Application Note #12

Design and test of a high quality illumination lamp for color samples and prints

1. Introduction

A high quality illumination lamp is required to make visual judgements on the color accuracy of manufactured objects and printed materials. By "high quality" we mean an artificial light source which has a spectral output which is equivalent or very close to a natural light source of the same Correlated Color Temperature (CCT, in kelvin). High quality light sources are sold either as stand-alone luminaires or with an enclosure, i.e. a light booth. The stand-alone version is simply suspended over a work area; it is thus the user responsibility to minimize or eliminate the contribution of other light sources in the environment, either from outdoor light through windows or room lights, and to prevent unwanted reflections from colored walls and furniture. A light booth not only minimizes the contribution of external light sources but is usually designed with very neutral light grey walls which improve the illumination uniformity within the work area. The lamp in this project was tested stand-alone although it could be placed in a light booth enclosure if required;[1] it is shown mounted on a camera tripod in the picture below.

The CCT of lamps are selected according to their final usage. A D50 source is generally specified in the print and graphic design industries, where "50" is shorthand for 5000 K, a blackbody temperature, and "D" indicates that its spectrum should correspond to the phase of daylight of the same CCT. The difference between a blackbody and a daylight source of the same CCT is that the daylight source is the blackbody spectrum filtered by the earth atmosphere, which affects the spectral content and slightly shifts the source chromaticity.

A D65 source, with a CCT of 6504 K, is usually selected in the paint business where the product is often viewed outdoor, on houses or cars for instance. As for Illuminant "A", a 2856 K blackbody, it corresponds closely to the light output of tungsten halogen incandescent lamps found indoors and used in many home viewing applications, when reading a magazine or for illuminating paintings for example.

Historically, it was quite easy to purchase a good quality Illuminant A lamp, i.e. a halogen lamp, since such lamps were ubiquitous and low cost. However, it was much more difficult and more expensive to build a viewing lamp at other CCTs and essentially impossible to build a variable CCT system. This explains why, even today,

[1] The characterization of a lamp will be affected by a light booth walls, so any measurement in one configuration is not directly applicable to the other configuration.

most light booths offered commercially are models with up to seven[2] fixed CCT light sources and variable CCT systems remain rare and expensive.[3]

However, in the last decade we have seen the emergence of light sources based on LEDs. While more expensive than legacy halogen and fluorescent lamps, their extended lifetime and low power consumption advantages are so convincing that the older lamps are being phased out, even if the light quality, i.e. their color rendering properties, are most often quite worse than the lamps they replace. In particular, most LED lamps which are designed to replace halogen lamps are poor performers in terms of color rendering.[4]

This is not to say that all LED based lamps are bad, in fact some of them are excellent, but caution must be exercised when selecting this technology. As in many other domains, excellence has a price, and as we will see, this price can be quite reasonable if you are ready to invest some time.

In this application note, we use a flexible strip of 432 LEDs in twelve rows manufactured by **Yujileds** where half of the LEDs have a CCT of 2700 K (nominally), which are identified as **WW** (Warm White), and the other half a CCT of 6500 K (nominally) identified as **CW** (Cool White).

Bi-color tunable LED strip:	**YJ-VTC-12HRB-2835L-24-2765**
Yujileds store site:	**https://store.yujiintl.com/**

The remote control (and associated receiver) can be used to select only the WW or CW LEDs and also to set intermediate CCTs. The LED panel is fixed to a heatsink fitted with a fan and a bezel. The various components are listed, with price and sourcing information, and dimensions of custom parts are provided. The detailed design and the colorimetric performance of the lamp fixture are presented.

The intent of this document is to provide enough information so that, knowing the various construction requirements, you can build a similar illumination system yourself. It may differ in many aspects, such as in heatsink and bezel design or even LED strip selection but you should have a better knowledge of what to measure and expect in terms of usability and performance.

Here are shortcuts to jump at other sections of this document:

- LED assembly
- Heatsink design
- Bezel design
- Final assembly/Integration
- Illuminator characterization
- Conclusion

You will find additional information in these appendices:

- Appendix A: Nuts and bolts
- Appendix B: Drill bits and taps
- Appendix C: Components info and cost breakdown
- Appendix D: TM-30-20 analysis grid
- Appendix E: Lamp base example

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[2] Some of the most popular CCTs are: D50, D65, TL-84, Illuminant A. TL-84 is a narrow band tri-phosphor fluorescent tube used mainly in Europe, China, and Japan with a CCT ≈4100 K.
[3] For example: JUST Normlicht LED Color Viewing Light 2.0 (5,5K+ US$) with adJUST LEDcontrol software (1,1K+ US$).
[4] Replacement LED lamps are often specified at the slightly "bluer", or less reddish, 3000 K color temperature.

2. LED assembly

2.1 LED selection

There are essentially three methods to create white light with LEDs:

- **a)** With a mix of separate Red, Green and Blue LEDs.
- **b)** With a combination of several (7+) LEDs emitting at different wavelengths.
- **c)** With a Blue or Violet LED exiting a phosphor mix.

Method "**a**" is the simplest method to generate white light with a variable CCT. It can simulate any color located within the chromaticity triangle defined by the three LEDs, which is the basis of how most color displays work. While this is a flexible approach, the color rendering quality of this method, as an illuminator, is very low. This is why it is used mostly in decorative lighting applications.

Method "**b**" is more complex but offers the possibility of fine-tuning the output spectrum in order to match a wide range of CCTs and even specific chromaticity coordinates. Dedicated UV emitting LEDs can be added to emulate the UV content of daylight sources. This is the method used in the **JUST Normlicht LED moduLight**[5] lamp for instance. The higher number of LEDs requires a more complex controller. It is the most flexible but also the most expensive method.

Method "**c**" with **blue** light excitation is the prevalent method used in LED-based white-lamps in the current market. A small portion of the blue light is sent directly out of the lamp while a large portion is used to excite phosphors which reemit light in a smooth spectrum between the bluish-green and red wavelengths. Various CCTs can be achieved by varying the ratio of the blue portion and the phosphor emitted portion (in separate LED chips). The problems with a blue exciter are that, in many designs, the blue peak is very noticeable in the spectral output shape and the quality of the phosphors is low; so, depending on design, the color rendering performance of such lamps varies between poor to excellent.

Method "**c**" with **violet** light excitation at 405 nm is much less common, if only because these LEDs are more expensive than blue LEDs. Also, since the violet exciter is at the bottom limit of the visual system sensitivity, the phosphor mix also requires a blue-emitting phosphor. This is the approach used by the manufacturer of the LEDs we selected, Yujileds, for their VTC series. As with the blue exciter, specific CCTs require separate LEDs. Yujileds offers a strip of 432 LEDs (12 rows x 36 columns on a 100x300 mm flexible support with an adhesive backing) where half of the LEDs have a CCT of 2700 K and the other half a CCT of 6500 K.[6] By mixing the output of these two LED types, all CCTs in between can be obtained.

The graphs on the next page compare the spectrums of traditional tungsten and halogen lamps to those obtained with LEDs using either blue or violet exciters with phosphors. For the purpose of the demonstration, the CCTs of the selected lamps were chosen between 2600 K and 3000 K (specification values, not measured values).

Lamp 1 is a very common legacy tungsten flood light. The output spectrum is very smooth and it essentially matches the blackbody emission curve. Lamp 2 output, obtained with a 300 W halogen lamp, is similar to lamp 1 output but corresponds to a slightly higher CCT typical of many halogen lamps. Lamp 3 is the LED strip used in this project, set at 3000 K for the purpose of this comparison. Lamps 4 and 5 are both blue exciter lamps with fixed CCTs. Lamp 4 is a high quality lamp designed for commercial applications by Yujileds while lamp 5 is a general purpose lamp of decent quality found in a home hardware store.

You will find additional comments on the page after the graphs.

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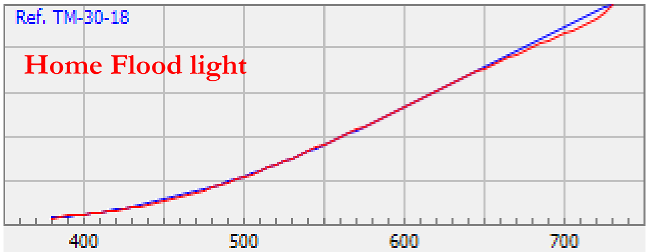
[5] The JUST LED moduLight, as described in their US patent 8,592,748 B2, is in fact a hybrid between methods "b" and "c" (with blue exciter). It uses five LEDs at discrete wavelength with two LEDs partially covered with fluorescent pigments (i.e. phosphors). An illuminator of similar quality based solely on LEDs with discrete wavelengths would require more than seven wavelengths.

[6] You should be aware however that these CCT values are nominal and will vary somewhat between manufacturing batches.

COMPARISON OF LAMP TECHNOLOGIES AROUND 3000 K
(GRAPHS AND COLORIMETRIC RESULTS)

1-



Tungsten: BR30, 120V, 65W, 2600 K

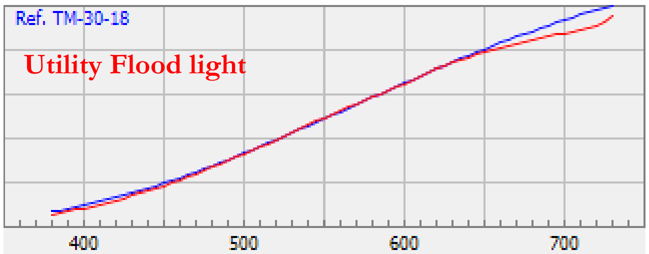
Manufacturer: GE

CCT: 2648 K

TM-30-20: *Rf* : 99 *Rg* : 99

CIE 13.3: *Ra* : 99 *R9* : 98

2-



Halogen: T3, 119 mm, 120V, 300W

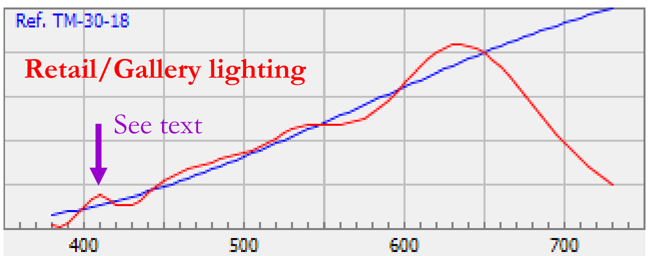
Manufacturer: generic

CCT: 3019 K

TM-30-20: *Rf* : 99 *Rg* : 99

CIE 13.3: *Ra* : 99 *R9* : 96

3-



LED multirow strip: tunable, 24V, set to ≈3000 K

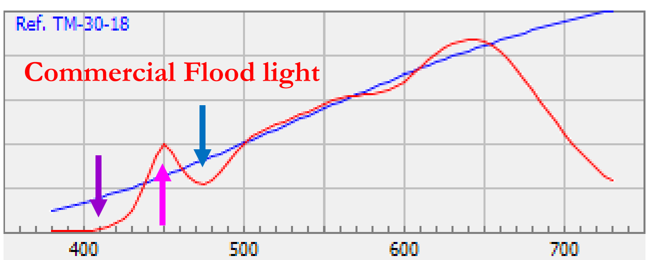
Manufacturer: Yujileds, YJ-VTC-12HRB-2835L-24-2765

CCT: 2997 K

TM-30-20: *Rf* : 95 *Rg* : 101

CIE 13.3: *Ra* : 94 *R9* : 90

4-



LED: PAR30, 110V, 16W, 3000 K, adjustable FOV

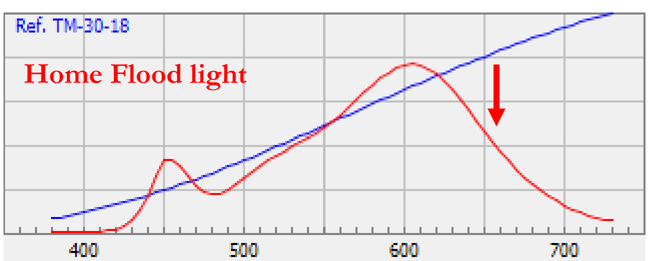
Manufacturer: Yujileds, YJ-BC-PAR30-16-110-30

CCT: 3232 K

TM-30-20: *Rf* : 97 *Rg* : 101

CIE 13.3: *Ra* : 98 *R9* : 98

5-



LED: PAR20, 120V, 7W, 3000 K

Manufacturer: Luminus

CCT: 3022 K

TM-30-20: *Rf* : 86 *Rg* : 95

CIE 13.3: *Ra* : 83 *R9* : 11

Note: TM-30-20 is identical to TM-30-18 in terms of methodology and computation; changes are essentially in the documents page layouts.

