED, obtained during the image acquisition routine, in the previously obtained function.

Although the image taken from the webcam is already divided into two smaller images, the areas of those images is still large to the software analyze and convert to a matrix of pixels in a regular time. So, to fasten this process, the area of converted image was reduced, to be the area were the laser and LED light spots passes. To limit this areas, it was used once again, the plaque with the 4 LEDs. To the laser, the plaque was placed in the surface of the target, with the two horizontal LEDs turned on, and the light spot formed by the laser placed in the middle of the two LEDs. Using the light spot detector algorithm, the two LEDs coordinates were taken, and used to limit the converted area. The same process was used to limit the area for the positioning LED. During some test made to this procedure, it was found that in some points, this area was too small, due to a large laser lateral shift, or even due to the not proportional distances viewed in the mirror. To correct this error, a 100 pixels margin was given to those limits. It was taken into account the usual distance between the laser and LED light spot to avoid the superposition of analyzed areas.

### 3.3 Experimental evaluation of prototype

The experimental apparatus built to test the parabolic trough evaluation model, was done with common and available materials and tools, hence the prototype is subjected to error sources. Table 3.1 shows the most significant existing manufacturing errors according to the structure/component. All of these errors interfere in the final results. These errors where minimized with the available means, but they are still not negligible. To obtain quantitative results with physical meaning, error margins were estimated considering the errors involved in this study.
<table>
<thead>
<tr>
<th>Component</th>
<th>Error type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminum structure</td>
<td>Positioning error when fixing aluminum tubes;</td>
</tr>
<tr>
<td></td>
<td>Inclination in the prototype structure;</td>
</tr>
<tr>
<td>Laser</td>
<td>Angle relative to the ground as a small error;</td>
</tr>
<tr>
<td>Support structure</td>
<td>It is only supported by the arm (with the extension of the arm, torque in arm increases, bending the arm and lowering the support structure; During the operation of the engine, sometimes the arm oscillates significantly;</td>
</tr>
<tr>
<td>HSUN module</td>
<td>The alignment of HSUN module with the laser structure is not definitive, so the module might be misaligned during the tests;</td>
</tr>
<tr>
<td>Mirror in front of webcam</td>
<td>Mirror is fixed in an hinge that might rotate and misaligned the mirror;</td>
</tr>
<tr>
<td>Webcam</td>
<td>Is fixed in a rotational structure, which may tilt during the tests;</td>
</tr>
<tr>
<td>Aluminum tubes</td>
<td>Aluminum tubes have gaps to allow the target and webcam supports to slide. With the weight of the pieces, tubes may tilt from the ideal position;</td>
</tr>
<tr>
<td>Target</td>
<td>The alignment is done by the focus line, formed by a piece of cord, connecting two small holes located in HSUN structure, in the exact coordinates of the focus, stretched to form a line. The cord line is then used to place the target, that might bend it, not visible to human eye, hence being displaced;</td>
</tr>
</tbody>
</table>

Table 3.1: Representation of the existing errors in the prototype built to test the parabolic trough evaluation model.

The errors relative to the tilt of the overall prototype structure are not taken into account due to HSUN module is supported by it, hence if it is tilted, HSUN module will have the same inclination (apart from structure that supports the module error, which is negligible). The error in the engine oscillation is also not taken into account. It was observed that the lower the functioning speed of the engine (lower applied tension), the oscillations where less frequent. This fact was used to try to decrease the effect of this error in the results. The parts that might tilt due to the weight of the pieces where not considered, to the exception of the laser. During the laser scanning, only the laser support moves so it was considered that this was the only case where the pieces might tilt. The other pieces, can tilt to but only after moving them to the next position.

