Short Throw Projection

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Short throw projection system

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30th November, 2012
Abstract

Since the release of James Cameron’s movie Avatar, where everyone was able to admire future new technologies directly coming from the imagination of its director, new ideas and perspectives have been emerging in the industrial world.

In this optic, the main purpose of this project is to evaluate the possibility of a short throw and compact projection system that could constitute a solid with the screen, and to create a prototype of such a system if it is viable. This system should fit in the cockpit and meet all stated requirements.

After going through the state of the art and patents study, the work will be divided in two main parts which are the imaging system and the light performances. In the imaging system part, the light source and the micro display will be chosen and the projection lens will be created, studied and optimized under CodeV, a simulation software for optical design. The performances of this system will fit the requirements. In the final part concerning light performances, different possibilities for the backlight will be tested but results are going to be unfortunately unexpected and disappointed.
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Finally, I also thank my beautiful family and friends – in Sweden and in France – for their constant love and support.
I. Introduction

1- Thales Avionics

a. Thales Group

Thales Group is a French multinational company that designs and builds electrical systems and provides services for the aerospace, defence and security markets [1]. It has 70,000 employees and generated over 13,000 billion Euros in revenues in 2011 and 18% of which are devoted to Research & Development.

The Thales Group is both a European and worldwide leader in aerospace and defence electronics. Its activities are divided into three divisions (cf. Fig 1):
- Defence, which represents 50% of the revenues and employs 25500 people;
- Security (services and information technologies), which represents 25% of the revenues and employs 20000 people;
- Aerospace, which represents 25% of the revenues and employs 23200 people.

The group is divided in 7 divisions and is present in no less than 50 countries all over the world (cf fig 2). The different divisions are listed below:
b. Thales Avionics

Thales Avionics belongs to the Aerospace Division of Thales group. It employs 6200 people in France and is also implanted in the rest of the world. Its revenues came to 889 million euros in 2011, split into 40% for the civil industry and 60% for the military industry.

It is the European leader in cockpit electronics, electrical generation systems and in multimedia on board. It is ranked 3rd worldwide after Honeywell and Rockwell Collins.

The services provided by Thales Avionics range from equipment related to conception and integration of complex systems that can ensure several functions on board for communication, navigation and surveillance. These services are designed for all kinds of
civil or military aircraft and helicopters. The company is also present on the space market by providing equipment for Ariane’s launchers as well as for numerous other national and international satellites.

Thales avionics is currently working, for example, with Dassault Aviation, Airbus, Eurocopter, Bombardier to name but a few.

c. Le Haillan and CKT department

Thales Avionics in Le Haillan (south-western town in France, near Bordeaux) belongs to the Aerospace Division. Main products realized here are Head-Down Displays (HDDs), Head-Up Displays (HUDs) and Helmet Mounted Displays (HMDs).

The CKT department is the Cockpit Competence Center of Thales. Its role is to define, design, develop and integrate Cockpits (a human-centric avionic system providing crew with a consistent set of means and functions in order to operate the aircraft) and associated products.

![Figure 3: Airplane cockpit with CKT products](image)
The Innovation Cockpit Design (ICD) department of CKT, where I am doing my internship, is positioned before the R&D department in the development process. There, future techniques and concepts in the Human/Machine Interface domain are imagined, studied and validated by about 40 people who are currently working here.

The department has several test benches and prototypes related to products, which are imagined, analysed, designed and tested here.

![Figure 4: civil and military aircraft simulators](image)

2- **Short throw projection system - Requirements**

A projector is needed to image the information on this screen. Due to configurations issues\(^1\), the projector shouldn’t be on the same axis that the one of the screen, it then requires some particularities. Designing such a projector is the subject of this report.

Two different configurations using two different screens with different sizes are considered for this research:

\(^1\) Non-Disclosure Agreement
- **Screen 1:**

  The size of this screen is 10 × 15 cm and the configuration used is front-projection. That is to say that the image is projected on the front surface of the screen and then reflected to be seen by the viewer.

- **Screen 2:**

  The screen size here is 15” diagonal (30.4 × 22.8 cm) and the configuration used is rear-projection. It means that the image is projected on the back of the screen and then transmitted through the screen to be seen by the viewer.

  To continue, the congestion of the system has to be minimized and made as compact as possible. However, this one shouldn’t be on the same axis as for the screen so the system should be off-axis. The throw ratio, which is defined by the ratio of the projection distance over the projected image diagonal size (cf. Figure 6), has to be minimized as well without losing image quality.

![Figure 5: Throw ratio](image)
Finally, two aspects need to be considered in this study:

- **Optical design:**

  The optical design of projection lens should be optimised to have low congestion, low cost and be as simple as possible while minimizing distortion, spherical aberrations and chromatic aberrations.

- **Illumination system:**

  We need to have enough light coming towards the screen in order to get a good contrast with the exterior brightness. Thus the light source and its collimation system have to be studied. Besides, micro-displays should be used since we want to minimize congestion so different technologies will be compared in order to choose the best micro-display according to the system requirements.
II. State of the art and Patents

1- State of the art

First of all, the state of the art with regard to short throw projection has been drawn up. It is a document aiming to describe everything which already exists on the market with a link to short throw projection. This document provides a useful starting point as it gives a general idea of what has already been done, by which company, and sometimes how it is done.

The different designations and keywords to find information on short throw projectors were:

- Short throw projection system
- Short projection
- Projection system
- Wide angle projection lens
- Wide angle projection system
- Ultra short throw projector
- ...

To continue, main applications where short throw projectors are found are education, business world (for meetings or presentations...) and also multi-display (such as movies or video game).

After this study, the conclusion is that there are two main techniques for projecting an image through the projector:

- Directly projecting an image using a wide-angle lens.
- Using an aspherical mirror to project an image after reflection on it.

Projectors using an aspherical mirror tend to be bigger and heavier. However, they also tend to have a better throw ratio, which means that the projection distance is minimized while the image size is maximized.
To continue, DLP and LCD are mostly used in what concerns the display apparatus and the size of the chip (for the diagonal) is generally smaller than 1”.

Finally, these projectors are all destined to be used to project big images (the smallest image size is approximately 1 m) and then, they don’t seem compatible for projecting small images such as 15” for the diagonal width and offering low congestion at the same time.

