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Abstract. New aeronautical ground lighting techniques are becoming increasingly important to ensure the safety and reduce the maintenance costs of the plane's tracks. Until recently, tracks had embedded lighting systems whose sources were based on incandescent lamps. But incandescent lamps have several disadvantages: high energy consumption and frequent breakdowns that result in high maintenance costs (lamp average life-time is ~1500 operating hours) and the lamp's technology has a lack of new lighting functions, such as signal handling and modification. To solve these problems, the industry has developed systems based on light-emitting diode (LED) technology with improved features: (1) LED lighting consumes one tenth the power, (2) it improves preventive maintenance (an LED's lifetime range is between 25,000 and 100,000 hours), and (3) LED lighting technology can be controlled remotely according to the needs of the track configuration. LEDs have been in use for more than three decades, but only recently, around 2002, have they begun to be used as visual aids, representing the greatest potential change for airport lighting since their inception in the 1920s. Currently, embedded LED systems are not being broadly used due to the specific constraints of the rules and regulations of airports (beacon dimensions, power system technology, etc.). The fundamental requirements applied to embedded lighting systems are to be hosted on a volume where the dimensions are usually critical and also to integrate all the essential components for operation. An embedded architecture that meets the lighting regulations for airport runways is presented. The present work is divided into three main tasks: development of an optical system to optimize lighting according to International Civil Aviation Organization, manufacturing prototype, and model validation. © 2014 Society of Photo-Optical Instrumentation Engineers (SPIE) [DOI: 10.1117/1.OE.53.6.066104]

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1 Introduction

One of the key elements for guiding aircraft within the airport are consist on visual aids. Aid to navigation was the first service provided to civil aviation at the end of World War I.¹ The main function of aeronautical lights and signals is to help the pilot leading the aircraft safely, both on land and in its approach to the runway. This information is complementary to the information provided by air traffic control. Light-emitting diodes (LEDs) have been in use for more than three decades, but only recently (around 2002) have they been introduced for airports' visual aids, representing the greatest potential change for lighting visual aids since their inception in the 1920s.² In the last years, LEDs have experienced a boom³⁻⁵ for aerospace uses and also as aids in runway applications, thanks to their multiple advantages versus conventional lamps.

- LED lighting consumes one tenth the power.⁶
- LED allows preventive maintenance (an LED's lifetime range is between 25,000 and 100,000 h).
- LED lighting technology can be controlled remotely according to the needs of the track configuration.

In this paper, we will carry out the design of a unidirectional beacon system based on LED technology that meets the International Civil Aviation Organization (ICAO) lighting requirements. For this purpose, our own collimator design will be employed.⁷

The analysis takes into account three different emission modes, corresponding to the three source models used. The system must achieve, through a common structure, a behavior as stable as possible for the three configurations and, by means of an optimization process, the final structure of the beacon will be adjusted.

An airport beacon unit includes a flashing and omnidirectional light to assist the pilot locating the boundaries of the track and one directional light source to guide the pilot on the final approach to the runway. This study develops the directional beacon system, and for this purpose, it is essential to devise a primary collimator device, which directs the light flux emitted by the LEDs through the optical beacon system.

2 Airport Beacon Requirements

ICAO lays down rules for airport ground lighting, which is divided into three categories (Table 3); this classification establishes the minimum visibility conditions needed at the landing time. In this study, we focus on the requirements

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Table 1 Luxeon’s Rebel light-emitting diodes (LEDs) datasheet.

LED	Reference	Typical flux	Typical power
Amber	LXM2-PL01-0000	70 lm	1.1 W
Green	LXML-PM01-0100	100 lm	1.1 W
Red	LXML-PD01-0040	40 lm	1.1 W

Table 2 Flux intensity and number of sources estimation.

LED	Flux intensity I	Requirements	Sources needed
Amber	129 cd	200 cd	2
Green	184 cd	200 cd	2
Red	72 cd	200 cd	3

for type II, which consists of an intermediate demand level and whose delimited areas are rectangular.

The LED sources to be employed are Luxeon’s Rebel models. This choice is based on their appropriate power and consumption characteristics as well as dimensions suitable for an embedded system and low cost. The technical characteristics of the Rebel LED models employed are shown above (Table 1).

One beacon can accommodate three different LEDs that may emit independently in case of failure. As can be observed (Table 1), typical flux varies significantly depending on the LED model. Among the multiple LEDs integrated in the beacon, only those of the same wavelength (same color) would emit simultaneously; therefore, flux rates will be harder to achieve with the red LEDs emission mode as they offer lower nominal flux.

3 Beacon System Design

The maximum number of LED sources is limited by the total size of the beacon housing, which has a maximum dimension limit for its proper integration at designated areas along the runway.