The angle that the laser makes with the HSUN module should be 90°, but the precision of this value is very hard to guarantee. To estimate the precision, the laser was tilted to 90°, incident into a flat mirror tilted 45°. The reflected laser beam was pointed to a wall, located 20m apart from the mirror. As the mirror as a 45° inclination, the height of the reflection point in the mirror should be the same as the height of
the reflection point in the wall. The precision ($\Delta\theta$) was calculated using the minimum variation of height attained ($\Delta l$) and the wall distance ($w$), according to the equation

$$\Delta\theta = \text{ArcTan} \left( \frac{\Delta l}{w} \right)$$

(3.8)

The precision obtained was approximately $\pm 1^\circ$. Considering the equation used to compute the slope error according to the angle of the reflected ray, the error propagation is

$$\Delta \epsilon_\alpha(\theta) = \frac{\partial \epsilon_\alpha(\theta)}{\partial \theta} \ast \Delta \theta = \frac{1}{2} \ast \Delta \theta = \pm 0.500^\circ$$

(3.9)

Considering now the webcam image, it has a limited resolution, the light spots are not punctual, hence an error to the estimation of the center is inherent in this process. Performing the error propagation to the error of position of the laser spot ($d$), the result is equation

$$\Delta \epsilon_\alpha(d) = \frac{\partial \epsilon_\alpha(d)}{\partial d} \ast \Delta d = -\frac{d}{2x \ast \left( 1 + \frac{(-d - f + \frac{x^2}{4})^2}{x^2} \right)}$$

(3.10)

Substituting the variables $x=-252$ mm (beginning of parabola), $f=109$ mm (focus of parabola), and $\Delta d=2$ mm (approximate value of the laser spot radius) the error in the calculated slope is $\Delta \epsilon_\alpha=0.0039^\circ$.

For the positioning LED, the error is associated with the position of the laser relative to the parabola (variable $x$). Applying the same methodology to compute the error propagation, $\Delta \epsilon_\alpha(x)$ becomes

$$\Delta \epsilon_\alpha(x) = \frac{\partial \epsilon_\alpha(x)}{\partial x} \ast \Delta x = \frac{8d \ast f^2 \ast x \ast (-4f \ast (d + f) + 3x^2)}{16d^2 \ast f^2 \ast (4f^2 + x^2) + (4f^2 + x^2)^3 + 8d \ast (16f^5 - f \ast x^4)}$$

(3.11)

Substituting the variables for $\Delta x=5$ mm (a relatively high value error in calculation of position, but possible considering a error in calibration due to the misalignment of HSUN module), $d=-50$ mm, and $f=109$ mm (focus of parabola) the error of in the computation of the slope of the mirror is $\Delta \epsilon_\alpha=0.0193^\circ$.

The sum of all error contributions from equations 3.9, 3.10, and 3.11 and the error margin considered in the results, is

$$\Delta \epsilon_{\text{total}} = 0.500 + 0.0039 + 0.0193 = 0.5232^\circ.$$ 

(3.12)

### 3.4 Experimental procedure

To evaluate the parabolic troughs using the developed method and prototype, a simple procedure was adopted. Two parabolic troughs were evaluated, one manufactured with a high precision machine, while the other was made using a circular approximation method (less precise). On each studied parabola, 5 different positions of the webcam were studied, as presented in Table 3.2. Each line (parabola), it was analyzed using the laser ray-tracer prototype. In the first analysis of each parabolic trough, a calibration procedure was done. As the parabolic troughs are well fixed in the support structure, in the parabolic troughs changing process, the HSUN module tends to get displaced from the initial position. Along the same parabolic trough measurements, the
### Table 3.2: Distances of each webcam position (from point A to point E). Ideally, points A and E should be placed at the exact beginning and end of the parabolic trough. That fact was not possible due to limits imposed by the HSUN module.

<table>
<thead>
<tr>
<th>Point</th>
<th>Position (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>9</td>
</tr>
<tr>
<td>B</td>
<td>25</td>
</tr>
<tr>
<td>C</td>
<td>50</td>
</tr>
<tr>
<td>D</td>
<td>75</td>
</tr>
<tr>
<td>E</td>
<td>97</td>
</tr>
</tbody>
</table>

calibration was not performed, as the laser, the target and the webcam supports can slide easily to the correct position, without changing the relative distances between them.