The following tables give the main companies producing short throw projectors and general characteristics about their product. The full document with detailed description of this information is named state of the art and won’t figure in this report due to non-disclosure agreement.
2- Patents

Once the state of the art has been made, the following step is to analyse all the patents already existing about short throw projection. This study goes further into details than the state of the art. Indeed, patents give access to detailed descriptions of technologies used to manufacture products. This leads to different ideas to start with.

There are three main website to find published patents:

- WIPO (World intellectual Property Organization)
- EspaceNet
- Google Patent

To find patents about short throw projection, the same keywords that for the state of the art have been used as well as companies name producing these kinds of projector. All the information taken from patents was synthesized in the state of the art document. Most information find in those patents is about:

- the optical design of projection lens

Optical designs about projection lens are drawn and described in tables as shown in the following figure:

![Figure 6: description of the projection lens. Patent reference: [2]](image)

We can get information about the number of lens, their dispositions, their size, their radius of curvature, their type, the magnification or the total track to name but a few (cf. Figure 7).
Figure 7: Tables about projection lens. Patent reference: [2]


- the display apparatus

Patents also give ideas on how to integrate the projector in its environment while still minimizing congestion.

- the imaging system

Information about imaging system includes light source, collimation lens, how to produce colour images, micro display, driving system and more.
III. Optical system

The optical system is composed of three parts which are:

- The light source
- The micro-display
- The projection lens

These three elements are going to be studied and explained separately in this part of the report.

1- Light source

There are three main types of light source currently used in the industrial world:

- Arc lamp
- Laser (Light Amplification by Simulated Emission of Radiation)
- LED (Light Emitting Diode)

The following table summarizes their drawbacks and advantages.

<table>
<thead>
<tr>
<th></th>
<th>Advantages</th>
<th>Drawbacks</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Arc Lamp</strong></td>
<td>High brightness</td>
<td>Not stable in temperature</td>
</tr>
<tr>
<td></td>
<td>Emitted light close to the one of the sun</td>
<td>Dangerous</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Fragile</td>
</tr>
<tr>
<td><strong>Laser</strong></td>
<td>High brightness and resolution</td>
<td>Speckle effect (can be reduced)</td>
</tr>
<tr>
<td></td>
<td>Directional light beam</td>
<td>Safety and security issues</td>
</tr>
<tr>
<td></td>
<td>Low consumption</td>
<td>MEM’s are needed</td>
</tr>
<tr>
<td><strong>LED</strong></td>
<td>Low cost</td>
<td>High consumption</td>
</tr>
<tr>
<td></td>
<td>Robustness</td>
<td>Low brightness</td>
</tr>
<tr>
<td></td>
<td>Small size of chip</td>
<td>Not directional</td>
</tr>
<tr>
<td></td>
<td>No speckle effect</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Can be almost Lambertian</td>
<td></td>
</tr>
</tbody>
</table>

Considering this table, the light source which is the most compatible with the project is the LED so that is what we are going to use as a light source for the short throw projector.
2- Micro-Display system

As already said earlier in this report, in order to minimized the congestion of the projection system, micro display are going to be used to produce the needed image. There are several micro displays which are mainly used today in the market and they are going to be introduced in this part of the report.

a. LCD Transmissive – Liquid Crystal Display

The LCD projector is composed of a backlight (which can be made with lamps, lasers or LEDs), a few diffusers and a LCD matrix.

The LCD matrix was the first technology used in video projection. This matrix consists of two polarizing filters, forming an angle of 90°, which are placed on either side of two glass plates. These two plates contain a thin layer of liquid crystal. They possess an electrode on one side and a matrix of thin transistors on the other side. Finally, the application of an electrical voltage will create a difference of potential between the electrodes of a pixel, causing the change in orientation of the liquid crystal molecules and therefore, a variation of the transparency of the LCD matrix.

![Figure 9: Working principle of liquid crystal][2]

To realize a colour LCD projector there are two main ways:
- Using an RGB backlight instead of a white one,
Using 3LCD technology: 3 LCD panels are used, each of them have a different backlight colour respectively Red, Green and Blue. The light is then recombined in a single beam with the help of a dichroic beam splitter prism or a PBS (polarizing beam splitter) cube for instance.

![3LCD technology and RGB backlight](image)

Figure 10: 3LCD technology [3] (on the left) and RGB backlight [4] (on the right)

The congestion when using an RGB backlight is minimized in comparison with 3LCD but the output luminance is then smaller too.

One of the main problems with LCD panels is called the “screen door effect”. This is a display artefact associated with LCD video projectors. The image projected by an LCD projector is made up of individual pixels which are separated by black borders. Besides, the electronic chip that controls the orientation of the liquid crystal is non-transparent and placed over each pixel. Then, as you increase the size of the projected image, these borders and electronic chips are more likely to become visible, giving the impression of viewing the image through a "screen door".

![Screen door effect](image)

Figure 11: "Screen door effect" [5]
To finish, the efficiency of the LCD panel is approximately 10%, which is not sufficient to produce the output light necessary to obtain a good image contrast.

b. DLP – Digital Light Processing

“Digital Light Processing (DLP) is a brand of projector technology that uses a digital micro-mirror device. It was originally developed in 1987 by Dr. Larry Hornbeck of Texas Instruments. DLP is used in a variety of display applications from traditional static displays to interactive displays and also non-traditional embedded applications including medical, security, and industrial uses” [6].

In DLP projectors, the image is created by microscopically small mirrors laid out in a matrix on a semiconductor chip, known as a Digital Micro-mirror Device (DMD). Each mirror represents one or more pixels in the projected image. The number of mirrors corresponds to the resolution of the projected image and can be repositioned rapidly to reflect light either through the lens or onto a heat sink to absorb the light. Rapidly moving (a mirror can move by an angle of ± 10°) the mirror produces grey-scales, controlled by the ratio of on-time to off-time.

Plus, for a small size chip, the resolution of DLP panel decreases due to the minimal size of mirrors.

To produce the colour of the image, a colour wheel is generally used in front of the DLP chip. This results in an illumination time for each colour three times quicker than with an LCD panel, which leads to a need for luminance three times greater.
Advantages for the DLP panel are that it is more efficient than the LCD type due to mirrors’ reflexion coefficients and since there is no boundary between the mirrors, there is no “screen door effect” either.