COMPARISON OF LAMP TECHNOLOGIES AROUND 3000 K (COMPARATIVE ANALYSIS)

Lamp 1 vs Lamp 2 (tungsten vs halogen)
Lamp 2 slightly higher CCT causes an overall spectral shift towards the blue wavelengths and a significant increase of the ratio of violet and blue in its spectrum compared to lamp 1. This explains why halogen lights are usually found more vibrant, and also why the "default" CCT for halogen-replacing LED lamps is quite often 3000 K.

Lamps 3 to 5 exciter wavelengths
The blue exciter near 450 nm in lamps 4 and 5 is very noticeable (**purple** arrow in lamp 4). The 405 nm violet exciter for the LEDs of lamp 3 is also noticeable but is much less predominant (**violet** arrow in lamp 3). Since the other wavelengths are obtained by fluorescence, they cannot be of a smaller wavelength (i.e. more energetic) than the exciting wavelength. We thus see the spectrum going to zero below the exciter wavelength. In other words, the blue exciter will never be able to provide violet light (**violet** arrow in lamp 4). We also notice a dip at wavelengths just above the exciter peak and it is more pronounced for the blue exciter (**blue** arrow in lamp 4; referred to as the "cyan dip" by some LED lamp manufacturers).

Lamp 4 vs Lamp 5
Lamp 4 has excellent color rendering performance compared to lamp 5. This can be attributed to a more optimized mix of phosphors in the 500 to 600 nm region and also because the phosphors of lamp 4 emit much farther in the red portion of the spectrum. The lower emission in the red region for lamp 5 (**red** arrow) explains the bad *R9* result (*R9*=11). Lamp 4 is an excellent choice for critical home, retail and commercial applications where color accuracy is important (Note: It also has an adjustable Field-Of-View (FOV) between 10 and 60 degrees). Lamp 5 remains a valid choice for general lighting where color accuracy is not essential, while still providing a pleasing feel.

Lamp 3 vs Lamp 4
Lamp 4 has slightly better rendering numbers and lamp 3 has a more precise CCT (since it's adjustable!). Please note that manufacturing differences are a fact of life in the LED lamp business and both are "**one of**" samples. Also, since the spectrum of lamp 3 is a mix of the WW and CW LED banks, the *Rf*, *Ra*, and *R9* indices of the mix cannot be higher than the maximum values of the individual banks (please consult the **Experimental results** table in the Colorimetric performance section to see how the indices vary with the adjusted CCT).

All lamps
We made a visual comparison between all lamps by looking at various white papers, some of which had Optical Brightening Agents (OBAs), and some not. The comparison was made on a white, neutral, and non-fluorescent backing plate similar to the one used for scanning targets with the i1Pro instruments. When viewed with lamps 1 and 2, we noticed that the papers with OBA appeared slightly bluish compared to the non-OBA papers and the backing plate. This tint was not present when the papers were illuminated by lamps 4 and 5, the lamps based on a blue exciter. Interestingly, the bluish tint was visible when viewed with lamp 3, based on a violet exciter. Now this raises a few questions:

- **With lamps 1 and 2, is the blue tint the result of fluorescence?**
  In theory "yes" since the emission of a blackbody extends to the UV, and with more UV energy for lamp 2 (3019 K) than for lamp 1 (2648 K). In practice, "maybe", since the lamps have a glass cover, one of which (for lamp 2) clearly labeled "UV filter". However, the presence of a filter does not mean that **all** UV is blocked, so it could induce fluorescence.
- **With lamp 3, is the blue tint the result of fluorescence?**
  Likely "no" since paper OBAs are sensitive to UV at around 350 nm. So this begs the next question…
- **Could the bluish appearance NOT be caused by fluorescence?**
  Let's see. Firstly, lamps 1, 2, and 3 all have more energy than lamps 4 and 5 in the violet spectral range below 435 and in the blue to cyan range between 465 nm and 500 nm. Secondly, the 450 nm bump of lamps 4 and 5 is centered on both the blue Color Matching Function curve (CMF, CIE 1931 and CIE 1964) and on the secondary peak of the red CMF curve; eliminating this bump reduces the blue input but also some of the red input. So, with less red and more violet and cyan, could this explain the apparent better match of lamp 3 with lamps 1 and 2? "Possibly", but this would need to be investigated more thoroughly.

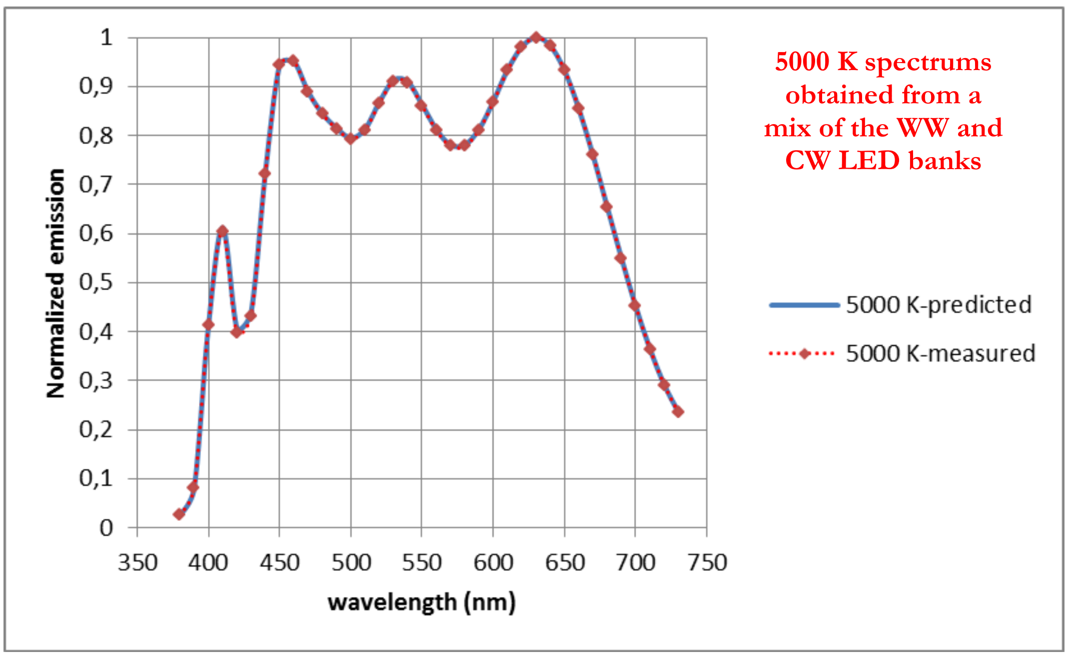
2.2 CCT tunability concept

It may not be intuitive but linearly combining the spectrums of two quite different blackbodies such as 2700 K and 6500 K can provide the spectrum of any CCT in between. This can be simulated by mixing each spectrum in a spreadsheet, wavelength by wavelength, and by using the resulting spectrum as an input in a program which computes the CCT.[7]

There is one important factor that you should be aware here: except for very specific products, such as D50 LED tubes, Yujileds uses blackbody temperatures to describe CCTs, and not daylight nomenclatures. So the upper limit here is 6500 K and not D65. However, our measurements show that this has minimal or no effect on the color rendering results (legacy CRI or TM-30-20[8] results) and the ISO 23603 Metamerism Index results are always within goal.[9]

As a proof of the validity of the CCT tunability method, we predicted the spectrum for 5000 K based on the measured spectrums of each LED bank in our LED strip. The low CCT bank is referred to as "WW", for Warm White, and the high CCT bank as "CW", for "Cool White. The measured CCTs of each bank are 2841 K and 6843 K respectively. The measured spectrums were normalized to 1000 lux and then linearly combined in varying proportions until the resulting spectrum was close to 5000 K. The target CCT was met with 30,5% of WW LEDs with the remaining portion (69,5%) from the CW LEDs.

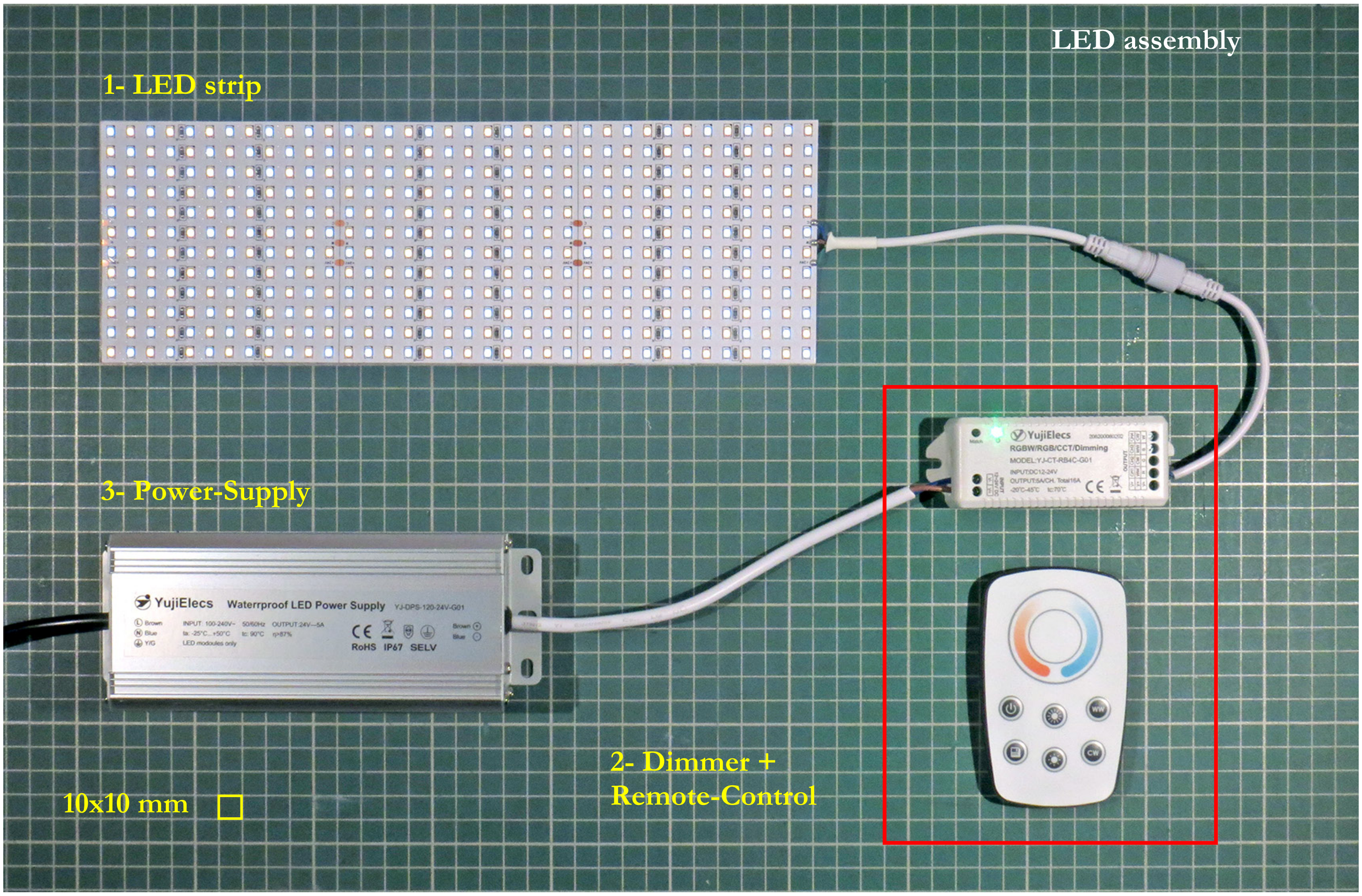
The graph below compares the predicted spectrum to the measured spectrum obtained by adjusting the remote control color ring. The spectrums are essentially identical and the **predicted colorimetric performance** (*Duv*, *Rf*, *Rg*, *Ra*, *Rg*, *u'v'* offset and *MIv*) is the **same as the measured performance** shown for 5000 K[10] in the Colorimetric performance section.



[7] You can process spectrums defined at 5 nm or 10 nm intervals with BabelColor CT&A CRI tool in demo/free mode.
[8] TM-30-20 is identical to TM-30-18 in terms of methodology and computation; changes are essentially in the documents page layouts.
[9] As measured with CT&A CRI and ISO3664+ tools. See the Illuminator characterization section for measurements.
[10] The "exact" CCTs corresponding to the spectrums are 5021 K predicted and 5014 K measured.

2.3 LED components

The image below shows the components of the LED assembly connected[11] and energized.



1- **LED strip: Yujileds model YJ-VTC-12HRB-2835L-24-2765**
   Full Spectrum CRI 98 Dynamic Tunable White Multirow.