### 3.5 Analysis and discussion of results

Two graphics were plotted, shown in Figure 3.8, where it shows the slope value for each measured location (at black) and the ideal (theoretical) slope values. Figure 3.8(a) represent the location C of the parabolic trough 2 (the best location). In the beginning the slope value is relatively far from the ideal, as expected after the parabolic trough previous examination. Along the parabola, the values tend to improve, being closer to the ideal locations. Examining Figure 3.8(b) the case is very different. In the beginning there is a small error, that tends to diminish, being almost zero. There is a relatively large parabola length where the actual slope and the ideal are practically the same. Slightly after the middle of the parabola, started to appear several peaks, where the values oscillated between two apparent lines.

In Figure 3.8(c) the slope errors were trasnferred to position errors. Analyzing the errors, the shape of the curve is concordant with the slope error graphic. Comparing the two figures, the areas with higher slope error are the ones where the position error is also higher. Figure 3.8(c) can be very interesting and important to the mirrors manufacturers as they can see where and how much is the position errors, and correct them by introducing an offset in the software that operates the machine. In Figure 3.8(d) the location efficiency graphic for location C of parabolic trough 2 is presented. Comparing this graphic with Figure 3.8(a) the loss zone corresponds to the area with the highest slope errors, as expected. To notice that besides the slope errors along the parabola, they are still captured by the SOE. The location efficiency graphic is very useful as it allows to locate the loss zones in a parabolic trough. Knowing which zones of the parabola are more damaged, it is possible to manually correct them. If every parabolic trough built with a certain manufacturing technique present losses zones in the same positions, it indicates a systematic error in the manufacturing, that after detection, can be corrected. This way, this result can be very useful to parabolic trough mirrors manufacturers to evaluate the quality of their products.
Figure 3.8: Graphics of Mirror point slope vs the position of the laser. In Figure a, the best result obtained by the prototype. In Figure b, the result in which the oscillation of the extensible arm is visible, is presented. The red and black lines, represent the actual and ideal mirror slopes, respectively. In Figure a), the locations obtained form a continuous line with no peaks or interruptions. In Figure b), from the middle of the parabola to the end, the actual slope data oscillates restricted between two apparent lines. In Figure c), the slope error was transferred to position errors. Comparing with Figure a), the results are concordant as higher the slope error is, higher is the position error (difference between the actual position and the ideal position). Figure d) shows the efficiency of each location to correctly reflect the rays to the SOE aperture for location C of parabolic trough 2. To notice that only the beginning of the parabola has losses. Comparing with Figure a), this results is expected as the first location are the ones with the largest slope error.

These figures represent almost every major error, existent in the laser ray-tracer prototype. Analyzing the x position values, an apparent error is found. The initial value should be around -252mm, while in Figure 3.8(a) begins at approximately x=-200 and in Figure 3.8(b) starts at x=-240. This fact is not an error, as analyzing the data, there were several cases where in the initial locations, the position was constant at an erroneous value. This fact could happen probably due to a tilt in the mirror that reflects the positioning LED light to the webcam. During the calibration, the mirror is inclined in order to the initial LED light, appears in immediately before the end of the mirror. If the inclination was changed, the LED light might not appear in the mirror, only being seen after the laser and LED moved several centimeters. The peaks that appeared in Figure 3.8(b) are come from the oscillation of the extensible arm. The fact that the peaks does not have random values, and are limited by an invisible line, support the fact that the oscillating between
extensible arm, change the inclination of the laser, relative to the parabola. This fact occurs only after the middle of the parabola, and stabilizes in the end (fact also observed in the graphics of other locations) due to the increasing torque applied in the arm, that in the middle of the laser scanning makes the arm oscillate, while in the end, the force is so high that the arm is completely tilted.

To perform the data treatment, the locations belonging to the curve relative to the oscillation of the arm where excluded from the analysis. In Table 3.3 are presented the results obtained Analyzing the results obtained of Table 3.3 one can see that in the first parabolic trough, the average slope error is lower in the extremities (locations A and E) as expected due to the aluminum mirror being fixed to the structure at those locations. Despite location A have a higher maximum error than location E, it has low % of losses due to the maximum error being located at the end of the parabola, location with higher tolerance to slope errors, while in location E the maximum error, even if low, is located at the beginning of the parabola. With the previous knowledge on the parabolic troughs errors (observed during HSUN module prototype analysis), the average slope error along the trough, should be lower in the edges and higher towards the middle (location C), fact confirmed by the results obtained.