A calculation will be made to check the feasibility of the design choosing the number of LEDs for each configuration. The calculation assumes a uniform angular emission that simplifies average light intensity estimation and applies a correction factor to consider the efficiency of the beacon. The widest angular region (horizontal semiaperture) is considered (Table 3) and a system’s efficiency, E_{ff} , of 70% is assumed (the validity of this hypothesis will be checked later). The light intensity is defined as the amount of luminous flux per solid angle unit. Its unit of measurement is the candela (cd) and it is expressed by the following equation:

$$I = \frac{F}{\Omega} = E_{ff} \left(\frac{F_{R,G,A}}{2\pi\{1 - \cos[\text{Max}(\theta_{\text{Hor}})]\}} \right), \quad (1)$$

where $F_{R,G,A}$ is the flux emitted by each LED depending on its wavelength. It is also assumed that the flux will be confined to the widest interest zone, $\text{Max}(\theta_{\text{Horizontal}})$, guided by the beacon’s geometry. This hypothesis will be confirmed as the experimental flux will be adapted at each specific zone.

From the flux intensity table (Table 2), it follows that it takes at least three red LEDs to meet the requirements. From now on, the simulations will employ red LEDs since their operational mode has the critical margin over the imposed requirements, even if three LEDs are assigned to this

configuration. Once the requirements are met for this configuration, the rest of the operation modes (amber and green) should also fulfil the requirements. Once assigned the number of sources for each emission type in the beacon, an optical system aimed to distribute the flux in each area of interest can be designed.

A beacon scheme with a basic layout is needed to get the proper orientation of the light that must focus on the required area (common basic schemes can be found on literature⁸). Zones of interest are focused to an approximate height of $\theta_{\text{out}} = 5 \text{ deg}$ (Table 3). Therefore, the system’s output flux is adjusted to achieve this specific vertical angle.

The beacon’s vertical output angle is derived from Fig. 1

$$\begin{aligned} \left\{ \begin{array}{l} \theta_1 = 90 - \varphi \\ \theta_2 = 2\theta_1 - 90 = 90 - 2\varphi \end{array} \right\} \theta_{\text{out}} &= \arcsin \left[\frac{n_1 \sin(\theta_2)}{n_2} \right] \\ &= \arcsin \left[\frac{n_1 \sin(90 - 2\varphi)}{n_2} \right]. \end{aligned} \quad (2)$$

Substituting the refractive indices by their values ($n_1 = 1.49$ PMMA) ($n_2 = 1$ air), and solving for tilt angle φ , the inclination of the beacon for a desired exit angle $\theta_{\text{out}} = 5 \text{ deg}$ can be determined.

$$\begin{aligned} \varphi &= \frac{90 - \arcsin \left[\sin \left(\frac{\theta_{\text{out}}}{n_1} \right) \right]}{2} = \frac{90 - \arcsin \left[\sin \left(\frac{5}{1.49} \right) \right]}{2} \\ &= 43.32 \text{ deg}. \end{aligned} \quad (3)$$

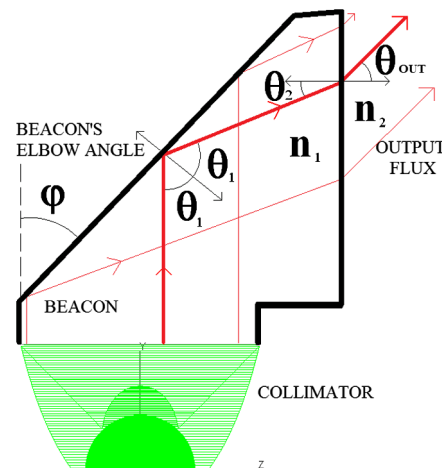


Fig. 1 Vertical output beacon’s scheme.