2- **Dimmer + Remote-Control kit: Yujileds YJ-RCT-RB2C-G01**
   For Single Color/Bi-color LED Strips.

3- **Power-Supply: Yujileds YJ-DPS-120-24V-G01**
   IN: 100-240VAC, 50-60Hz; OUT: 24VDC, 5A, 120W; IP67 Waterproof
   This power supply is available in 24V and 12V versions. Make sure you select the 24V model.

Warning: For testing purposes, the LED components can be connected and powered without mounting the LED strip on a heatsink; however, you should not apply maximum power for more than a few seconds in order to protect the LEDs.

Please consult this Yujileds store Web page for a short video on how to match/pair the remote control to the dimmer:

https://store.yujiintl.com/products/yujielecs-remote-control-dimmer-kit-for-single-color-bi-color-led-strips

The video is also available on YouTube: https://www.youtube.com/watch?v=DvVu62gDQXs

[11] Please refer to Yujileds documentation for proper connection instructions.

2.4 Design pros and cons

The following comparison table is to be interpreted in the context of this project only; in particular, many of the “Cons” are a direct consequence of how we decided to mount and control the LED strip. For instance, it is certainly possible to get or build a different controller which would have many CCT presets instead of a single memory key. You will also note that the “Cons” are irrelevant for commercial products, but many commercial products do not have all the “Pros” of the table either!

Pros	**Cons**
Wide CCT range (2700 K to 6500 K)	Requires a spectrocolorimeter to adjust the CCT
Excellent colorimetric and color rendering performance at all CCTs	6500 K LEDs CCT specified as blackbodies (i.e. NOT as a Daylight phase)
Violet exciter enables violet content in output spectrum	No UV content for any CCT
One LED strip provides sufficient illuminance for desktop use (ISO 3664 P1 and P2 conditions)	Requires purchasing additional components for fixture
No consumable parts	Requires tools, manual work, and assembly
Very low cost (see cost breakdown) ≈ 400.00 CAN$/310.00 US$ for LED and fixture	

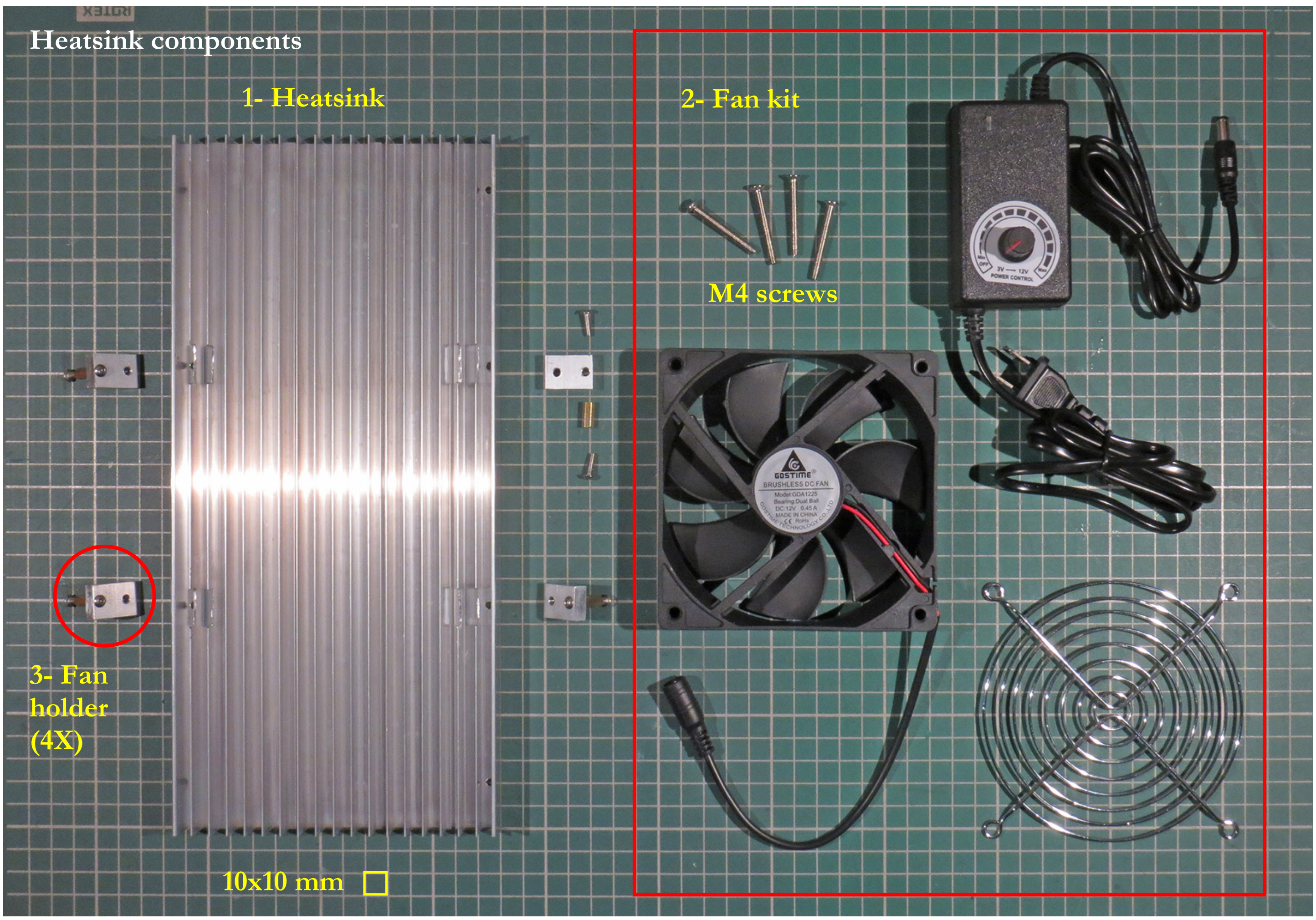
3. Heatsink design

3.1 Heatsink assembly

Having to use a heatsink with such a LED strip should not be a surprise if you ever "played" for a few minutes with unmounted LEDs and a heatsink is indeed recommended by the manufacturer. What is less obvious is the need for forced or active cooling, obtained by fitting a fan to the heatsink for instance. In fact, you probably have already noticed that most, if not all, LED lamps sold commercially for home use only have a passive heatsink.

So why would active cooling be required in this application? Well, there are two main consequences to temperature variation in a LED, a **light output shift** and a **CCT shift**. These two effects are not important in a home lamp and as long as the LED assembly is below a temperature at which the assembly integrity would be affected, no compensation is required. Such effects are of more concern if the final use is color assessment, not to mention that more cooling will likely extend the useful life of the illuminator. You will find comparative output measurements with and without active cooling in the Heatsink performance section.

The picture below shows all the heatsink components before assembly.



1- **Heatsink: YaeCCC Aluminum Heatsink 300x140x20 mm (alternate source)**
   See the Heatsink machining section for info on modifications.

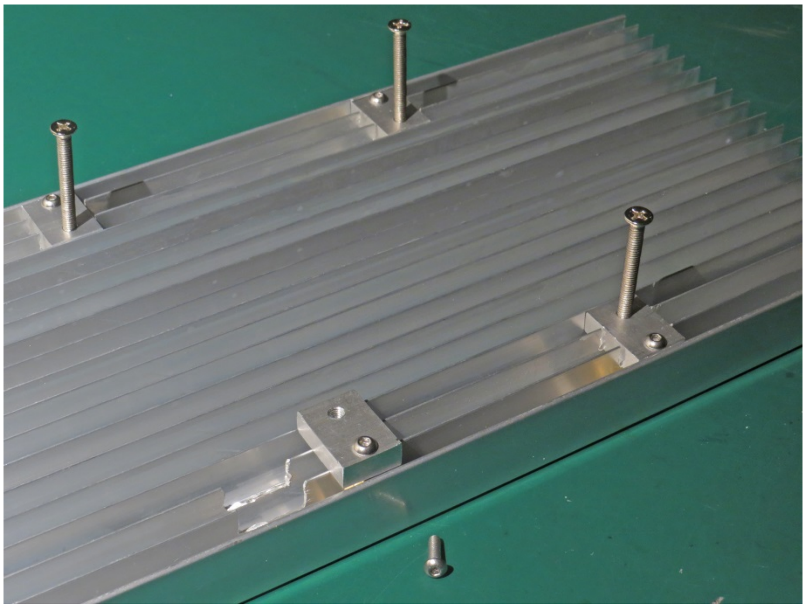
2- **Fan kit: GDSTIME BRUSHLESS DC FAN, Model GDA1225 (alternate source)**
   120mm AC 100V-240V DC 12V Powered Fan with Speed Control

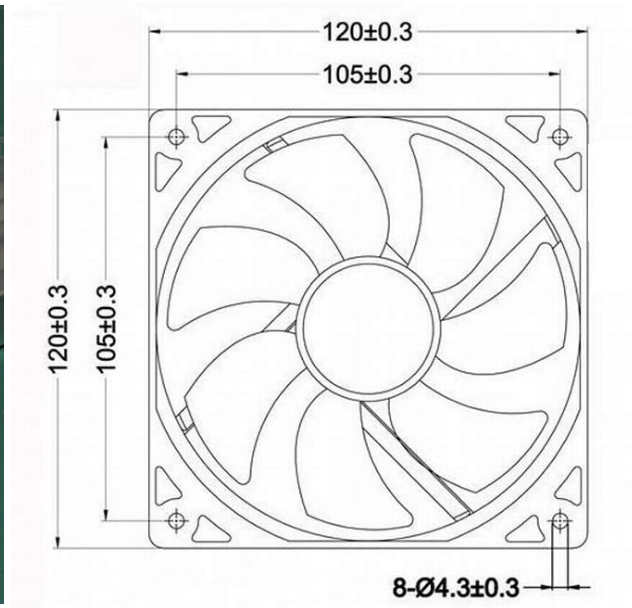
3- **Fan holder bracket: Custom built parts to adapt the fan to the heatsink**
   See the Fan holder bracket section for construction details.

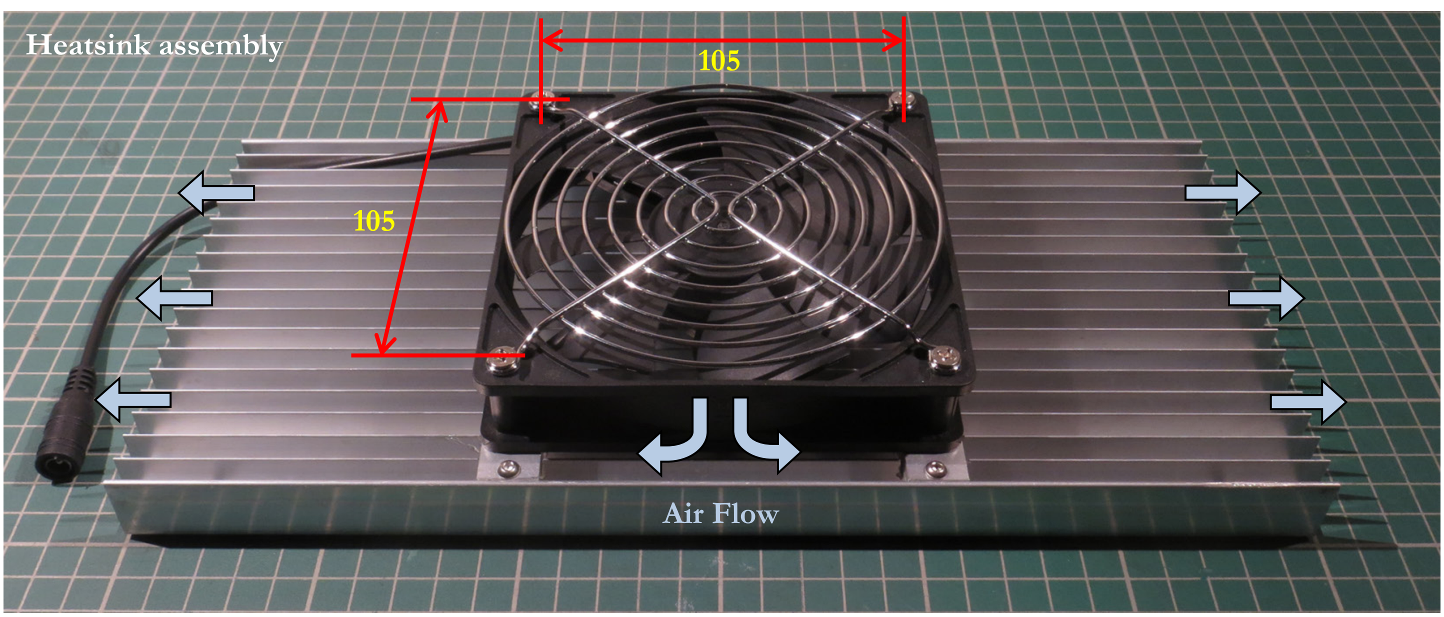
The drawing below on the right shows the fan external dimensions and the positions of the mounting holes. The picture just below on the left shows the heatsink with three of the four brackets installed and with the fan mounting screws, the long screws, partially screwed in the brackets. The picture at the bottom shows the fan mounted on the heatsink. We can see that the positions of the fan mounting holes correspond to the threaded brackets holes.