But on the other hand, there is an effect known as “rainbow effect” which is introduced with this micro display. This effect is due to the colour wheel and the persistence of vision. It leads to the effect of a rainbow on the image when there is a strong contrast or a fast movement on the screen or of the eye.

c. Reflective LCoS – Liquid Crystal on Silicon

LCoS ("Liquid Crystal on Silicon") projectors are a more recent variation of LCD technology, with the difference that LCoS uses reflexive technology as opposed to transmissive.

LCOS combines both LCD and DLP technologies. Indeed, it is a reflective technology that uses liquid crystals, which are applied to a reflective mirror substrate, instead of individual mirrors. As the liquid crystals open and close, the light is either totally reflected from the mirror below, blocked, or partially reflected to produce grey levels. This modulates the light and creates the image.
LCOS-based projectors typically use three LCOS chips, as with LCD panels, each one to modulate light in the red, green, and blue channels.

One can also use a colour wheel to produce a colour image so that the congestion is minimized but then, as for the DLP chip; the illumination time for each colour is three times quicker, which leads to a need for luminance three times greater.

To continue, since LCoS use a reflective technology, the efficiency of the LCoS matrix is 96% which is greater than with an LCD matrix. However, the dichroic prism should also be taken into consideration and subsequently; the actual efficiency of the micro display is about 40%, which is still greater than that of the LCD matrix.

Finally, the reflective mirror allows the electronic chips which control the pixel transparency to be much less visible. Consequently, the “screen door effect” is significantly reduced.
d. Conclusion

After going through these different micro display systems, it is clear that a trade-off between congestion and output luminance has to be made. In addition, the negative effects, such as rainbow effect or screen door effect, should be avoided where possible.

We can firstly eliminate the DLP panel because, if we want to get rid of the rainbow effect, we have to use 3 DLP panels which does not result in a gain in volume in comparison with the two other technologies.

Now between LCD and LCoS technologies, the choice is rapidly going towards the LCoS panel. Indeed, the efficiency is still better with LCoS than with LCD and then, there is no screen door effect.

As a conclusion, research points to the use of LCoS technology. In particular, we are going to use the micro-display FLCoS from FDD Company (Forth Dimension Display), whose characteristics are given below:

<table>
<thead>
<tr>
<th>Active Area</th>
<th>17.43mm × 13.95 mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Display Diagonal (Active Area)</td>
<td>22.3mm / 0.88&quot;</td>
</tr>
<tr>
<td>Pixel Pitch</td>
<td>13.62μm</td>
</tr>
<tr>
<td>Inter Pixel Gap</td>
<td>0.54μm</td>
</tr>
</tbody>
</table>

Figure 16: datasheet of the FDD

3- Projection lens

The projection lens is used to image the micro display on a diffusing screen with an important magnification. This optical system should answer the needs and be as simple and low cost as possible in the same time. This is what is going to be studied in the following part of the report.
a. List of solutions

Below is a list of all the solutions that have been considered to answer the needs. They are listed from the least to the most adapted.

- Matrix of projection

Matrix of projection is new on the market and “consists of hundreds of tiny micro-projectors in an array, each of which generates a complete image” [9]. This matrix of projection has the dimension of the micro display so the volume of the system can be very small. Yet, this technology is not really well known today and it seems difficult to integrate it in the short throw projector for now.

![Image of matrix of projection](image)

Figure 17: Micro lens array from the Fraunhofer Institute [9]

- Simple lens with light source perfectly collimated

Supposing that we have a perfectly collimated source, the incoming rays will then propagate in a direction parallel to the optical axis. In this case, the object (that is to say the micro-display) would be at infinity and a simple diverging lens would be sufficient to create an image on the diffusing screen. The problem of chromatism and aberration would disappear and only the distortion would be left to correct.

However, it is really difficult to obtain a perfectly collimated source in reality and then, a single diverging lens would not be sufficient to get a good image quality. But still, the smaller the angle of incidence is, the better the image quality will be.
This solution consists of creating a design of a projection lens with the help of simulation software. This solution seems to be the easiest since the different solutions already found in patents can be used, adapted to the needs and then tested with the software. It will optimise the shape, the size and the material of each optical component and will also give expected performances for specific designs.

This is the solution that have been chosen to create the projection lens and whose different steps are describe below.

b. CodeV

CodeV is a powerful tool for designing and analysing optical systems. It can be used for many purposes. Here are some typical tasks:

- To evaluate and adapt an existing optical design for suitability in a new application or to reduce fabrication cost.
- To create a new design based on requirements for a specific product or application.
- To evaluate quality of the formed image.
- To prepare an optical design for fabrication through tolerance analysis.

Optical system designed through CodeV can be found in many fields such as cameras, medical systems, projectors, aerospace’s applications and so on.

Alternative to CodeV exists, of course. Oslo or Zemax can be named, for instance.

c. Requirements

As already said, the optical system should be optimised to have small congestion, low cost and be as simple as possible while minimizing distortion and chromatic aberrations. Requirements are:
- The system should be off-axis due to configuration issues\textsuperscript{2}.
- The size of the spot diagram should be less than the size of one pixel so that the chromatism and other aberrations don’t affect the image quality. Indeed, the spot diagram gives indication about the image of a point object. In the absence of aberrations, a point object will converge to an Airy spot.
- The distortion can be corrected before using “warping” and sending a pre-distorted image on the micro display. Still, the distortion shouldn’t be too big so that it can be corrected by the software.
- The glasses have to be correctly chosen in order to minimize the chromatism.
- The number of lens shouldn’t be too high so that the cost is minimized. But it shouldn’t be too small either since the less numerous the lens are, the worse the image quality is.
- The lens surfaces should be as simple as possible; it would be preferable to avoid aspherical or free-form surfaces as possible still in order to minimize the cost of the projection lens.
- The thickness of the lens shouldn’t be too small too so that the fabrication is easier, cheaper and that the lens are not easily breakable.
- The MTF (Modulation Transfer Function) should preferably be more than 50% for a spatial frequency = 1/(2×image pixel size) (corresponding to 1 cycle/mm or to 1 linepair/mm) in order not to see a blurred image. Since we know the dimensions of a pixel on the micro display, its size and the size of the diffusing screen, we can calculate the image pixel size which is approximately 250 µm × 250 µm. Then the MTF should be more than 50% for a spatial frequency of 2 lines/mm.

d. Constraints

To meet all the requirements, it was necessary to fix some constraints. Fixing constraints means fixing all the parameters that we already know for sure or that we want to obtain in the end. They are listed below:

\textsuperscript{2} Non-Disclosure Agreement
The size of the image on the screen is fixed and its diagonal size is 15" or 10×15 mm².