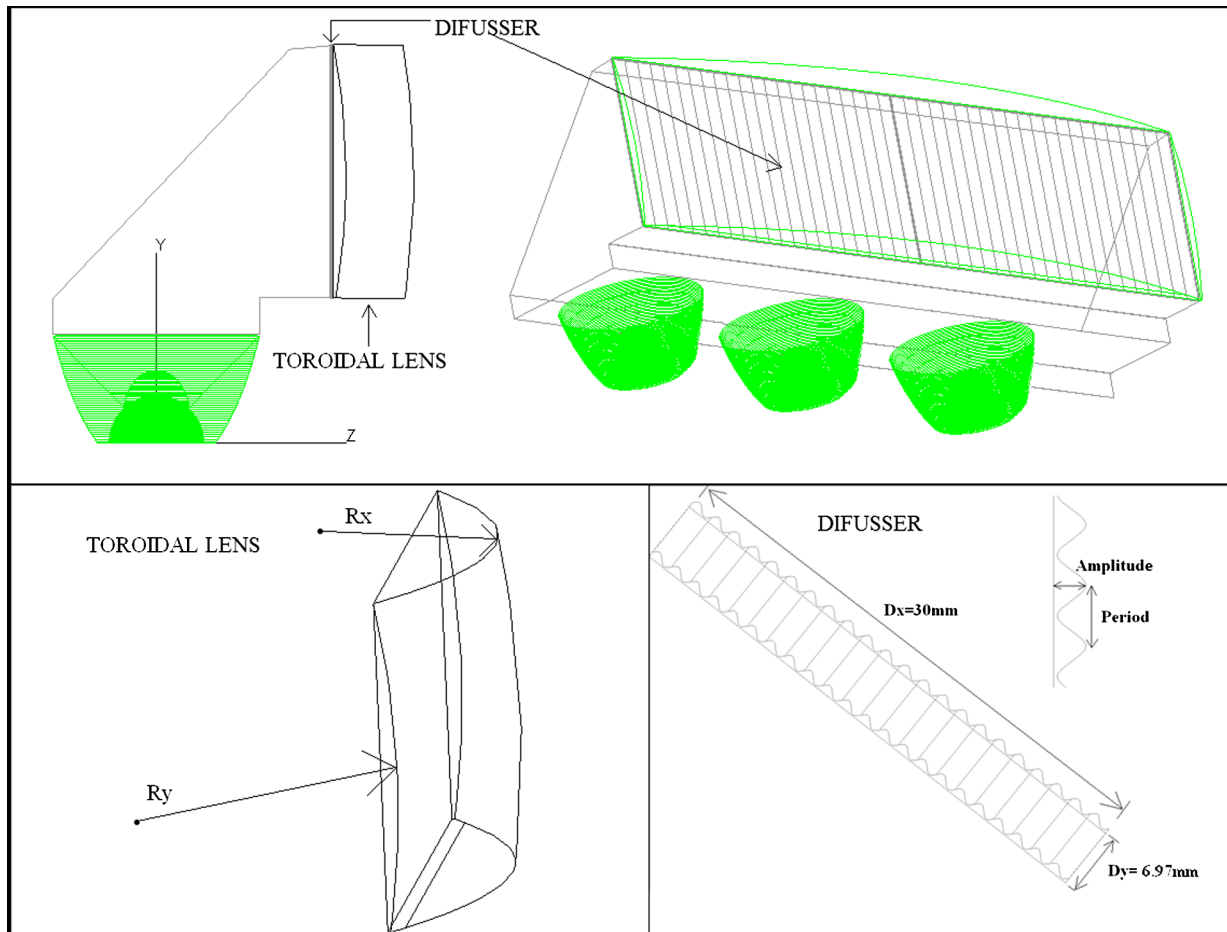


Fig. 2 Beacon system complete configuration.

The value obtained for the elbow angle of the beacon, φ , [Eq. (3)] is within the limits of total reflection, thus avoiding reflection losses inside the beacon. The critical angle φ_{\max} is derived by Snell's law

$$\left\{ \begin{array}{l} n_1 \sin(\theta_{1 \min}) = n_2 \sin(90) \Rightarrow \theta_{1 \min} = \arcsin\left(\frac{n_2}{n_1}\right) \\ 180 = \theta_1 + 90 + \varphi \Rightarrow \varphi = 90 - \theta_1 \end{array} \right\}$$

$$\varphi_{\max} = 90 - \theta_{1 \min} = 90 - \arcsin\left(\frac{n_2}{n_1}\right) = 47.78 \text{ deg.} \quad (4)$$

The next design step consists of expanding the system's aperture to cover a suitable angular region, aiming to distribute the flux emitted by the beacon according to the area bounded by the specifications in Table 3. For this purpose, a set of simulations are carried out using a lens to increase the aperture of the beacon and rugged materials that act as diffusers to increase flux uniformity. The main drawbacks of these modifications consist of introducing losses and adding a large number of optical interfaces.⁹ The entire lighting system is shown in the following scheme (Fig. 2), in which new optical elements (convergent lens, diffuser) are added to the basic beacon layout.

As a result of adding new optic elements, the optical system increases its complexity, and it will be necessary to define a certain set of parameters for full characterization.

The rough material can be characterized by the relationship between its period and the amplitude of the ripple, as its section can be approximated to a sinusoidal. Assuming a fixed amplitude, only the period is considered as a characteristic parameter of the system.

After introducing the new optical elements, the beacon system configuration can be defined by a set of parameters that have a decisive influence on the behavior of the beacon. Thus, the optical system's results, in terms of efficiency, uniformity, and average light intensity at each zone of interest, can be analyzed according to parameters gathered in Table 4.

Uniformity is defined by the average luminous intensity divided by the intensity maximum, considering each specific region.

Table 3 International Civil Aviation Organization lighting requirements for beacon systems.

Type	Average main zone (cd)	Minimum main zone (cd)	Horizontal degrees (deg)	Vertical degrees (deg)	Remarks
II	200	100	-10 + 10	1 to 9	Rectangular
II	200	100	-3.5 + 3.5	1 to 9	Rectangular
II	100	50	-19.25 + 19.25	1 to 4	Rectangular

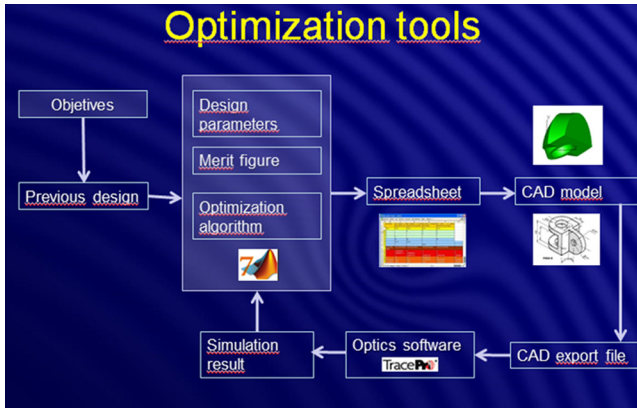


Fig. 3 Optimization procedure.