Important: Except for the M4 size mounting screws which came with the fan kit, all other screws in the project are **M3** size with a **0,5 mm thread** and **Allen key, i.e. hex key, driven**. The screws should have either a **button head** or a **flat head** depending on usage. See the Nuts and bolts appendix for details.

The fan is assembled in such a way that air is pushed towards the heatsink. Cool air thus travels all along the heatsink fins on each side and exits at both ends.

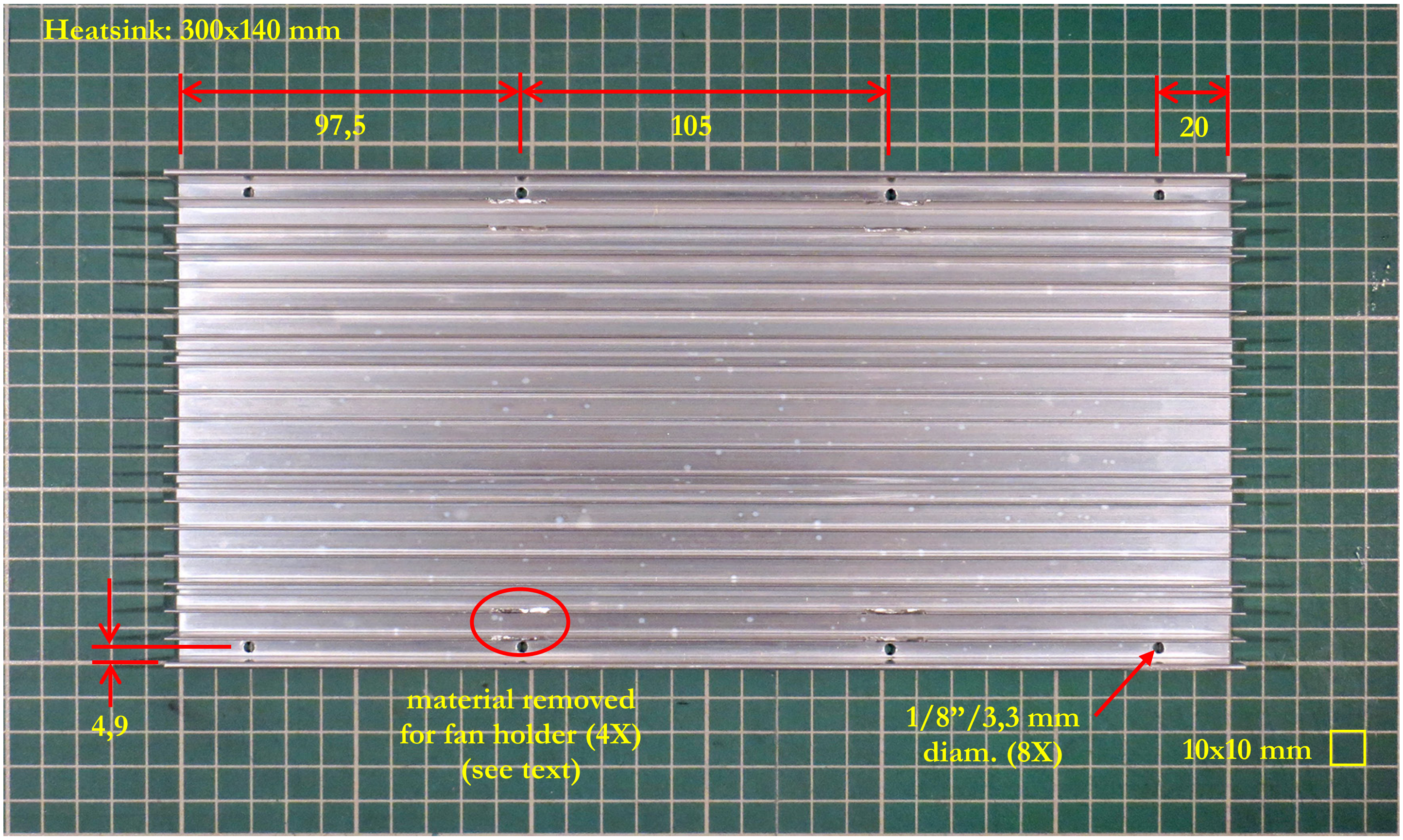






3.2 Heatsink machining

The heatsink requires a few modifications in order to attach the fan and the bezel. The modifications consist of eight (8) identical holes and removing some of the heatsink fins material at four places where the fan holder bracket is positioned. The holes positions are shown in the picture below.



All eight holes are used to attach the bezel which will be located on the other side of the heatsink. However, the four holes in the center not only hold the bezel but also the four fan holder brackets. The fan itself is then attached to the brackets in a subsequent step.

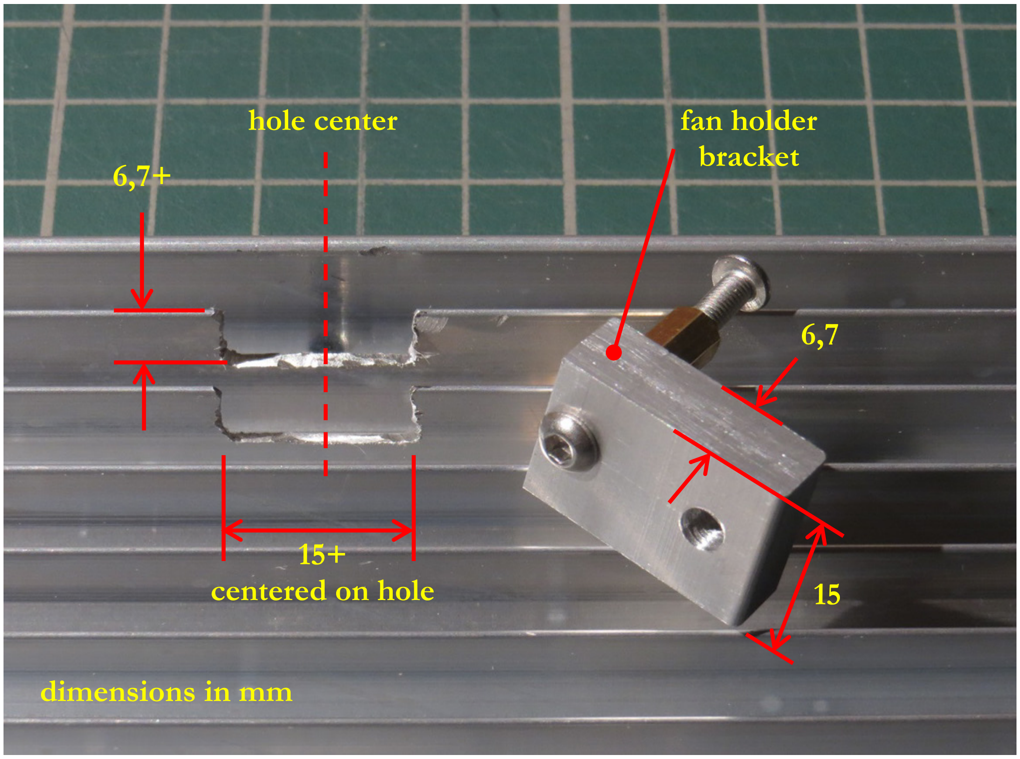
Warning: The 105 mm distance between the two center holes on the top and bottom of the image corresponds to the distance between the fan mounting holes.[12] When drilling the holes, you should thus place more effort on the accuracy of the distance between the center holes (105 mm) than on the distance between the holes and the heatsink sides (97,5 mm). You should also take precautions to properly align the corresponding top and bottom (relative to the image above) center holes.

Note: Make sure the four holes on the top of the image are aligned **horizontally** since they will be fixed to fasteners located in the middle of the same bezel extrusion. The same is true for the four holes on the bottom of the image.

Note: The 20 mm horizontal distance of the four holes on the left and right sides of the image is not critical because the mating fastener in the extrusion, a T-slot nut, can glide at any position.

[12] The fan mounting screws do not pass through these holes but these holes are used to hold the bracket which acts as an adapter between the heatsink and the fan body.

The image below shows a detailed view of the zone where the material is removed in order to fit the fan holder bracket. Please note that while the hole center position is indicated, the hole itself is not visible in the picture. However, we do see it indirectly by reflection on the top heatsink fin.



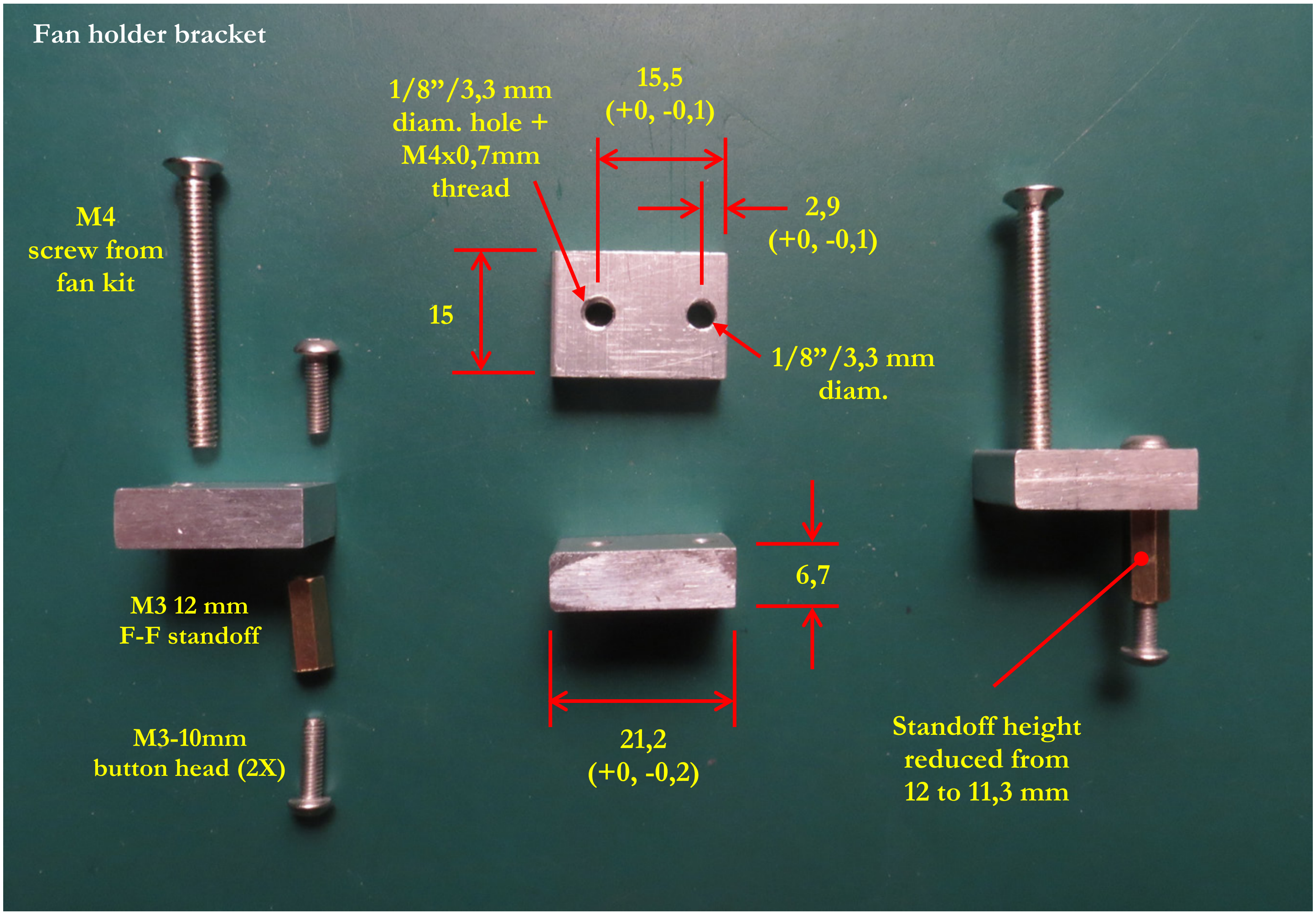
Hint: Removing material on the heatsink fins in order to make place for the fan holder bracket is a delicate operation if you do not have access to a milling machine, which is our case! For this project we did it with a Dremel™, which explains the rather rough edges of the opening. Make sure you "visualize" all the process steps before attempting it. At each bracket location we placed masking tape with markings defining the zones to remove on the two fins. We also placed thin stainless steel plates (held with masking tape) against the neighboring fins that did not require material removal in order to protect them from the hand tool. We then fitted the Dremel with cut-off wheels, i.e. small round saws, and carefully carved the openings. We used new saws to start the work and replaced them with smaller diameter secondhand saws for deeper material removal (you do keep your partially worn out saws do you!). And, finally, you should wear a dust mask, ear plugs, and protection goggles for such a task.