In the same way that for the image, the size of the micro display is fixed too. The chosen micro-display is the FLCoS FDD and the dimensions have been given earlier in this report.

The presence of the PBS cube has to be represented since it will determinate the beam of light coming on the first lens of the total projection lens. The size and the materiel of the cube are then fixed and the position of the cube in front of the micro display is fixed too. The distance between this two is really small (≈ 0.1 mm).

In order to fix the angle of incidence of the light coming on the projection lens, the system should be telecentric in object space, which means that the entrance pupil is at infinity and that the incident beam of light will remains unchanged even after optimising the optical system. If the system is not telecentric in the object space, the angle of incidence of rays is set to fit the size of the aperture stop placed somewhere on the optical axis after the first lens of the optical system.

![Figure 18: System respectively not telecentric in the object space (left) and telecentric in the object space (right)](image)

Finally, the incident angle of light coming on the cube has to be fixed too. Indeed, if the incident angle of light coming on the polarised beam splitter is wide, the contrast is going to decrease because of the different reflections through the cube. Then, this angle should not be more than ± 15° (cf Figure 19 and Figure 20).
However, the bigger this angle of incidence is, the worse the image quality becomes. Indeed, aberrations are going to be more significant when the beam going through the projection lens is wide. Then this angle of incidence should be as small as possible. But obtaining this small angle means that the light coming from the LED source should be collimated or quasi-collimated. Rays coming from the LED then propagate in a direction perpendicular to the first face of the cube, which is actually really difficult to obtain.

Upon reflection, a good angle of incidence on the cube is around ± 5°. This means that the beam going out of the LED and the collimation lens will have a field of ± 5°. This angle of more or less 5° corresponds to a numerical aperture N.A = 0.087.
e. Problems encountered

Several problems were encountered when working on the optical design of the projection lens.

To start with, some system have been entered with their value find in patents and then optimised without adding or deleting optical elements. Then, a problem was created when adding a PBS cube just after the micro display. The whole system had to be optimize once again and most of the time it was not working anymore.

Another encountered problem was the fact that, at first, the system was studied in only one direction (case 1 on fig.19), which means that studied points on the micro display were all belonging to the same direction. But the trouble occured when the same system was then studied in two dimensions, the performances were getting worse. So it is necessary to directly work with two directions (case 2 in fig.19) when studying the system. Besides, it is also necessary to study points corresponding to the corners of the micro display (case 3 on fig.19) so that no problem occurs when taking a rectangular aperture for the micro display instead of a circular one.

![Figure 21: possible configuration to study the design](image)

To finish, there was another problem with the place and size of the aperture stop, also called diagram stop. Indeed, all the rays are supposed to pass through this aperture, which is not always the case, and more important, this aperture is supposed to fix the field of view of the system. This means that no ray should travel out of the aperture stop.
and, when it is the case, the software is not able to calculate performances or to optimise the design. To solve this problem, more constraints have been added:

- The place of the pupil is set to be free by using a function called “decenter and return”, which allows the pupil to tilt or translate around the optical axis without changing it.
- To force the rays to pass through the pupil, the chief ray for each position studied on the micro display is forced to pass by the centre of the aperture stop.
- The size of the aperture is directly calculated by the software and the position can be adjusted by the user.

**f. Tests and Results**

Once all the previous problems have been solved, different solutions can be put under study and results can finally be obtained. Here is a summary about most interesting designs, describing their advantages and drawbacks.

- **Cube PBS**

As already said earlier, after a while it appeared obvious that the presence of a PBS cube was needed to simulate a good design with all the needed characteristics. The PBS cube was also created under CodeV, using datasheets from Thorlabs Company found on the Internet. The cube size is 1” (25.4 mm) side and it’s made of NSF1 glass.
Now that the PBS cube is settled, different designs can be studied.

- **Design A**

First of all, a solution of direct projection (without using a fold mirror) is tested. The dimension of the projection lens is $8 \times 6 \text{ cm}^2$, the image is projected at 10 cm in front of the last lens and the system contains 9 lenses. The throw ratio is 0.27.

![Figure 23: 2D view of design A (on the top), corresponding spot diagram (on the left) and distortion (on the right)](image-url)
On the previous figure, RMS is corresponding to Root Main Square and represents the radius of the circle containing 80% of the energy. The following result (100%) represents the radius of the circle containing 100% of the energy.

The left column of the picture is field position and gives the coordinates of studied points.

The size of the spot diagram is too big here to fill the requirements. Plus, the distortion is very important and the MTF requirements are not meet.

But the configuration at the start wasn’t good, the cube PBS used here is not the good one, the system is not telecentric in the object side, and the design is only studied in one direction. This example illustrates well the impact of the problems described earlier by showing how bad the image quality is.

Another problem is that the large lens at the end of the combination which could be a problem when considering its size. If one wants to decenter the lens, the distortion is going to be bigger and the performances are going to decrease.

A conclusion for this configuration is that it’s not going to work for a short projection distance. Indeed, the last lens is either too large or the distortion is way too important. The solution to solve this problem is to use a fold aspherical mirror which can reduce the throw distance and minimized the aberration at the same time.

- **Design B**

The following configuration is using a design found in a patent from Optinvent Company [13]. The dimension of the projection lens is 13 × 5 cm, the image is projected 0.5 cm in front of the bottom face of the PBS cube and the design requires 14 lenses. The throw ratio is then 0.5. The system is still studied in one dimension and its performances are given below:
The spot size diagram requirement is satisfying and the distortion is small so it should easy to correct by warping.