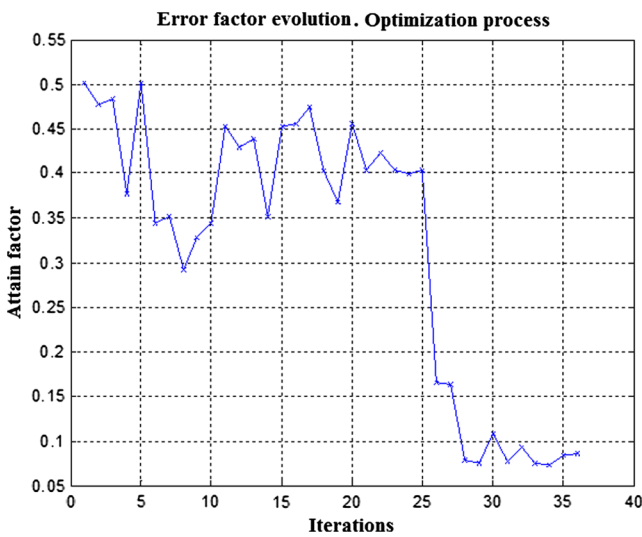


Fig. 4 Optimization error evolution.

Table 4 Optimization parameters.

Optimization parameters	Output variables
<ul style="list-style-type: none"> ■ Toroidal lens radius: R_x, R_y ■ Diffuser period: P 	<ul style="list-style-type: none"> ■ System's efficiency: E_{ff}. ■ Average flux intensity in each specific region: I_1, I_2, I_3 ■ Uniformity in each specific region: U_1, U_2, U_3

$$U_n = \frac{I_n}{\max(I_n)}, \quad (5)$$

where I_n is the flux intensity in each zone and U_n is its corresponding uniformity factor.

4 Beacon System Optimization

Throughout the design process, we have obtained a beacon configuration that can be treated as a multivariable function

with multiple output variables. It is, therefore, possible to carry out an optimization process applied to the beacons' geometry, achieving an optimal configuration to ensure it meets requirements.

The optimization process (which flow diagram is shown in Fig. 3) employs a collection of functions to minimize or maximize nonlinear general functions implementing specific optimization algorithms. Specifically, a sequential quadratic programming (SQP) based function solves a problem characterized by an objective function, reaching a number of targets defined by the user. This kind of function is an effective method to optimize the lighting system performance¹⁰ since it allows target prioritization and the definition of a certain minimum number of thresholds (efficiency, uniformity) along with exact targets (average light intensity). In addition to restrict the range of function's variables by means of limit values, the optimization process will search for the most efficient and uniform beacon system configuration, maintaining (Pareto optimization¹¹) light intensity levels at each of the three zones.

Following is a brief description of the optimization algorithm employed; this function solves the problem of achieving multiple objectives and is described by the following equation:

$$\text{Minimize}(\gamma)_{x,\gamma} \Rightarrow \left\{ \begin{array}{l} F(x) - \text{weights } \gamma \leq \text{goal} \\ lb < u < ub \end{array} \right\}, \quad (6)$$

where $F(x)$ is the objective function to optimize, x is the input variables vector, $weight$ is the weight vector, $goal$ is the target (or goal) vector, γ is the parameter to minimize (error), and $[lb; ub]$ are the upper and lower limit values of each vector's variable x_i . As can be seen in the set of equations [Eq. (6)], the optimization function evaluates the inequality $[F(x) - \text{weights } \gamma \leq \text{objectives}]$, modifying the value of variable vector x (always within the range $[lb, ub]$) to minimize the γ which can intuitively be interpreted as an optimization error. The sign of the weight vector indicates whether the corresponding target is an upper or lower limit and, therefore, must be overcome or lowered as much as possible.

The progress and results of the optimization process will be analyzed as it achieves the optimal settings among the multiple configurations tested.

Figure 4 shows the error factor evolution against the goal; its value is reduced as the number of iterations increases. This means that the system tends to an optimal configuration. If the trend of normalized output variables is analyzed (not strictly normalized because the maximum value can be greater than unity if a variable exceeds its corresponding output target), then the effect of optimization on the system's response can be observed.

Figure 5 shows a remarkable evolution of the system response. The weight vector ensures a balance between the output variables. Therefore the optimization process will not conclude at a final configuration in which a variable exceeds its corresponding target (value > 1) if that setting does not assure simultaneously an improvement of the rest variables.