Note: It is considered that the bracket can be built with closer tolerances than the opening. This is why the depth and width of the opening are specified to be larger than the bracket thickness and width. In this design, the opening for the bracket does not directly contribute in holding the bracket. In other words, it does not need to perfectly fit the bracket and, more specifically, the machined fins do not need to contact the bottom or sides of the bracket.

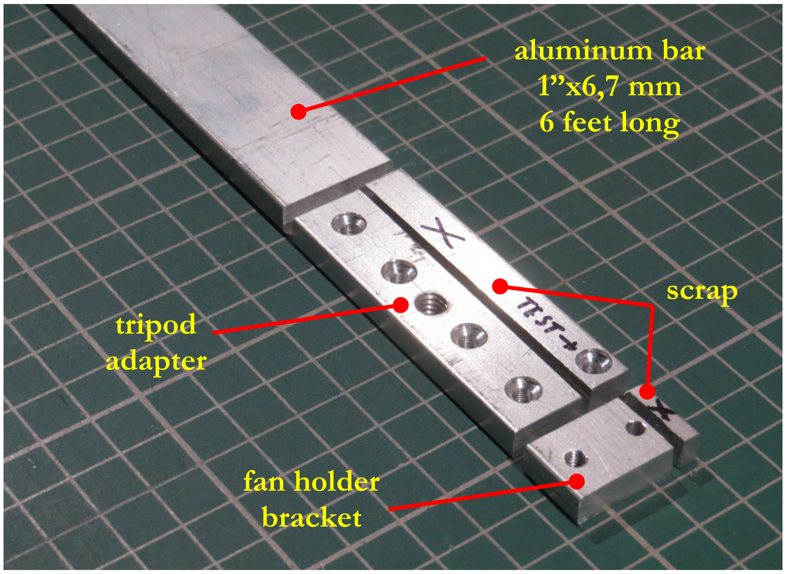
The fan holder bracket is described in the next section.

3.3 Fan holder bracket

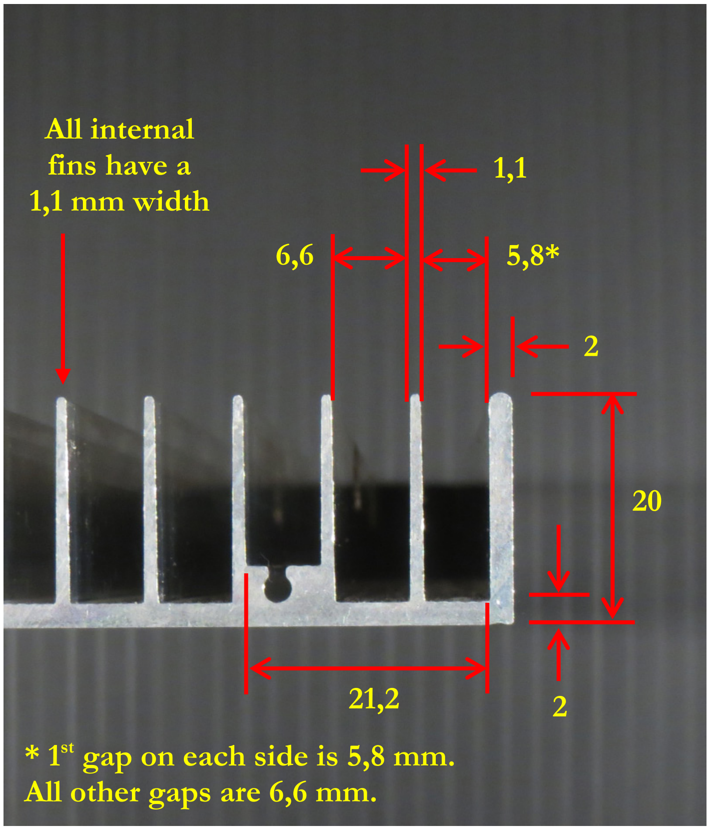
The purpose of the heatsink fan holder bracket is to attach the fan assembly on top of the heatsink. Such an adapter is required because the top of the heatsink is not a solid surface but is made of thin fins onto which it is difficult to attach a fastener. The bracket design and dimensions are shown in the picture below:

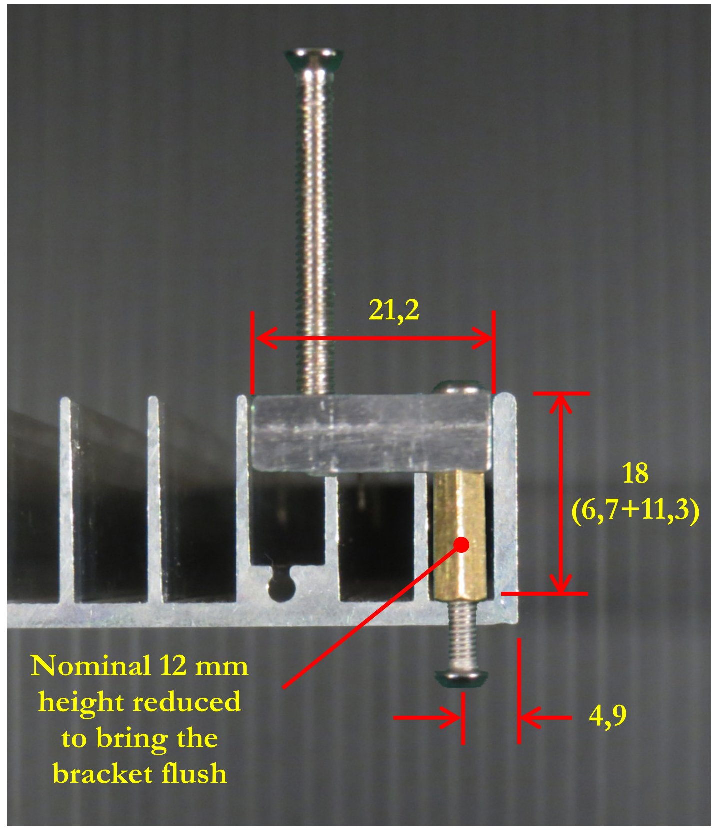


The bracket was (hand) machined from an aluminum bar available at home hardware stores.



The picture below on the left shows heatsink dimensions which are important for the design of the fan holder bracket. The picture on the right is a composite where a bracket image is superimposed on the heatsink image; it illustrates how the parts fit.





Note: M3 standoffs are available in various sizes, defined by the distance between two parallel surfaces of their hexagonal shape. You should use the smallest sizes for this design, with 4,5 to 4,7 mm between faces. This is usually the size you will get when you purchase low cost standoff kits on the Internet.

The main design goal for this bracket was to assemble the fan flush with the top of the heatsink. The goal was met with this rather peculiar and delicate to machine component. For simpler machining you may replace the aluminum by a hard plastic, in which you can make a thread of course, or change the design completely based on your available tools. You must just make sure that any screw going through the heatsink base does not go into the LED strip area!

Note: In order to have the bracket top surface flush with the top of the heatsink, we had to reduce the height of the M3 standoff from 12 mm to 11,3 mm. By doing so the bracket plate height (6,7 mm) plus the standoff height (11,3 mm) equals the inside height of the fins (18 mm). A flat file was used to reduce the standoff size.

Important: The bracket was designed specifically for the heatsink and the fan we had. If you want to use the same design, you should first measure your heatsink and fan and make modifications where required.

4. Bezel design

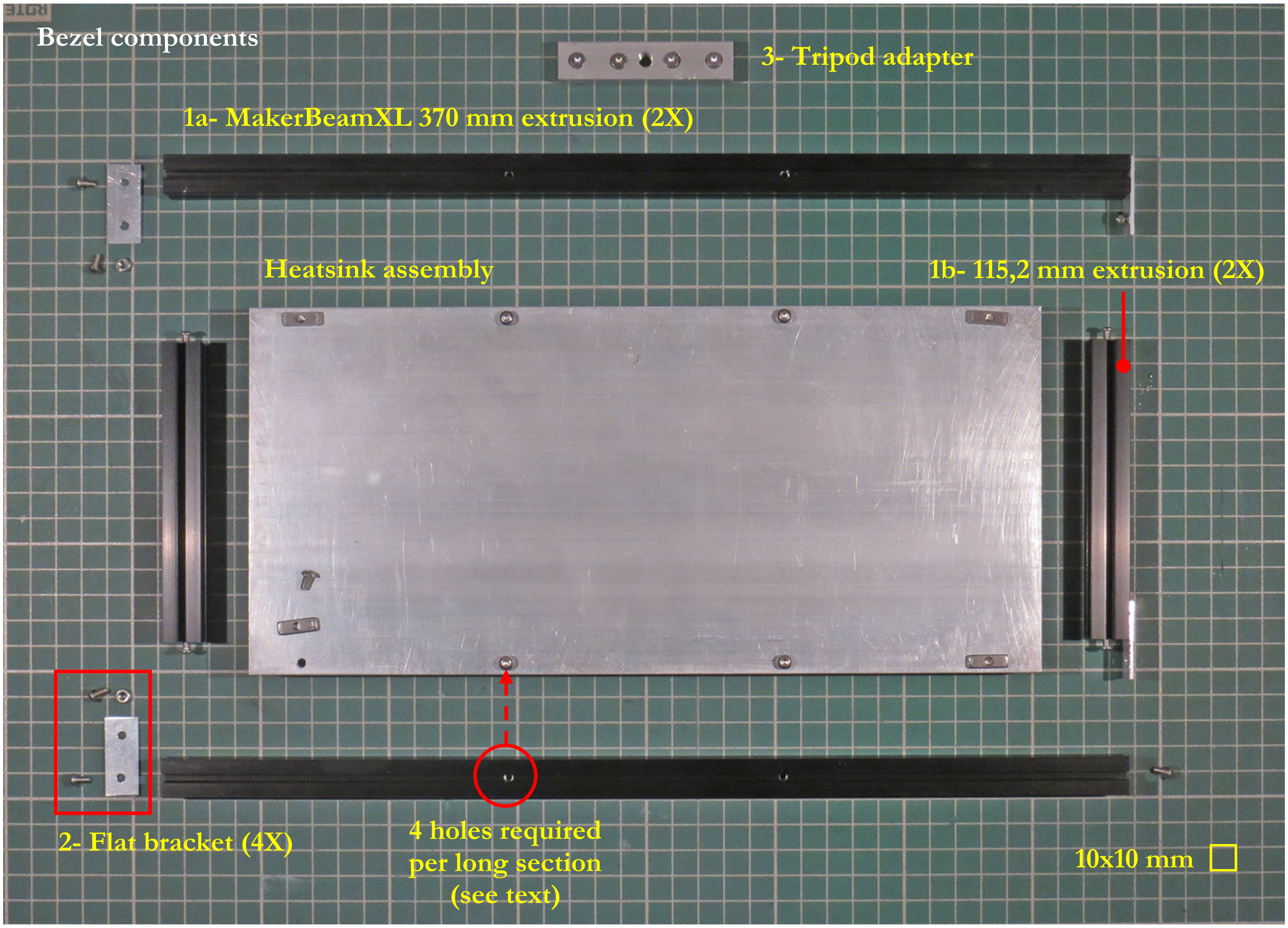
4.1 Bezel assembly

You may not see the need for a bezel if using a sturdy heatsink… and this would be a valid thought! The reasons to justify a bezel are many. Firstly, you certainly would appreciate some protection for the LEDs; without a lamp bezel the LEDs would be in contact with any surface on which you put down the lamp, a highly insecure storage method. Secondly, you will likely need a method to hold the lamp while you work, and a bezel offers a more sturdy structure than mounting the lamp using the heatsink alone. Thirdly, you may also want to have the remote control dimmer close to the LEDs and having a structure to hold it is a plus. Fourthly, if you ever decide to add a shade to your lamp, having a bezel makes the task easier.