But, on the contrary, the MTF requirement is not met. This problem could also be visible when using the image simulation function. This function creates an accurate representation of a 2D input object as it is imaged through the optical system defined in
CodeV. This simulation includes the effects of distortion aberration blurring, diffraction blurring, relative illumination and, optionally, blurring due to the detector size. The result of this simulation as following:

As can be seen there, the image is not too much distorted but it is blurred. This is coherent with the MTF of the system. Besides, the system is only studied in one dimension and could get worse when studying it in 2 dimensions. This is why the following designs are all going to be studied in two dimensions according to the case 3 in figure 19.

- **Design C**

The following design is still inspired from Optinvent Company [13] and is, this time, studied in 2 Dimensions. After several optimisations, the size of the projection lens is 20 × 8 × 5 cm³ and is composed of 13 lenses and 1 aspherical mirror. The throw ratio is 0.52.
Talking about the performances, there is really little distortion but the size of the spot diagram is larger than it should be (< 0.250 µm) and the MTF doesn’t fit the requirements. Still, the image simulation (cf. Figure 29) doesn’t seem too blurred but this might be due to the loss of contrast through the system.
The following design is inspired from the previous one and tends to have a smaller volume. Through experience, characteristics that should have the projection lens become clearer. The size of the projection lens is $15 \times 7.5 \times 5 \text{ cm}^3$ and is composed of 11 lenses and 1 aspherical mirror. The throw ratio is 0.39.

As for the previous design, the spot diagram is too large, the MTF is not good and in this case the distortion is more important. The image simulation is still not too much blurred and there is still a loss of contrast.
Figure 30: 3D view of design D

Figure 31: Distortion of design D

Figure 32: Spot diagram and MTF for each field of design D

Figure 33: Object (on the left) and simulated image (on the right) for design D
Design E

This design is inspired from the patent US 0231690 A1. The size of the projection lens is $20 \times 4.5 \times 3 \text{ cm}^3$ and is composed of 8 lenses and 1 aspherical mirror. The throw ratio is 0.5.

The size of the spot diagram meets the requirements in RMS (80% of the total energy) but is a little bit too large for the global pattern. The distortion is not too important and concerning the MTF, this is the best one that has been obtained so far. The MTF is above 50% for a special frequency of 3.5 line/mm and above 15% for 7.7 line/mm. This means that the resolution is good.
The simulated image is still blurred at the and there is higher image contrast comparing to the previous design. This design is the one closest to the requirements and besides, it is the simplest to make.
IV. Light performances

In this part, a photometric study will be presented. First, the required output luminance from the projector will be calculated for the two different screens and then, from these results, studies of the collimation system and the configuration of the backlight are going to be given too.

1- On the screen

- Screen 1: 10×15 cm²

The maximum luminance due to the sky is 34000 cd/m² and the illuminance from the sun on a surface is 86000 lux. To continue, from previous experience, optimal contrast with exterior brightness is set to be C = 1, 2.

Then, we can now calculate the screen output luminance to have an optimal contrast:

\[ F_{projector} \geq 780 \text{ lm} \]
Using the same method of calculation for this screen and considering that the screen transmission is 90%, results indicate that the short throw projector should deliver at least 1150 lm.

\[ F_{\text{projector}} \geq 1150 \text{ lm} \]

2- **From the illumination system**

The projector system is represented in the following drawing, showing the different parts in it and their respective transmissions of light.

![Diagram of the projector system](image)

*Figure 36: Constituent of the projector*

The transmission of the projection lens should be around 70% (measures should be made in order to determine this number more precisely), the one of the micro-display together with the PBS cube is set to be around 40% and finally, the one of the collimation system is set to 70% for now (a study of this system later on this report will give a good approximation of this number).
Starting from this figure, we can deduce the total transmission of the light through the projector: $T_{tot} \approx 20\%$. That is to say that we need the LED to deliver at least 5750 lm for the screen 2 and 3900 lm for screen 1 to have a reasonable contrast in the image plane. This will obviously lead to the use of a powerful LED.

Moreover, as already explained in the previous part, the field of light coming on the PBS cube should be $\pm 5^\circ$ to get both a good contrast and a good image quality.

So the backlight providing light to the micro-display should deliver at least 5750 lm for the screen 2 to have a sufficient contrast compared to the sun and emits light in a cone of $\pm 5^\circ$ to have good contrast and image quality.

### 3- Configuration of the backlight

In this part, two different backlight configurations have been studied. One of these configurations is using an LED panel and the other one is using a single LED as a point source and a collimation lens. Only the screen 2 is considered here.

**a- With an LED panel**

This solution uses a panel of green, red and blue LEDs. The emitted Light then propagates in an integrator tube which consists of mirrors in order to uniformly mix the red, green and blue lights. To continue, the light passes through a lambertian diffuser, causing the light to be emitted in all the directions of the half-space and then propagates in the PBS cube to illuminate the micro-display, creating an object for the projection lens.

![Figure 37: backlight using a LED panel](image)
Since the field of light in the projection lens is limited to be ± 5° by a diaphragm, only rays which propagate in this field will be useful to make an image on the screen. To calculate ratio between useful rays and lost rays, luminous flux should be considered:

\[ F = \Omega L S \]

With \( \Omega \) is the solid angle, \( L \) is the luminance and \( S \) is the surface of the diffuser. Since the diffuser is lambertian in a demi-space, the solid angle \( \Omega = \pi \). Thus:

\[ F_{\pm 5^\circ} = \pi \sin^2(5^\circ) L S_{diff} \]
\[ F_{tot} = \pi L S_{diff} \]
\[ \frac{F_{\pm 5^\circ}}{F_{tot}} = \sin^2(5^\circ) = 0.76\% \]

Then, only 0.76% of the emitted light will be used in the projection lens.

To continue, using one Led panel with the FDD micro-display signifies that the sequential colour mode has to be used (otherwise, if the micro-display is enlightened by red, green and blue light at the same time, the emitted light will be white). This means that the micro-display is successively enlightened with red, green and blue light. The switch between colours is so fast that it can’t be seen by the eye due to its persistence. In one cycle, each group of LEDs (red, green and blue) is working during 7% of the time. They are switched-off the rest of the time. This ratio should also be considered when calculating the efficiency of the light box.