In this case, the optimization process finds a configuration that cannot be improved and stabilizes the attain factor (error) in its minimum value. The optimization process

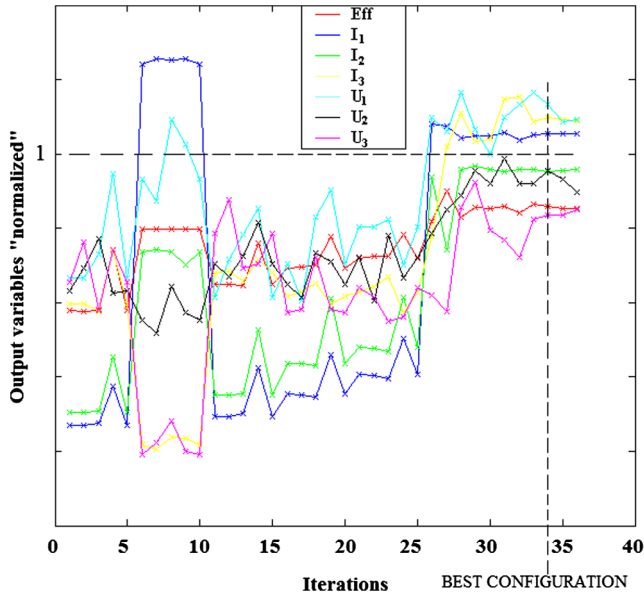


Fig. 5 Output variables optimization progress.

ends (after more than four days of execution), reaching a deviation of input variables lower than the precision parameter set among the optimization function's option. This parameter limits the precision of finding an optimal configuration. The best configuration's parameters are shown in Fig. 6.

The isocandelas map obtained (Fig. 7) shows an improved uniformity and high intensity levels for each of the three zones. These parameters are precisely the goals of the optimization process.

Figure 7(c) shows the optimal isocandelas' map that generates the optimization process. In this intensity map it can be seen how the outcome flux of the beacon is perfectly suited to the three zones of interest. Resulting brightness levels, uniformity, and efficiency are shown in Table 5.

Table 5 shows beacon's lighting results that the flux intensity requirements while maintaining appropriate values of uniformity and efficiency. This system configuration provides an adequate benchmark to manufacture a beacon prototype with whom to measure the experimental performance and compare it against simulations' results.

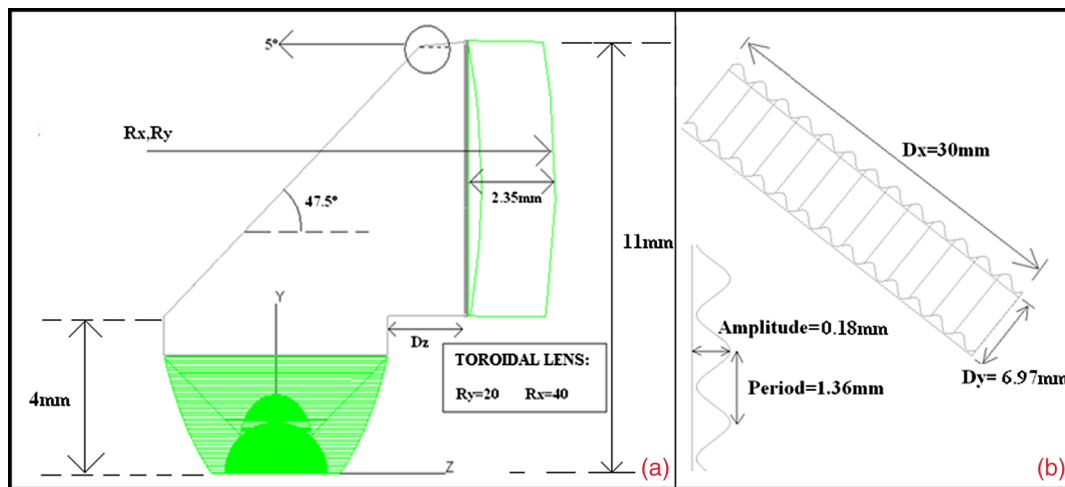


Fig. 6 Beacon system, best configuration parameters.