Many options were evaluated and we decided to make a bezel based on off-the-shelf extruded aluminum profiles used by many hobbyists/makers/do-it-yourselfers. One popular product is made by "**MakerBeam**" (www.makerbeam.com). According to the company Web site, MakerBeam started as a Kickstarter project in 2009. The first product they sold was a 10x10 mm profile to be used to create frames and mount components. The design was refined to be more compatible with standard nuts and bolts and new profile formats were introduced. The profiles are now available in a refined 10x10 mm format simply called MakerBeam, and two 15x15 mm formats called MakerBeamXL and OpenBeam. Products are sold directly from the company, located in the Netherlands, and from distributors, some of which through Amazon™.

The **MakerBeamXL** profile format was selected for this project. The main reasons were the availability of this profile and some accessories from Amazon stores, the additional benefit of threaded holes on each end (more importantly the center hole), and a larger variety of assembly options (T-slot nut, brackets from other sources). Unfortunately, not all accessories are readily available (or at a reasonable cost!) with Amazon, and "equivalent" hardware was used. For those living in Europe, the main company store is an attractive solution, even more so because they offer to cut extrusions at custom lengths for a flat fee.

A picture with the bezel assembly components is shown on the next page.



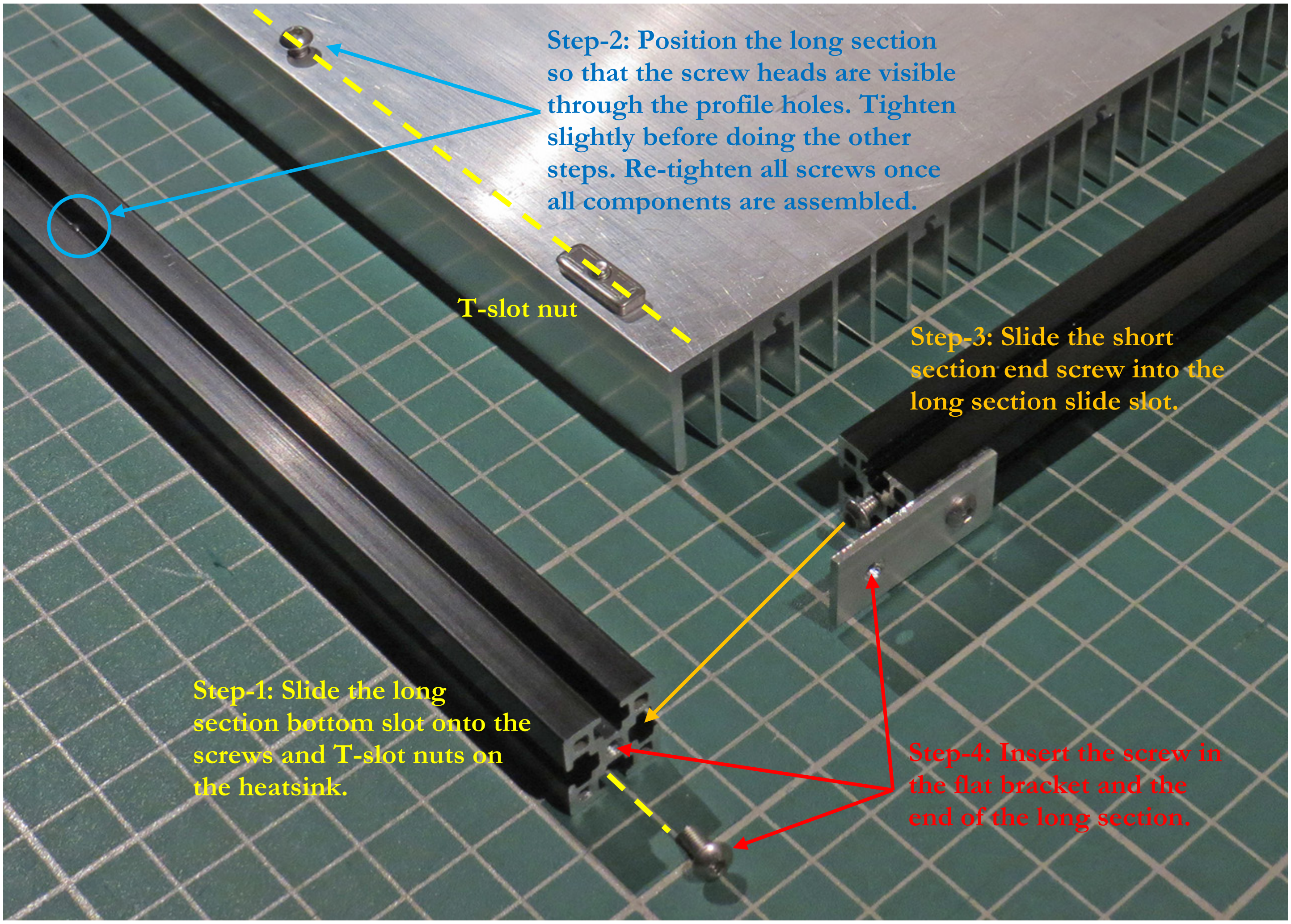
1- **Aluminum profile: [MakerBeamXL]; one 1000 mm extrusion or two 500 mm extrusions**
  1a- 370 mm length (2X). **Four holes** need to be drilled in **each section**. These holes are "pass-throughs" for an **Allen key**, i.e. hex key, to be used to tighten the screw heads located within a profile slot. See the Profile machining section for the holes size and their positions.
  1b- 115,2 mm length (2X)

2- **Flat bracket: Custom built part used to add structural rigidity (4X)**
  See the Flat bracket section for construction details and alternate off-the-shelf fasteners.

3- **Tripod adapter: Custom built part to hold the lamp with a standard photography tripod**
  See the Tripod adapter section for construction details.

One 1000 mm extrusion is sufficient (or two 500 mm extrusions) to get the four sections of the bezel. Since the extrusions are usually available in multiple items packages, for example a pack of four 1000 mm sections, you will get spares for other projects! It may be advantageous to order precut sections if this service is available.

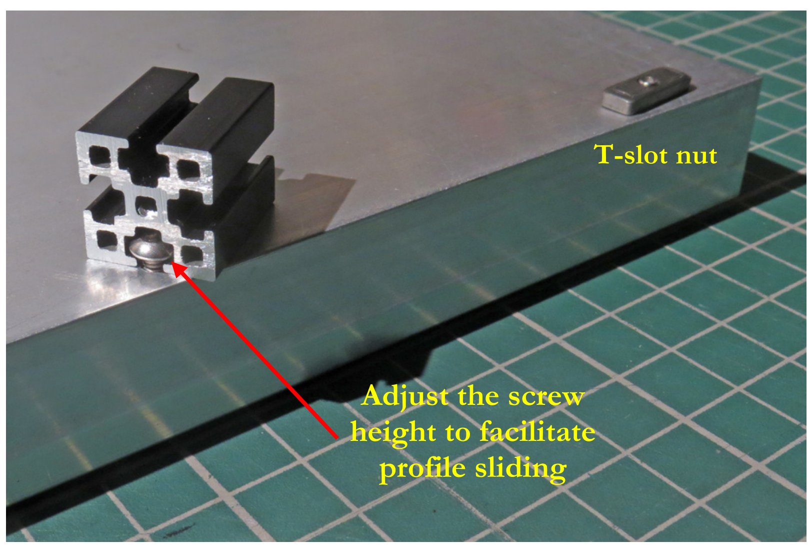
Some important assembly steps are described in the picture below where the text color is to be used in conjunction with the similarly colored lines and arrows.

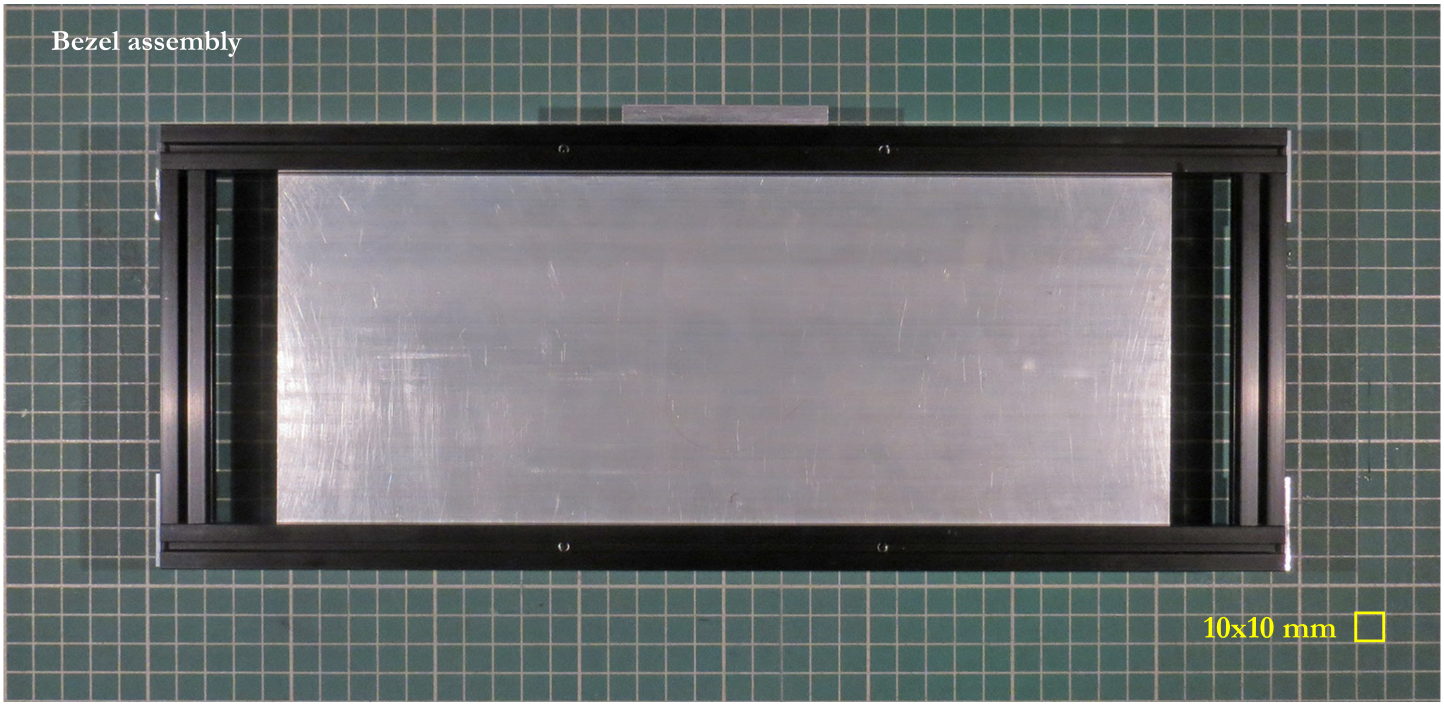


The image on the right illustrates how a profile (here a small surplus piece) is inserted on a screw head. A T-slot nut such as the one visible on the right can be inserted similarly.

Hint: Keep a short profile section like the one in the picture that you can use to pre-adjust the screws and nuts height before sliding the long sections.

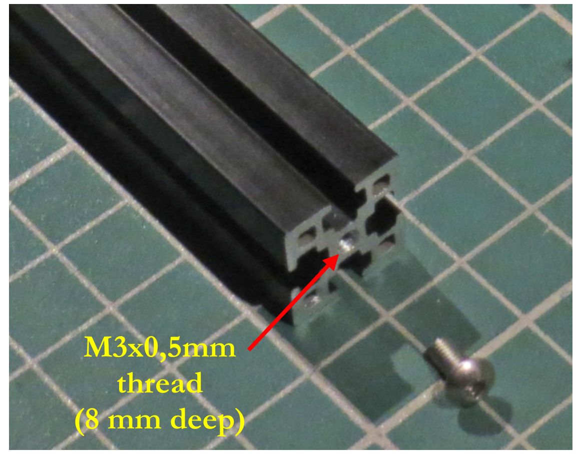
The images on the next page show the fully assembled bezel fixed to the heatsink base.





Design variant: In the above design, since the smaller profile sections are sandwiched between the two long sections, and because the long sections positions are defined by the holes in the heatsink, this can result in the smaller sections being slightly too short (a gap will show) or slightly too long (they will not fit). There are two solutions to this potential problem: wait until the long sections are fixed on the heatsink to determine the exact size of the short sections, or change the design so that the long sections are inserted between the shorter ones. Here we added an extra 1 mm to the short sections before making final size adjustments. If you decide to change the "sandwich" direction, and if you want to keep the same bezel size, the longer sections would have to be 340 mm in length (=370-30) and the shorter sections would be 145,2 mm in length (=115,2+30).