Moreover, colour ratios are also important to obtain the required white and should be integrated in the calculation. These ratios are given by an already made program and are the following: Red (24.4%) / Green (69.4%) / Blue (6.1%).

Now concerning the integrator bar and the lambertian diffuser, the transmission is set to be 75% but thus, the size of the diffuser must be about the one of the LED panel or greater. Indeed, if the size of the diffuser is smaller than the one of the LED panel, rays are going to be reflected in the wrong direction and go back towards the LEDs. Since the...
LED panel is not a reflective surface, most of the rays are going to be lost (cf. figure 42) and the transmission is going to be a lot smaller.

Since the diffuser is really close to the PBS cube, its size should be around the one of the micro display to enlighten its entire surface. Thus the size of the LED panel should be close to the size of the FDD which is $17.43 \times 13.95 \text{ mm}^2$. Plus, to get well uniform light, the length of the integrator bar is about 20 mm.

![Figure 38: On the left => Integrator bar with diffuser size smaller than LED panel size On the right => Integrator bar with diffuser size equals to LED panel size](image)

Finally, to make calculations, we will use an LED panel already made in a previous research. This panel consists of 15 LED (6 Red, 7 Green, 2 Blue) taken from the LUXEON REBEL catalogue which are disposed as following:

![Figure 39: Configuration of the LED panel](image)

The size of one LED is $3 \times 5 \text{ mm}^2$ which means the emitting surface of the LED panel is $15 \times 15 \text{ mm}^2$ which is close to the micro-display surface $13.95 \times 17.43 \text{ mm}^2$. Then, the transmission of the integrator bar and the diffuser can be taken to be 75%.
All the previous comments have been taken into consideration in the following table which gives the luminous flux generated by the projector in its totality. All the data concerning the LED are taken within the Luxeon Rebel Datasheet given in Appendix 1.

<table>
<thead>
<tr>
<th></th>
<th>Red</th>
<th>Green</th>
<th>Blue</th>
</tr>
</thead>
<tbody>
<tr>
<td>colour ratios</td>
<td>24%</td>
<td>69%</td>
<td>6%</td>
</tr>
<tr>
<td>Number of LED</td>
<td>6.0</td>
<td>7.0</td>
<td>2.0</td>
</tr>
<tr>
<td>Total number of LEDs</td>
<td>15.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Flux for 1 LED at 700 mA (lm)</td>
<td>100</td>
<td>160</td>
<td>70</td>
</tr>
<tr>
<td>peak to peak for one LED when considering colour ratio (lm)</td>
<td>66</td>
<td>160</td>
<td>49</td>
</tr>
<tr>
<td>Total flux (lm)</td>
<td>394</td>
<td>1120</td>
<td>98</td>
</tr>
<tr>
<td>Tension (V)</td>
<td>2.3</td>
<td>3.25</td>
<td>3.3</td>
</tr>
<tr>
<td>Current (mA)</td>
<td>459</td>
<td>700</td>
<td>492</td>
</tr>
<tr>
<td>Puissance for 1 Led (W)</td>
<td>1.1</td>
<td>2.3</td>
<td>1.6</td>
</tr>
<tr>
<td>lm/W</td>
<td>62</td>
<td>70</td>
<td>30</td>
</tr>
<tr>
<td>Ptot with time ratio (W)</td>
<td>0.4</td>
<td>1.1</td>
<td>0.2</td>
</tr>
<tr>
<td>Ptot RGB (W)</td>
<td></td>
<td></td>
<td>1.8</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Total flux after the screen for each colour (lm)</th>
<th>0.034</th>
<th>0.097</th>
<th>0.0085</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total flux after the screen (lm)</td>
<td>0.139</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Flux needed after the screen (lm)</td>
<td>1150</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Flux needed after the screen for each colour considering ratios (lm)</td>
<td>281</td>
<td>798</td>
<td>70</td>
</tr>
<tr>
<td>Ratio between needed flux and obtained flux (%)</td>
<td>0.012%</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 40: calculation of flux obtained after the screen with a LED panel
As a conclusion, the projector is consuming 1.8 W and the luminous flux after the projector is 0.139 lm which is really low and represent only 0.012% of the requested flux to contrast with the sun. This result is due to the very small quantity of light effectively used in a field of ± 5° (the ratio is 0.76%).

The calculation was also made starting from the requested flux and giving the requested number of LED to meet this need. It results in a need of around 102100 LED to fill the need which actually is not possible to make.

A solution to improve the efficiency of the projector when using an LED panel would be to increase the field from ± 5° to ± 10° for instance. But then, the image quality will be degraded.

b- With a point source (single LED)

In this second solution, the backlight consists of one single LED used as a point source and a collimation lens. The study is once again made only for the case of the screen 2.

The collimation lens is designed using a perfect point source placed in its object focal plan so that the rays will propagate at the infinite after the lens. The light source would then be perfectly collimated. In reality, the light source is not a perfect point source but a single LED with a certain emitting surface. This will result in the fact that rays will propagates in a field of more or less a few degrees which fit the requirement since the field is wanted to be ± 5°.

Now, in order to determine the maximal emitting area of the LED to stay in a field comprised between 0° and ± 5°, a calculation regarding the geometrical “étendue” G can be made. The disposition of the LED, the collimation lens and the PBS cube is as follow:
We have:

\[ G_{\text{led}} = S_{\text{led}} \cdot \Omega_{\text{led}} = S_{\text{led}} \cdot \pi \]

With \( \Omega_{\text{led}} \) the solid angle of the LED = \( \pi \) since the LED is emitting in the \( \frac{1}{2} \) space.

\( S_{\text{led}} \) the emitting surface of the LED

\[ G_{\text{screen}} = S_{\text{screen}} \cdot \Omega_{\text{screen}} = \pi \left( \frac{D}{2} \right)^2 \cdot \pi \cdot \sin^2 \beta_{\text{max}} \]

With \( S_{\text{screen}} \) the surface of the screen

\( \Omega_{\text{screen}} \) the solid angle of the screen = \( \pi \sin^2 \beta \)

\( D \) the diagonal of the micro display = 0.88" = 22.3 mm

\( \beta_{\text{max}} \) the maximum incident angle of light on the cube = 5°

Knowing that the geometrical "étendue" is preserved through an optical system, we get:

\[ G_{\text{screen}} = G_{\text{led}} \]

\[ S_{\text{led}} = \frac{S_{\text{screen}} \cdot \Omega_{\text{screen}}}{\Omega_{\text{led}}} = \frac{3}{\pi} \text{mm}^2 \]

So the surface of the emitting area of the LED is 3mm\(^2\) at maximum.
Emitting surface of the Luxeon Rebel LED is 1 mm² so it fits the previous conditions which is why the following calculation of output luminous flux still use this LED as an example.