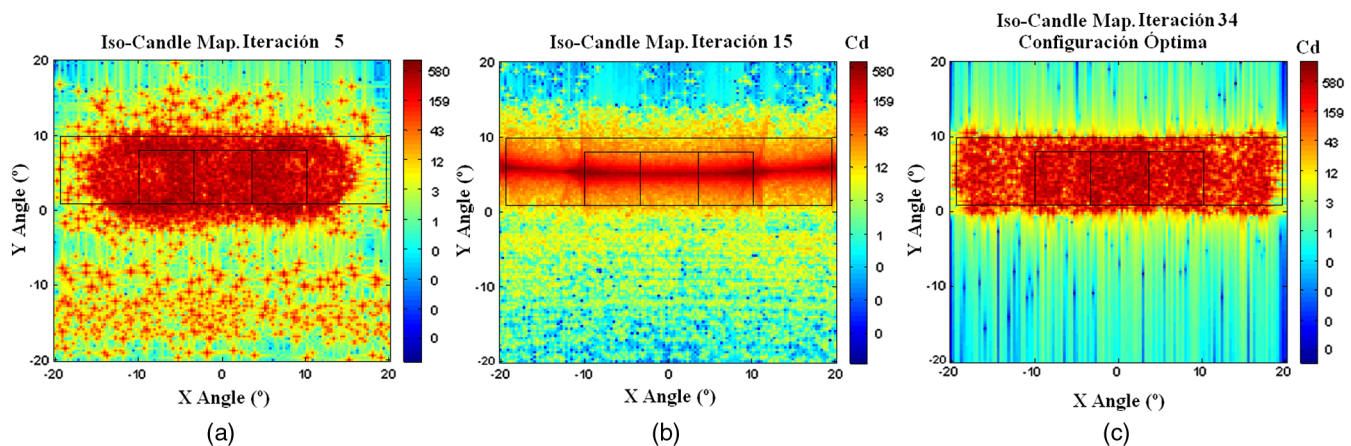


Fig. 7 Candelas map evolution. Beacon optimization process.

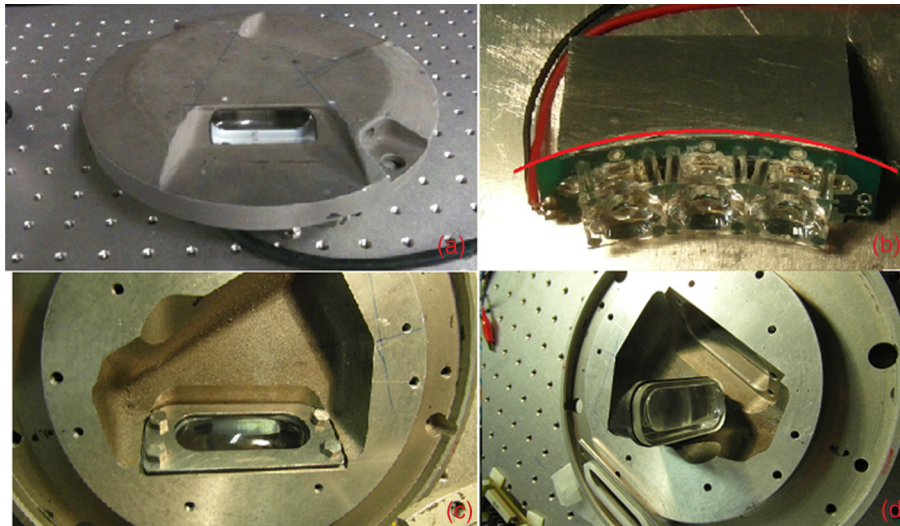


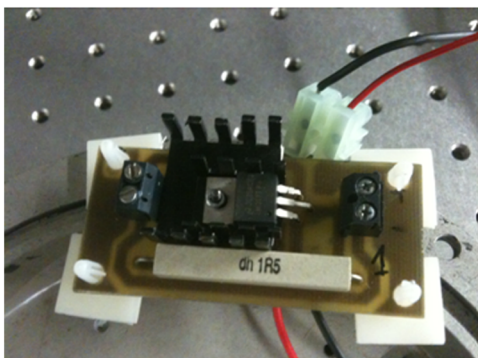
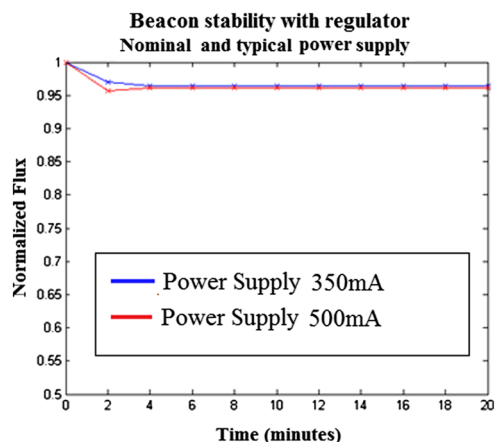
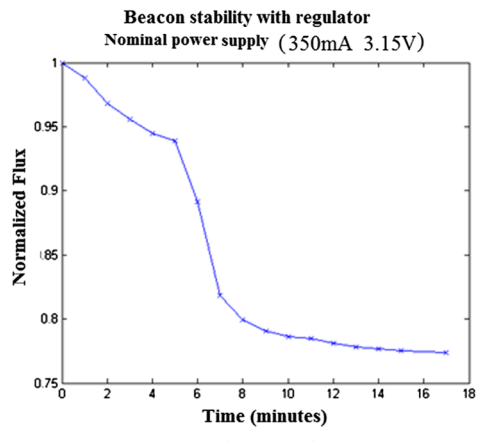
Fig. 8 Beacon system prototype. (a) Beacon chasing. (b) Light-emitting diode collimators. (c) Inside chasing. (d) Torodial lens + prism.

Table 5 Optimization results. I_n , U_n : average flux intensity and uniformity at each zone.