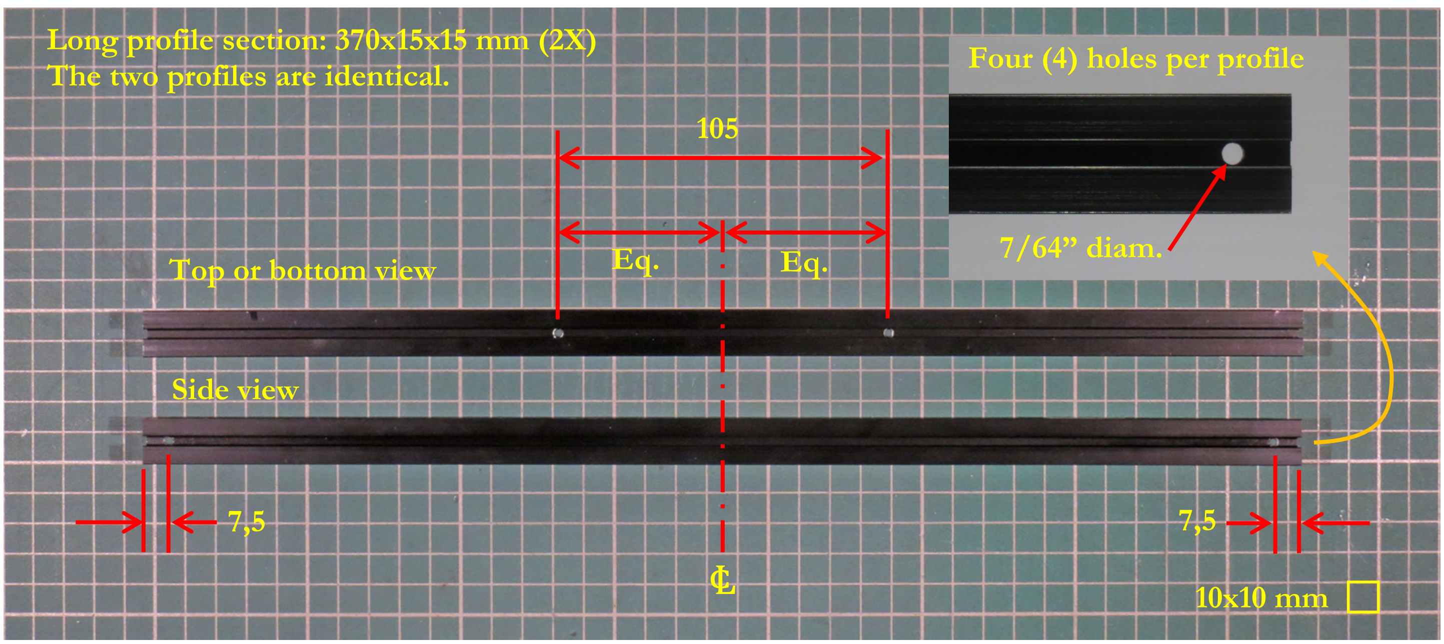
4.2 Profile machining



All MakerBeamXL profiles are shipped with a M3x0.5mm thread in the center hole at each end, as shown on the picture at the right. This thread is about 8 mm deep. Of course, if you cut the profile the new end pieces are not threaded. In our design we need the ends of all sections (short and long) threaded, so we used a standard M3 tap for this task (see the Drill bits and taps appendix for an image of this tap). It is also possible to purchase custom cut and threaded profiles from MakerBeam.

We also need to drill four holes in each long section. These holes are "pass-throughs" for an Allen key, i.e. hex key, to be used to tighten the screw heads located within a profile slot. This assembly method, called a blind fastener, is illustrated on the MakerBeam Web site (no purchase necessary if you have a drill bit, screws, and a hex key!): https://www.makerbeam.com/90-degree-blind-fastener.html .

The positions of the holes are shown in the picture below. The extrusions are identical but the profile identified by "Side view" is rotated 90 degrees relative to the profile identified as "Top or bottom view" to show the holes near each profile extremity.

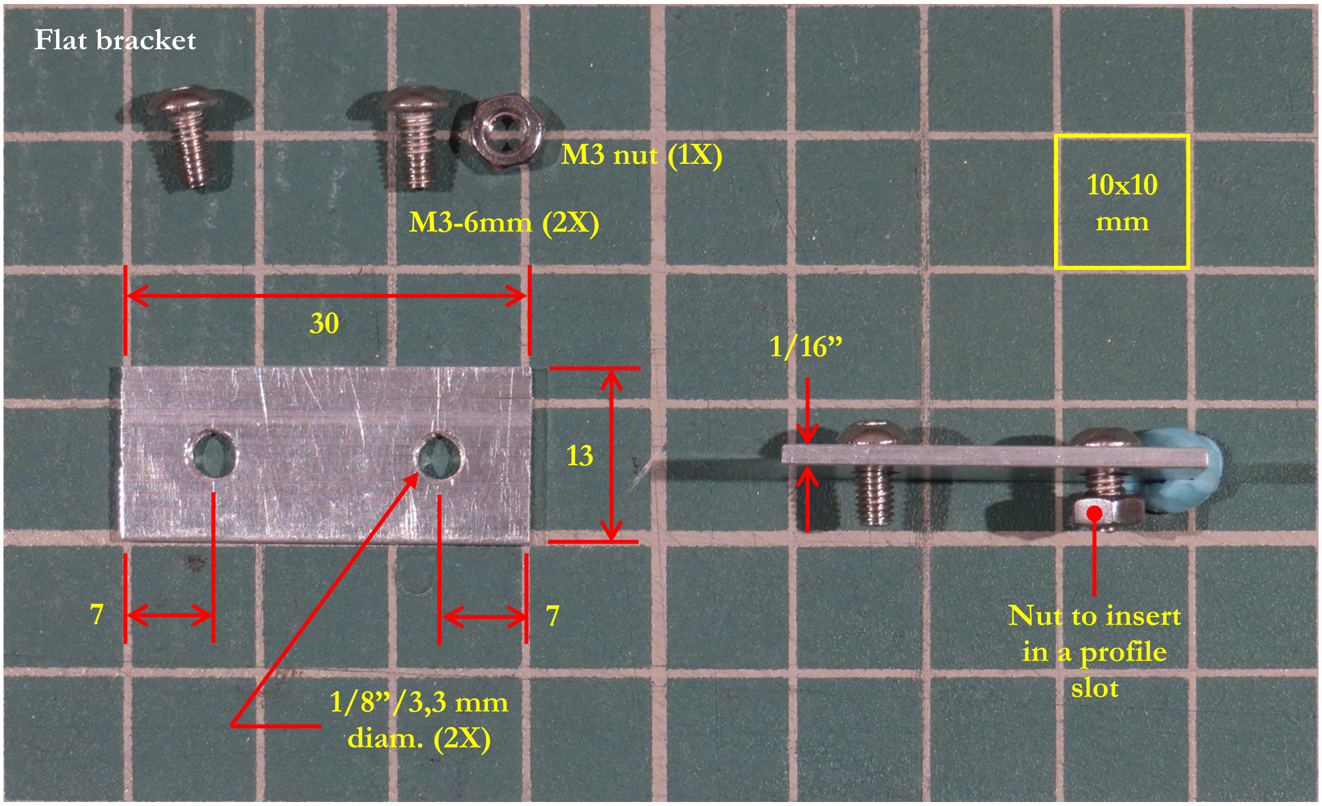


In the top view, the two holes are positioned relative to the center of the profile. The 105 mm separation corresponds to the fan assembly holes as described in the Heatsink assembly section. You need to use these holes to secure the screws that hold the Fan holder brackets on the other side of the heatsink (the side with cooling fins).

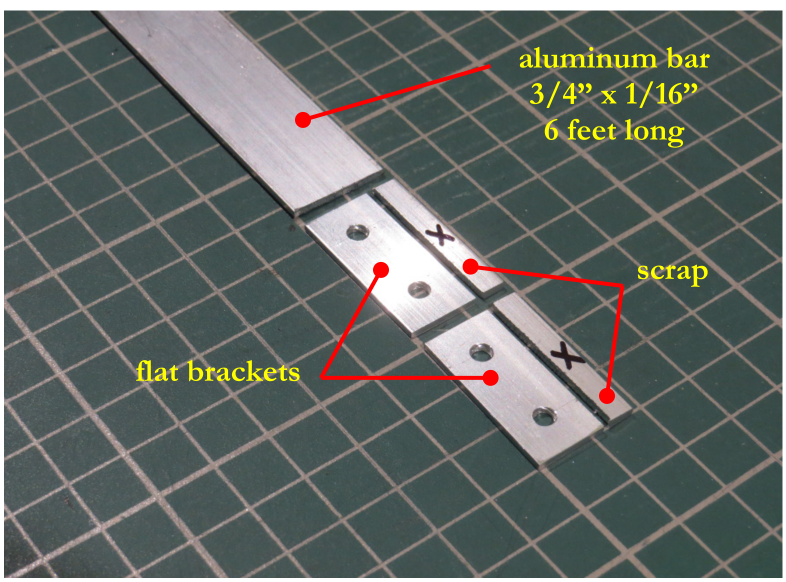
The holes visible near the extremities of the profile in the side view are used to secure the screws going into the **threaded** short profiles ends (as shown in the picture on the top of this page).

4.3 Flat bracket

The purpose of the flat bracket is to prevent the rotation of the short sections along their axis[13] and to improve the rigidity of the bezel structure. The bracket design and dimensions are shown in the picture below:

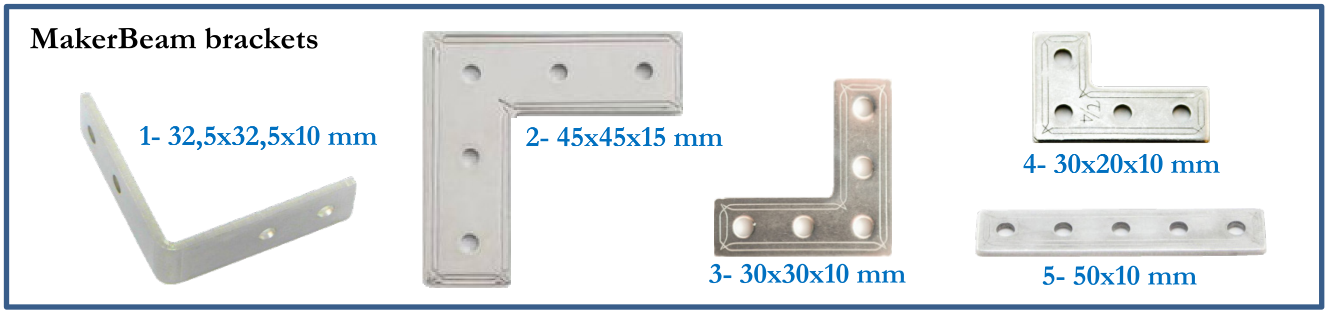


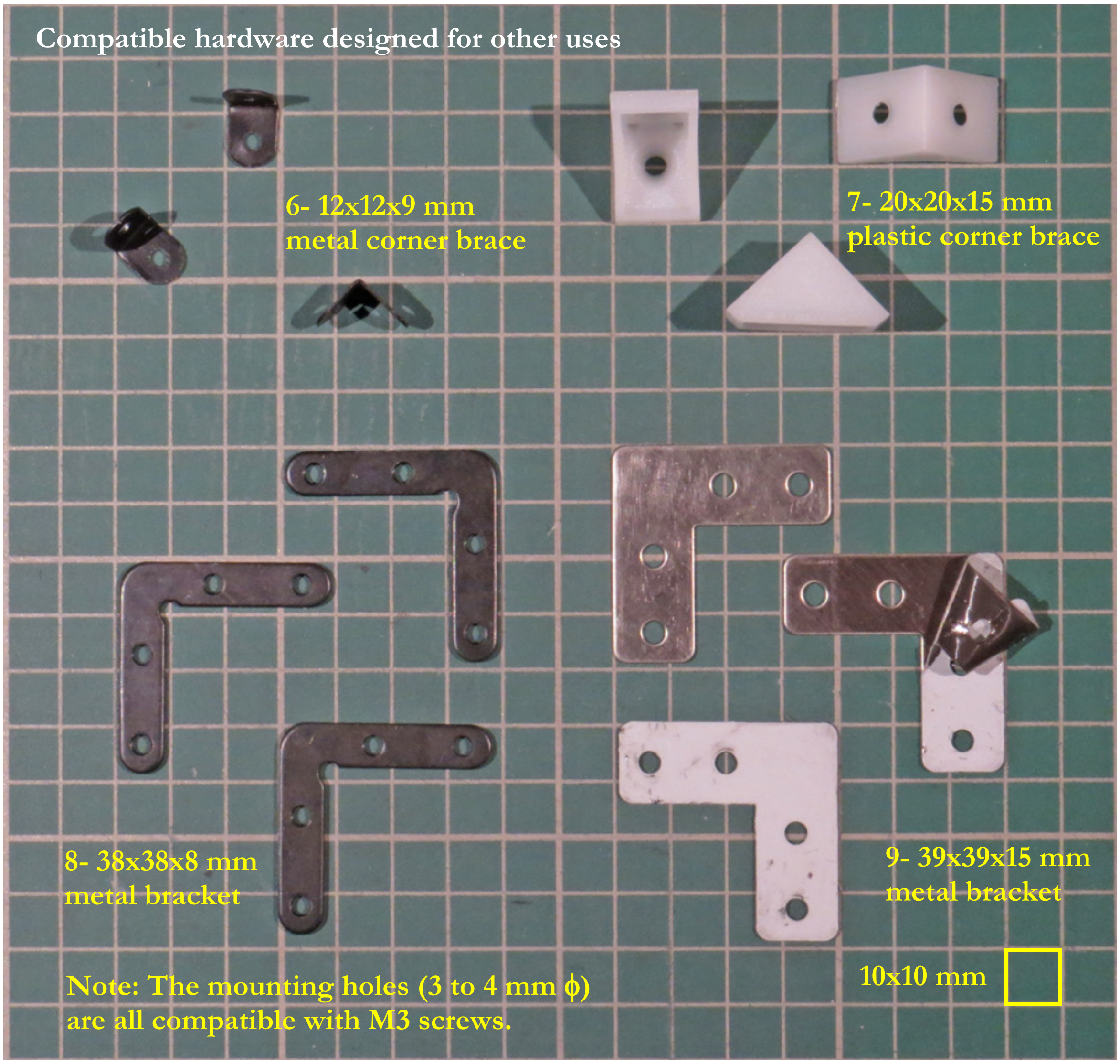
The bracket was (hand) machined from a thin aluminum bar available at home hardware stores.