In order to produce colour and use the sequential colour mode, three LED (one for each colour) and three collimation lenses will be used. The different coloured beams are then recombined before the PBS cube by using dichroic films. To avoid losing light because of the distance between the collimation lens and the PBS cube, an integrator bar made of mirrors is also used such as represented on the following figure:

![Figure 42: Backlight configuration when using a point source](image)

To continue, since the LED emits in all the directions of the half-space, rays propagating in a perpendicular way comparing to the entry face of the collimation lens won’t be collected by this one, this is why the collimation lens only transmits 85% of incoming rays. Moreover, the lens emits light in a circular aperture but the shape of the micro display is rectangular. This means that approximately only 60% of rays are coming on the useful area and the rest is lost (cf. Figure 43).

![Figure 43: Useful area enlightened by the collimation lens](image)
All the previous comments have once again been taken into consideration in the following table which gives the luminous flux generated by the projector. Colour ratios have obviously to be considered as for the previous solution.

<table>
<thead>
<tr>
<th>Colour ratio</th>
<th>Red</th>
<th>Green</th>
<th>Blue</th>
</tr>
</thead>
<tbody>
<tr>
<td>Red</td>
<td>24%</td>
<td>69%</td>
<td>6%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Number of LED</th>
<th>1,0</th>
<th>1,0</th>
<th>1,0</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>Total number of LEDs</th>
<th>3,0</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>Flux for 1 LED at 700 mA (lm)</th>
<th>100</th>
<th>160</th>
<th>70</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>Flux tot with good ratio (lm)</th>
<th>56</th>
<th>160</th>
<th>14</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>Tension (V)</th>
<th>2,3</th>
<th>3,25</th>
<th>3,3</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>Current (mA)</th>
<th>394</th>
<th>700</th>
<th>141</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>Puissance for 1 Led (W)</th>
<th>0,9</th>
<th>2,3</th>
<th>0,5</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>Im/W</th>
<th>62</th>
<th>70</th>
<th>30</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>Ptot with time ratio (W)</th>
<th>0,063</th>
<th>0,159</th>
<th>0,032</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>Ptot RGB (W)</th>
<th>0,3</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>Flux after the screen (lm)</th>
<th>0,506</th>
<th>1,439</th>
<th>0,127</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>Total flux after the screen (lm)</th>
<th>2,072</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>Total flux needed after the screen (lm)</th>
<th>1150</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>Flux needed after the screen for each colour considering ratio colour (lm)</th>
<th>281</th>
<th>798</th>
<th>70</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>Ratio</th>
<th>0,18%</th>
</tr>
</thead>
</table>

**Figure 44**: calculation of flux obtained after the screen with a near-point source

As a conclusion, the projector is consuming 0.3 W and the luminous flux after the projector is 2.072 lm which is really low and represent only 0.18% of the requested flux to contrast with the sun.
This result is due to the fact that, for a small emitting surface of LED, the generated flux is too low.

The same calculation was also made with an LED (reference : PT-121) from Luminus Company, using LED generating at maximum 2225 lm for the Red, 5400 lm for the Green and 1050 lm for the blue. As a result, the output luminous flux was 70 lm which represents 6% of the required flux. This efficiency is greater than for the Luxeon rebel LEDs but here, the emitting surface of the luminous LEDs is equals to 12 mm², which means that the incident angle of light incoming on the PBS cube is going to be more than ±5°. This means that the image quality will be degraded.

An ideal case would be to have a really small emitting surface with a great output luminous flux (such as 10000 lm for instance). This Led still doesn’t exist in reality but, with researches, it may exist later in the future.

As a conclusion, the solution using a single LED as a near-punctual source gives better efficiency than the solution using LED panels. In the same time, the volume occupied by this second solution is smaller than the one occupied by the near punctual source solution. Then a trade-off between efficiency and congestion appears. But still, results are far from filling the flux requirement. Maybe laser use should be reconsidered.
V. Realization of a prototype

1- COTS – Commercials Off-The-Shelf

COTS, short term for Commercial Off-The-Shelf, is an adjective that describes software or hardware products which are ready-made and available for sale to the general public. For instance, Microsoft Office is a COTS product that is a packaged software solution for businesses [12]. COTS products are designed to be implemented easily into existing systems without customizing it. Using COTS parts helps reducing production costs of products as well as difficulties of fabrication.

Concerning the short throw projector, the purpose of the COTS study is to find already existing lenses having the same characteristics than the ones simulated with CodeV in order to use them in the optical system without degrading image quality. Concerning the aspherical mirror, it is going to be really difficult to find its equivalent among already existing products so a solution is to have this one made by another company using its exact characteristics.

The three main companies which sell optical components and among which lenses are going to be picked are:

- Thorlabs
- Edmund Optics
- Newport Corporation

2- Process

To start with, there are four main characteristics about lenses which are the thickness, the diameter, the material and the focal length. These data can be found using the Lens data manager of the software and using a program which give the focal lens and the diameter of each lens. The next step is to search compatible lenses among companies catalogues and to use them instead of simulated lens.
Rapidly it seems obvious that achromatic doublets or meniscus lenses (lens having two convex or two concave surfaces (cf. Figure 46) are difficult to replace with available lenses on the market (since there are only a few of them produced by companies) and using doublets or meniscus lens having different characteristics than simulated ones degrades the image quality.

![achromatic doublet and meniscus lens](image)

To solve this problem, the optical system has to be modified to contain only simple lens such as plano-convex, plano-concave, bi-convex or bi-concave lenses.