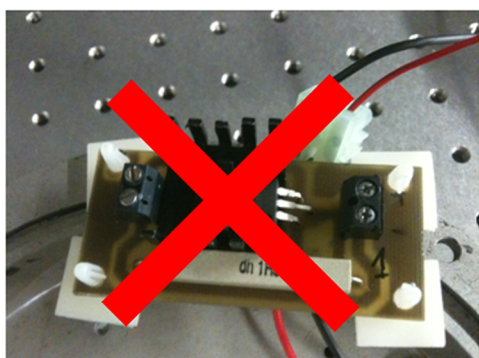
E_{ff}	I_1 (cd)	I_2 (cd)	I_3 (cd)	U_1	U_2	U_3
%	263	238	134	0.22	0.19	0.08

5 Experimental Results

This section shows the experimental results of the beacon lighting system. Based on the configuration obtained, by means of the optimization process, a prototype is produced. However, some modifications are applied to facilitate its manufacture. These modifications to the geometry are intended to accommodate the beacon in its housing and



(a)



(b)

Fig. 9 Beacon system stability. (a) System's stability without integrated regulator. (b) System's stability without integrated regulator.

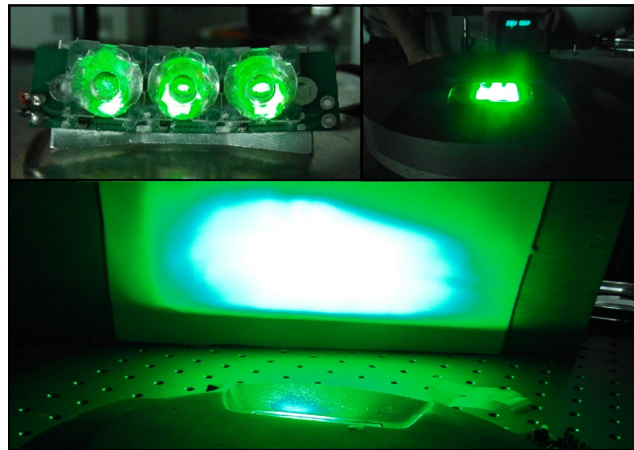


Fig. 10 Beacon emitting.

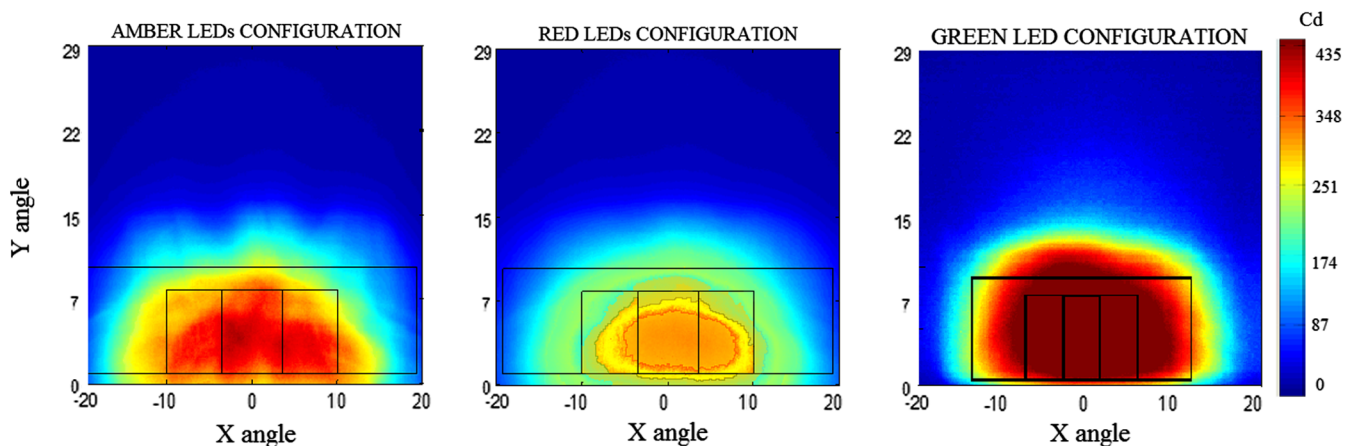


Fig. 11 Candelas maps. Prototype final result.

do not change the emission and propagation of the luminous flux.

The beacon prototype (shown in Fig. 8) contains three LEDs inside the casing, together with their corresponding optical devices (collimators, lens prism, roughness material). Notice that a slight curvature in the LEDs' metal support is introduced, which mildly modifies the orientation of the LEDs. This deviation is caused by technical reasons and, as will be seen later, does not deteriorate the actual behavior of the beacon system as the horizontal angular range allows such a small deviation within the widest interest zone. The chasing also integrates electrical devices, such as power and control devices. As a prerequisite to start the experimental analysis, it is necessary to carry out a stability analysis, ensuring the validity of the measures regardless of time. The stability gives an idea of the robustness of the system that must maintain a constant luminous flux level in each area of emission to meet the ICAO requirements (Table 3).

Figure 9 shows that the integrated intensity regulator increases the instability of the beacon. As the regulator begins to operate, it warms the LEDs and the flux emitted decreases. The solution consist on placing the regulation system as far as possible from the LED sources. Once the stability adjustments are applied, then experimental measurements of the prototype can be carried out to characterize the actual behavior of the beacon system (prototype emitting Fig. 10).