In the parabolic trough 2, the average error tends to decrease with the proximity to the middle section (location C). This fact should not occur as the fixing of the mirror in the support structure, so the extremities of the parabolic trough should be more close to the ideal parabola than the middle section. The average slope error is lower than in parabolic trough 1 (averaging 1.68 versus 2.52, respectively, although the % of losses is much higher, 31.185 versus 10.53, respectively. Analyzing the profile of both mirrors, the parabolic trough 1 have more errors in the end of the parabola while the parabolic trough 2 has more errors in the beginning that despite being lower, are in a more critical area.

<table>
<thead>
<tr>
<th>Parabolic trough</th>
<th>Location</th>
<th>Worst slope error (°)</th>
<th>Average slope error</th>
<th>% of losses</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>A</td>
<td>19.24</td>
<td>2.20</td>
<td>00.00%</td>
</tr>
<tr>
<td></td>
<td>B</td>
<td>25.48</td>
<td>3.24</td>
<td>15.96%</td>
</tr>
<tr>
<td></td>
<td>C</td>
<td>23.22</td>
<td>3.01</td>
<td>13.08%</td>
</tr>
<tr>
<td></td>
<td>D</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>E</td>
<td>4.94</td>
<td>1.64</td>
<td>13.08%</td>
</tr>
<tr>
<td>2</td>
<td>A</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>B</td>
<td>7.42</td>
<td>1.89</td>
<td>45.24%</td>
</tr>
<tr>
<td></td>
<td>C</td>
<td>3.94</td>
<td>0.34</td>
<td>13.33%</td>
</tr>
<tr>
<td></td>
<td>D</td>
<td>9.01</td>
<td>1.92</td>
<td>39.00%</td>
</tr>
<tr>
<td></td>
<td>E</td>
<td>20.71</td>
<td>2.57</td>
<td>27.17%</td>
</tr>
</tbody>
</table>

Table 3.3: Results obtained for the evaluation of the parabolic troughs, using the laser profilometer. Location A to E represent the location of the analyzed section (a parabola). Locations D from parabolic trough 1 and A, from parabolic trough 2 were excluded due to corrupt data.
3.6 Summary

In this chapter, a model to evaluate parabolic trough mirrors was successfully developed. By using the focus of the parabola, it was developed an analytical method to evaluate a parabolic mirror, piece-by-piece. A model to determine the efficiency of parabolic troughs, taking into account the SOE aperture was also developed. This model allows to compare different parabolic troughs, and tell if they are defined well enough, to ensure the good functioning of HSUN module.

To test the model in real parabolic troughs, it was built a prototype to apply the model to real parabolic trough mirrors, used in HSUN. The laser ray-tracer prototype gave information about the slope of the locations analyzed in the parabola, that by comparing to the ideal parabola, tells the error in slope and the direction of the error. Considering the SOE aperture, it was developed a function that computes the minimum and maximum angle deviation that each mirror slope can have. Comparing location-by-location, the values of slope errors with the limit values calculated from the previous function, a graphic was plotted representing the areas of the parabola that are properly reflected or not the sun rays.

The results show that several improvements are necessary to be made, to avoid the appearance of peaks, that prevents a more complete analysis of the results. The location efficiency graphic obtained is a very useful tool for evaluating the efficiency of a parabolic trough within a certain optical system. It allows also to locate the most damaged zones, and with that information, some adjustments can be made to correct those errors. This model could also be used to parabolic trough manufacturers companies to evaluate their manufacturing equipment and detect a systematic error and the quality of their products.

Several errors were identified, namely the oscillation of the extensible arm during the laser scanning, and the positioning method (using a LED) is too sensible to errors in the mirror inclination. Some suggestions to correct these errors are: the support structure were the laser is fixed, should be assent in the aluminum structure, instead of just being supported by the extensible arm; the engine used is not suited to this type of projects, has a high precision is required. An engine with an extensible arm could be used, but it should guarantee a more constant velocity along the arm movement, and the start and end of the engine should be controlled by the software. The manual start of the engine, introduces an error in the synchronization between the start of the laser scanning and the initial position from the calibration; the laser should be replaced by a laser specialized to measurement procedures, has the laser used has a spot relatively large (2mm of radius) and the fixing of the laser in the vertical, was hard to guarantee, due to the irregular shape of the laser, and the difficulty properly align it; the HSUN module should be more fixed to the laser ray-tracer structure to avoid misplacement in the changing of parabolic trough mirrors; the calibration procedure should be fully automatic, and the positioning system should be done in a more precise manner. If the engine velocity was constant, by knowing the time at each photo was taken, the distance could be calculated with a much higher precision and avoiding a time consuming calibration.