Once this step is done, the resulting optical system contains 9 simple lenses, its total track is 200 mm and its performances are sufficient. This design is going to be the starting point for COTS.
3- Results

As lenses are replaced one by one, the system is regularly optimised and some lens are added or removed to keep sufficient performances. But as the number of COTS lens increases in the optical system, performances decrease and when it comes to replacing the last lens of the system, performances get worse and don’t fill the requirements anymore. This is, for instance, the case for the following system which contains 11 lenses all chosen among companies’ products. The size of the spot diagram is eight times bigger than needed and the MTF criteria are not respected either.
Since replacing all the lenses in the system is degrading too much performance, a trade-off would be to replace as many lenses as possible and to have the others made by the same company which is probably going to make the aspherical mirror.

This is the case of the following design which consists of 12 lenses among which 11 lenses are replaced with COTS. The performances are acceptable, the total track of the system is still 200 mm and the simulated image quality is good as shown in the following figures:
This optical design seems to fit the requirements in terms of image quality. But when considering the position of the lenses relative to each other, there are often translated or tilted (cf. Figure 53) which can create a problem when thinking about the fabrication of the barrel (the lens container).
Reducing the difficulty when fabricating the barrel implies that tilt and decentre should be avoided as much as possible. This is the case for the following system which consists of 9 lenses with 10 of them replaced by COTS lenses. There are two visible groups of lenses which are tilted and decentred relative to each other but inside groups, lenses aren't tilted or decentred except for the second group when some lenses are only decentred. The spot diagram and the MTF are in accordance with the needs but the simulated image seems to be slightly blurred. Finally, the cost for replacing these 9 lenses is around 500 euros.
Figure 54: optical system with 9 COTS lenses on 10 lenses

Figure 55: Spot diagram and MTF of optical system with 9 COTS lenses on 10 lenses

Figure 56: Object (on the left) and simulated image (on the right) of previous design
Now concerning the barrel, there is always the presence of small plays in it which allow lenses to slightly move from their original position. These small movements are going to make performances go wrong and the image quality will be degraded. This is why the next step of this COTS study is to make a tolerancing study to know how worse get the performances of the system when considering these plays in the barrel and then, to evaluate if the image quality is still satisfying.

Since this report in handed out before the end of the internship, this study will unfortunately be made later and will not figure in this report.

This tolerancing study, together with COTS study, should help us deciding if a prototype is worth to be made, considering the production cost, the image quality and the viability of the system. Light performances are also a determining factor when it comes to the fabrication of a prototype. Indeed, what is the point of having a performing optical system if there is no enough output light to get an image? This decision of making a prototype, as for the tolerancing study, is going to be taken later.
VI. Conclusions

In this project, the concept of a short throw and compact projection system has been studied.

First, the state of the art and patent study was made in order to know what already existed on the market and also to get some ideas to start with. The next step was to decide which micro display would be better to use and with which light source by comparing all technologies available on the market and fitting the need of the projector. Moreover, the optical system for the projection lens was designed with software of optical conception in accordance to the requirements and a COTS study was made in order to try to reduce fabrication cost and difficulties. Finally, a performances review was made to characterize the efficiency of the projector in term of luminous flux. There are still things to do with this project such as a tolerancing study and the production of a prototype. But the actual performances of the system are not so great and the future of the project should be seriously considered.

Throughout this project, I developed my optical knowledge as well as my ideas about what is the industrial world and what exactly is an engineer work. I really enjoyed working at the Innovation & Advanced Study Department of Thales Avionics because it is the place where new technologies have to be found in order to make innovation and research go further and create tomorrow’s products. The only regrets about this internship were to have not made manipulations and optical measures which would have been necessaries if I had the time to lead the project until its end.
References


[3] Silicon Optix inc, patent n° US 7239360 B2, Short throw projection system and method

[4] InFocus Corporation, patent n° US 2006 0290897 A1, Projection device and screen


[13] Optinvent company, patent n° WO 2011 089042 A1, Dispositif de projection courte distance raisonnablement grand angle avec zoom de mise au point
# Appendix 1: Luxeon Rebel LED datasheet

## Flux and Efficacy Performance Characteristics

### Luminous Flux Characteristics for LUXEON Rebel Color Portfolio,

### Thermal Pad Temperature =25°C

<table>
<thead>
<tr>
<th>Color</th>
<th>Part Number</th>
<th>Min Luminous Flux (lm)</th>
<th>Min Luminous Power (mW)</th>
<th>Typ Efficacy Flux (lm/W) or Radiometric (Im/W)</th>
<th>Typ Efficacy for Royal-Blue and Deep Red Power (mW)</th>
<th>Min Luminous Flux (lm)</th>
<th>Min Luminous Power (mW)</th>
<th>Typ Efficacy Flux (lm/W) or Radiometric (Im/W)</th>
<th>Typ Efficacy for Royal-Blue and Deep Red Power (mW)</th>
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*All LUXEON Rebel color emitters except royal-blue emitters are tested and binned for dominant wavelength. Royal-blue emitters are tested and binned using peak wavelength.*

LUXEON Rebel ES royal-blue emitters are tested and binned at 700 mA.
Electrical Characteristics

**Electrical Characteristics at 350 mA for LUXEON Rebel color; Thermal Pad Temperature = 25°C**

<table>
<thead>
<tr>
<th>Color</th>
<th>Part Number</th>
<th>Min.</th>
<th>Typ.</th>
<th>Max.</th>
<th>Typical Temperature Coefficient of Forward Voltage ($\Delta V_f / \Delta T_j$)</th>
<th>Typical Thermal Resistance junction to Thermal Pad ($R_{J,C}$)</th>
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<tr>
<td>Green</td>
<td>LXML-PM01</td>
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<td>2.50</td>
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<td>Blue</td>
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<td>Red-Orange</td>
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Electrical Characteristics at 700 mA for LUXEON Rebel ES Royal-Blue; Thermal Pad Temperature = 25°C

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<tr>
<th>Part Number</th>
<th>Min.</th>
<th>Typ.</th>
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**Notes for Table 3:**
1. LUXEON Rebel ES royal-blue measured between 25°C = $T_j$ = 110°C and if = 700 mA.
2. Measured between 25°C = $T_j$ = 110°C at $I_f$ = 350 mA.
3. Philips Lumileds maintains a tolerance of ±0.06V on forward voltage measurements.

**Typical Electrical Characteristics at 700 mA for LUXEON Rebel color; Thermal Pad Temperature = 25°C**

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