Finally, the prototype's results are shown (Fig. 11) to make sure the coherence among optimization and experimental results. The emission results are achieved with a nominal power supply, so there is still a wide margin for increasing the operation power supply to the typical mode.

Table 6 Experimental results.

LED configuration	Analysis zone	Average intensity (cd)	Minimum intensity (cd)
Amber	1	255	123
Amber	2	191	118
Amber	3	139	82
Red	1	212	125
Red	2	168	113
Red	3	124	61
Green	1	309	148
Green	2	243	127
Green	3	192	113

Table 6 shows that flux intensity requirements are achieved for all analyzed areas. The minimum levels are also exceeded; however, it must be said that these threshold levels depend heavily on the images processing accuracy, where the minimum levels are particularly affected by the resolution of the display on the irradiance map (map count) and the dimensions of the matrix employed to store isocandela maps.

It can be assured that the flux emitted by the lighting system is adapted very precisely to the limits of the most extensive area. Therefore, the flux is neither wasted nor interferes with the emission of other potential beacon devices. The vast majority of the flux emitted is included in the ICAO margins with a deviation of ~ 3 deg in the vertical axis in the worst case.

6 Conclusions

Mathematical optimization algorithm techniques applied to optical design are able to lead to high efficiency solutions wherever these solutions cannot be automatically achieved with classical methodologies. The use of mathematical tools together with raytrace evaluation software can help to obtain complex solutions, which are very difficult to find without both tools.

Throughout this project, a beacon system based on LED technology has been developed with the aim of complying with the ICAO rules governing airport ground lighting. The lighting system has certain degrees of freedom due to the adjustment of optical devices that comprise it; therefore, an optimization process is carried out, taking into account a number of significant variables.

The optimization process is carried out for different initial systems configurations and optimization parameters. Through this process a beacon system configuration, that meets the ICAO requirements, is reached, showing the best optical characteristics.

Through this project it has been implemented a simulation routine using MATLAB® that manages the rest of software tools (raytrace & CAD software).¹² A technique like this has proven to be very useful not only for this work but also for a multitude of tasks in the field of optical design. In this way, it may be possible to combine the potential of complex optical systems simulations together with optimization functions and algorithms, obtaining an optical system that is able to suit the requirements imposed while this automated technique reduces the design work and facilitates the designer task.

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Complutense University of Madrid (UCM). Authors acknowledge to Lambda Research Corporation the donation of TracePro for their work.

References

1. G. Gilbert, "Historical development of the air traffic control system," *IEEE Trans. Commun.* **21**(5), 364–375 (2003).
2. C. Zegger, "Visual guidance: solar LED aviation lighting and solar power systems technology solutions," in *Worldwide Airport Technology Transfer Conf.*, Carmanah Technologies Corporation, pp. 3–4 (2007).
3. J. Richard, "Enhanced detection of LED runway/approach lights for EVS," *Proc. SPIE* **6957**, 695703 (2008).
4. W. Lu et al., "Light-emitting diodes for space applications," *Opt. Quantum Electron.* **41**(11–13), 883–893 (2009).
5. J. T. Petrick, "High-brightness LEDs in aerospace applications," *Proc. SPIE* **4776**, 34–50 (2002).
6. S. Liu and X. Luo, *LED Packaging for Lighting Applications: Design, Manufacturing, and Testing*, John Wiley & Sons, Portland, OR (2011).
7. D. Vázquez-Moliní et al., "High-efficiency light-emitting diode collimator," *Opt. Eng.* **49**(12), 123001 (2010).
8. H. Ahlen and L. Ek, "Embedded light fitting for runways," U.S. Patent 5438495 (1995).
9. R. Winston, J. Minano, and P. Benitez, *Nonimaging Optics*, Elsevier, New York (2005).
10. F. Anrys and P. Dutré, "Image-based lighting design," in *Proc. of the 4th IASTED Int. Conf. on Visualization, Imaging, and Image Processing*, p. 4 (2004).
11. J. Legriel et al., "Approximating the pareto front of multi-criteria optimization problems," in *Proc. of the 16th Int. Conf. on Tools and Algorithms for the Construction and Analysis of Systems*, Vol. 6015, pp. 69–83, Springer (2010).
12. Lambda Research Corporation, <http://www.lambdares.com/tracepro> (2014).

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Daniel Vázquez has been a professor in the optics department of UCM since 1988. He received a PhD in architecture from Universidad Politécnica de Madrid. He works on developing lighting systems applied to several fields: natural lighting devices, signalling, LED panels, and solar energy. His areas of interest include color perception and lighting systems applied to cultural heritage. He is the manager of the color and lighting team of the Applied Optics Complutense Group (<http://portal.ucm.es/web/iluminacionycolor/inicio>).

Antonio A. Fernandez-Balbuena received his graduate diploma in optics and optometry in 1994 from the University Complutense of Madrid. Since 2000, he has been working in the Faculty of Optics in the photometry laboratory in the area of natural lighting and light-emitting diode (LED) optics design. He earned an MS degree in technical optics from UCM in 2008 and a PhD degree in 2011. He is a professor at Universidad Politécnica de Madrid.

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