As a method to test the parabolic trough evaluation model, the built prototype was successful, but to be a precise and reliable measurement tool, it needs some improvements.
Chapter 4

Conclusions and future work

4.1 Conclusions

The development of new photovoltaic concentrators is a very complex process, which requires methods to evaluate, both experimentally or by simulations, the performance of the system. It is also necessary to study the effect of positioning errors, and determine a limit to them (tolerancing) and the effect that those errors have to the performance. The work described in this thesis had as main objective to develop those methods and tools to apply to the new concentrator HSUN, that did not exist at WS Energia. The developed methods successfully corrected some errors existent in the prototype and improved the optical design, increasing the efficiency and potential of HSUN. The experimental model was tested and the results were very promising, resulting in a tool for WS Energia and mirror manufacturers to test and quantitatively evaluate the manufactured mirrors.

The first study of this thesis consisted in a series of tests that aimed the computation of the positioning tolerances of HSUN. The tests were performed using a ray tracing software that is prepared to perform this studies. To obtain more information about the results, a large number of simulations were performed to obtain the variation of performance with the variation of a specific parameter, instead of obtaining just a number for the tolerance. Finally it was evaluated the total performance decay with the sum of all tolerances.

The second objective consisted in the development of a new SOE design for the HSUN concentrator. For this step, a design algorithm was implemented and two well known design methods were adapted to HSUN optical system. The results from the algorithm were not the ideal but with some improvements it might be a very useful tool for SOE designing. The application of the other methods was done using a new concept: the equations and limits were designed in a CAD software. This way the design process was much faster and simple, opposed to the coding of an algorithm to apply the specific methods. The optimization was also easily performed by the new method. The results confirmed the success of the method, being both new SOE design, one based in asymmetrical CPC and the other on asymmetrical CEC, better than the actual SOE.

To choose the best design, the optical parameters of each new SOE were calculated and compared to best fit the specifications of HSUN.

The last objective was to develop a model to evaluate parabolic troughs. The model uses the focus property
of the parabola to evaluate the contour errors and that way determine which zones of the parabola are worst. The model also allows to integrate the SOE and that way calculate if the mirror, even with errors, is reflecting radiation to the SOE aperture. To test and validate the model, a prototype was built. The results showed that the model functioned and it had great potential. With some improvements, the method can be a very useful tool to evaluate the parabolic troughs used to assemble HSUN. It can also be a tool for parabolic mirror manufacturers to evaluate their products and even detect systematic errors in their machines, and then correct them.

4.2 Future work

The methods and models developed in this thesis revealed useful but still some improvements are necessary to perfect them. The tolerancing method used was not able to determine errors in the manufacturing of pieces (such as a periodic error in the profile of the parabola, a change along the parabolic trough, etc). The tests made were extensive and required a lot of time to be performed, so a possible improvement would be an automatized routine that could test all parameters. The algorithm developed to design SOEs requires also some upgrades, such as a great flexibility in the curve adapted, the possibility to change and optimize the position of the receiver, etc. A genetic algorithm might be able to satisfy this conditions but the implementation of such software is a true challenge, which requires a lot of time and effort to complete. The experimental model to evaluate parabolic troughs was a success, require a more perfect prototype in order to achieve the full potential.
Chapter 5

Appendices

5.1 Tolerancing results

5.1.1 Test 4 - 2\textsuperscript{nd} Optics 1 (top) change in $X'$ position

Figure 5.1: Variation of percentage of total incident irradiance with displacement of 2\textsuperscript{nd} Optics 1 (top) in $X'$ position.

Figure 5.2: Close view of figure 5.1 for a displacement of 2\textsuperscript{nd} Optics 1 (top) in $X'$ position range that yields total power decay to 90% in receiver.
5.1.2 Test 5 - 2nd Optics 1 (top) change in $Y'$ position

Figure 5.3: Variation of percentage of total incident irradiance with displacement of 2nd Optics 1 (top) in $X'$ position.

Figure 5.4: Close view of figure 5.3 for a displacement of 2nd Optics 1 (top) in $X'$ position range that yields total power decay to 90% in receiver.

Figure 5.5: Acceptance curve for a secondary optics mirror 1 (top) displacement in $Y'$ position of 1.8mm.
5.1.3 Test 6 - 2\textsuperscript{nd} Optics 1 (top) change in Z tilt

Figure 5.6: Variation of percentage of total incident irradiance with displacement of 2\textsuperscript{nd} Optics 1 (top) in Z tilt.

Figure 5.7: Close view of figure 5.6 for a displacement of 2\textsuperscript{nd} Optics 1 (top) in Z angle range that yields total power decay to 90\% in receiver.

Figure 5.8: Acceptance curve for a secondary optics mirror 1 (top) displacement in Z tilt of -25\textdegree (red curve) and 28\textdegree (blue curve).
5.1.4 Test 7 - 2\textsuperscript{nd} Optics 2 (bottom) change in $X'$ position

![Graph of percentage of total incident irradiance against $X'$ position.]

Figure 5.9: Variation of percentage of total incident irradiance with displacement of 2\textsuperscript{nd} Optics 2 (bottom) change in $X'$ position.

5.1.5 Test 8 - 2\textsuperscript{nd} Optics 2 (bottom) change in $Y'$ position

![Graph of percentage of total incident irradiance against $Y'$ position.]

Figure 5.10: Close view of figure 5.9 for a displacement of 2\textsuperscript{nd} Optics 2 (bottom) change in $X'$ position range that yields total power decay to 90% in receiver.

5.1.6 Test 9 - 2\textsuperscript{nd} Optics 2 (bottom) change in $Z$ tilt

![Graph of percentage of total incident irradiance against $Z$ position.]

Figure 5.11: Variation of percentage of total incident irradiance with displacement of 2\textsuperscript{nd} Optics 2 (bottom) change in $Y'$ position.
Figure 5.12: Close view of figure 5.11 for a displacement of 2nd Optics 2 (bottom) change in Y’ position range that yields total power decay to 90% in receiver.

Figure 5.13: Acceptance curve for a secondary optics mirror 2 (bottom) displacement in Y’ position of -1.5mm.

Figure 5.14: Variation of percentage of total incident irradiance with displacement of 2nd Optics 2 (bottom) change in Z tilt.
Figure 5.15: Close view of figure 5.14 for a displacement of 2\textsuperscript{nd} Optics 2 (bottom) change in Z tilt position range that yields total power decay to 90\% in receiver.

Figure 5.16: Acceptance curve for a secondary optics mirror 2 (bottom) tilt in Z angle of -19.5\^\textdegree{} (red curve) and 20\^\textdegree{} (blue curve).
5.1.7 Test 10 - Both SOE and receiver change in $X'$ position

![Graph showing variation of percentage of total incident irradiance with displacement of Both SOE and receiver change in $X'$ position.]

Figure 5.17: Variation of percentage of total incident irradiance with displacement of Both SOE and receiver change in $X'$ position.

5.1.8 Test 11 - Both SOE and receiver change in $Y'$ position

![Graph showing variation of percentage of total incident irradiance with displacement of Both SOE and receiver change in $Y'$ position.]

Figure 5.18: Variation of percentage of total incident irradiance with displacement of Both SOE and receiver change in $Y'$ position.
5.1.9 Test 13 - Primary optic (Parabolic trough) change in focus

Figure 5.19: Variation of percentage of total incident irradiance with primary optic change in focus

5.1.10 Test 13 - Primary optic (Parabolic trough) change in middle section due to gravity effect

Figure 5.20: Stress analysis performed on SolidWorks to test the effect of gravity in the change in middle section of the primary optic (parabolic trough)
Bibliography