There are many off-the-shelf fasteners which can be used to attach two profiles at a 90 degrees angle. MakerBeam offers a variety of models and some brackets designed for other uses are also compatible. Examples with Internet links are provided on the next page.

[13] This is a consequence of using blind fasteners, located near the end of the long sections, which hold the short sections from a threaded hole in the center of the profile (shown in the top picture in the Profile machining section).



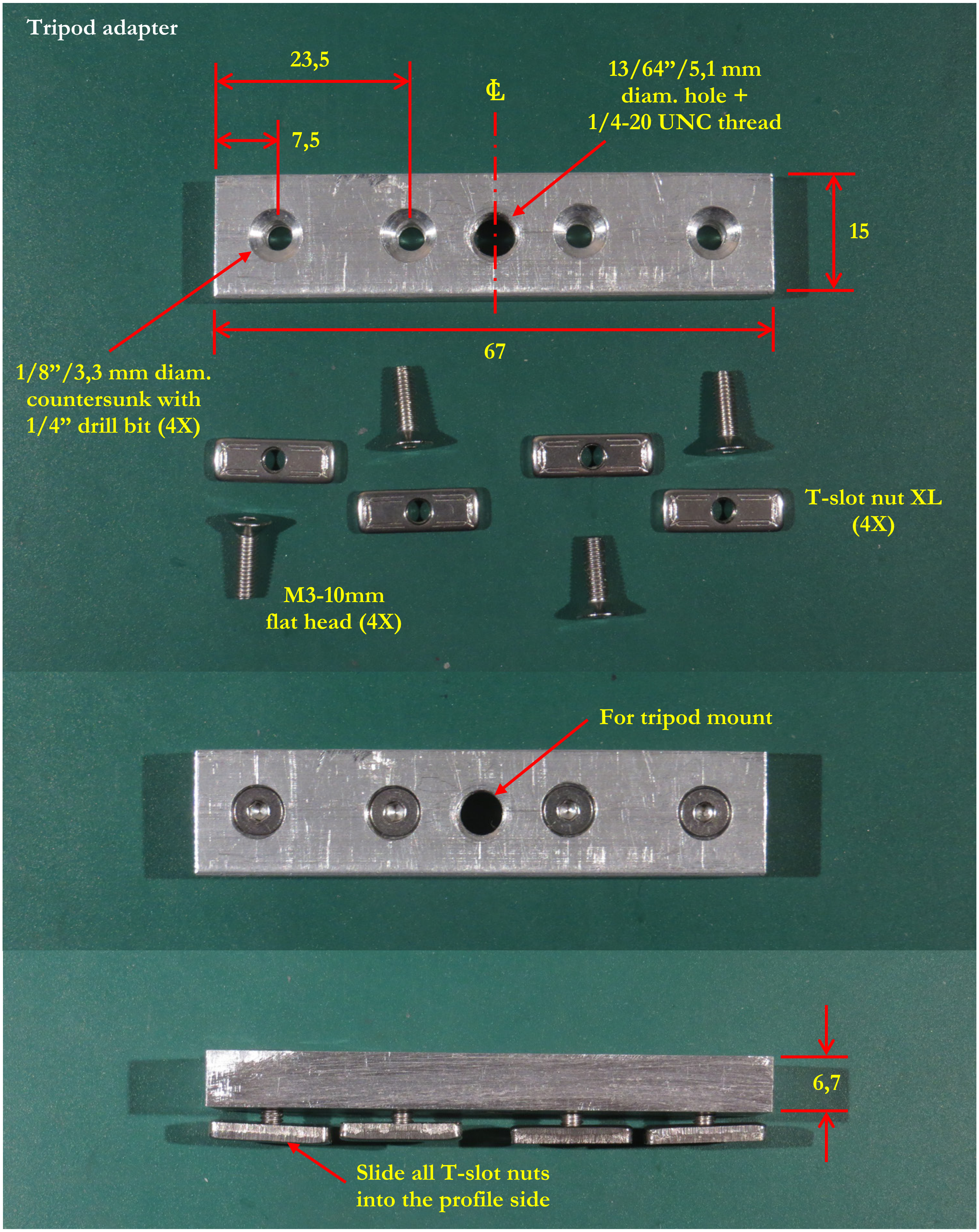


1- MakerBeam corner bracket 32,5x32,5x10 mm
2- MakerBeam XL right angle bracket 45x45x15 mm
3- MakerBeam right angle bracket 30x30x10 mm
4- MakerBeam right angle bracket 30x20x10 mm
5- MakerBeam straight bracket 50x10 mm
6- Amazon: uxcell 50pcs Angle Bracket Metal 12x12 mm Metal Black Corner Brace with Screws[14]
7- Amazon: uxcell 20pcs Shelf Cabinet Door 90 Degree Plastic Corner Braces 2 Holes Angle Bracket
8- Amazon: uxcell 25pcs Flat Right Angle Bracket 38x38 mm Metal Black Corner Brace with Screws
9- Amazon: uxcell 12pcs Angle Plate Corner Brace Flat L Shape Repair Bracket 39x39 mm

[14] The provided screws are designed for wood use and cannot be used with MakerBeam profiles.

4.4 Tripod adapter

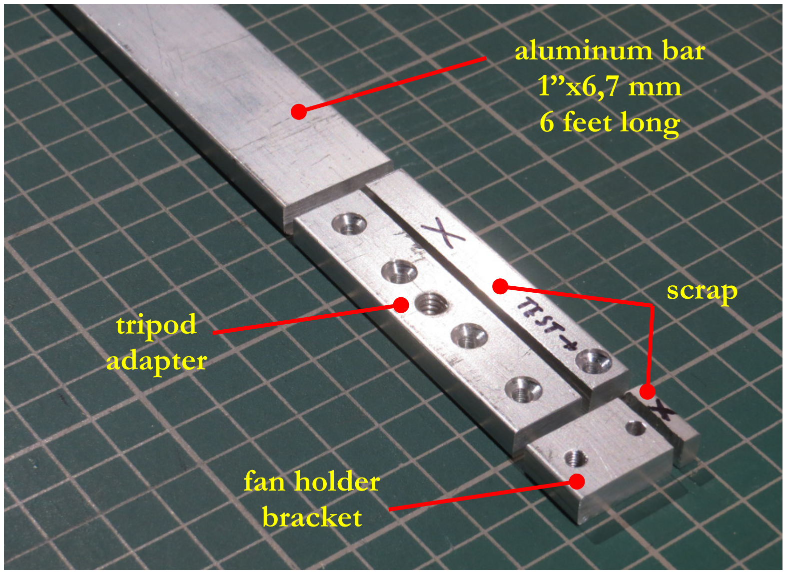
Instead of designing a custom lamp support structure, we decided it was simpler (and less costly) to just add a camera tripod adapter since many users of such a high quality lamp are also photographers. The adapter design and dimensions are shown in the pictures below:



Note: The four (4) T-slot nuts could be replaced by standard M3 nuts for cost or availability reasons but we do not recommend it since this adapter supports the entire lamp with its bezel and heat sink assembly.

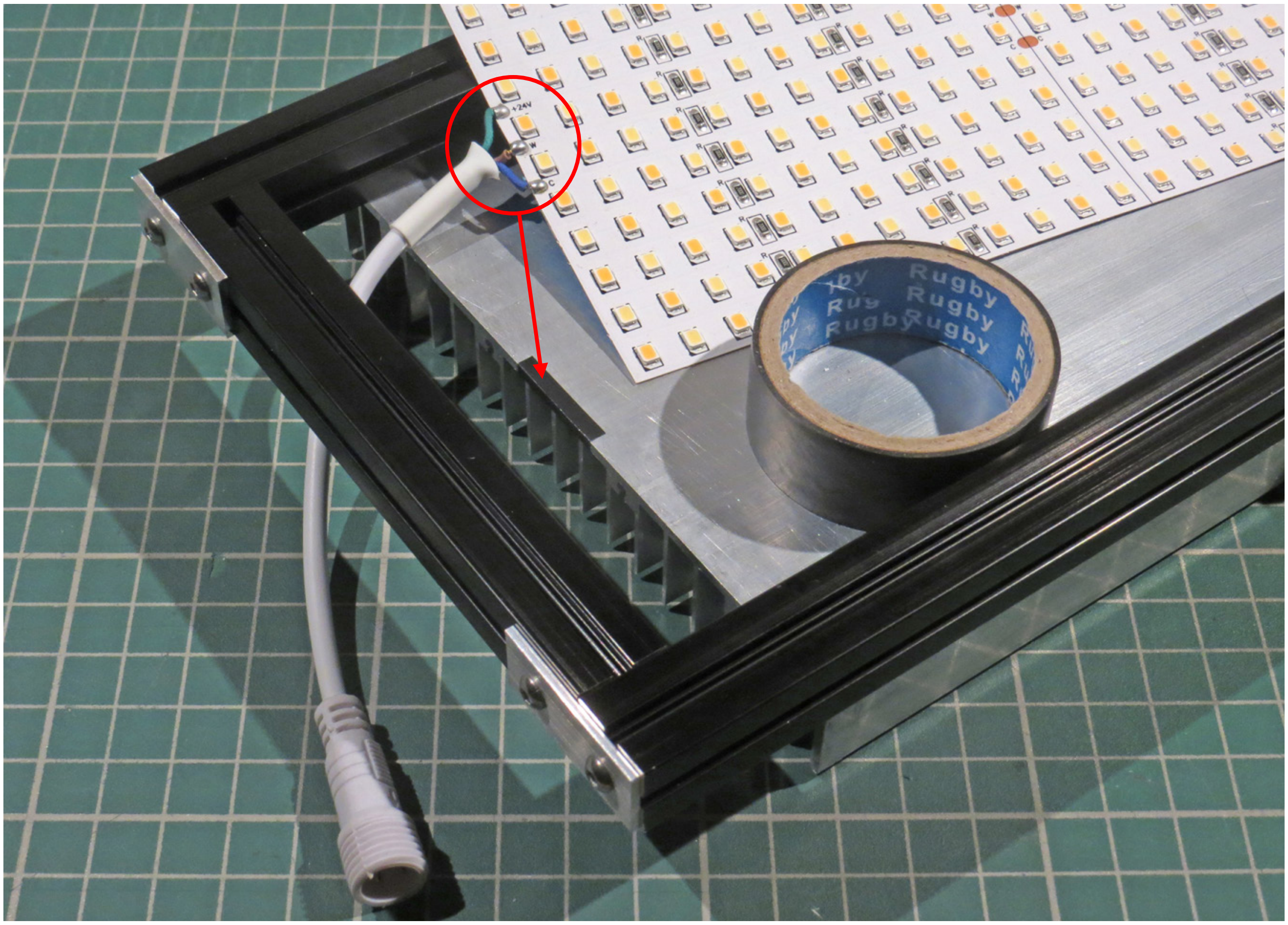
Note: The 1/4-20 UNC tripod mount thread is found on most consumer tripods and cameras although larger professional equipment may use 3/8-16 UNC threads.

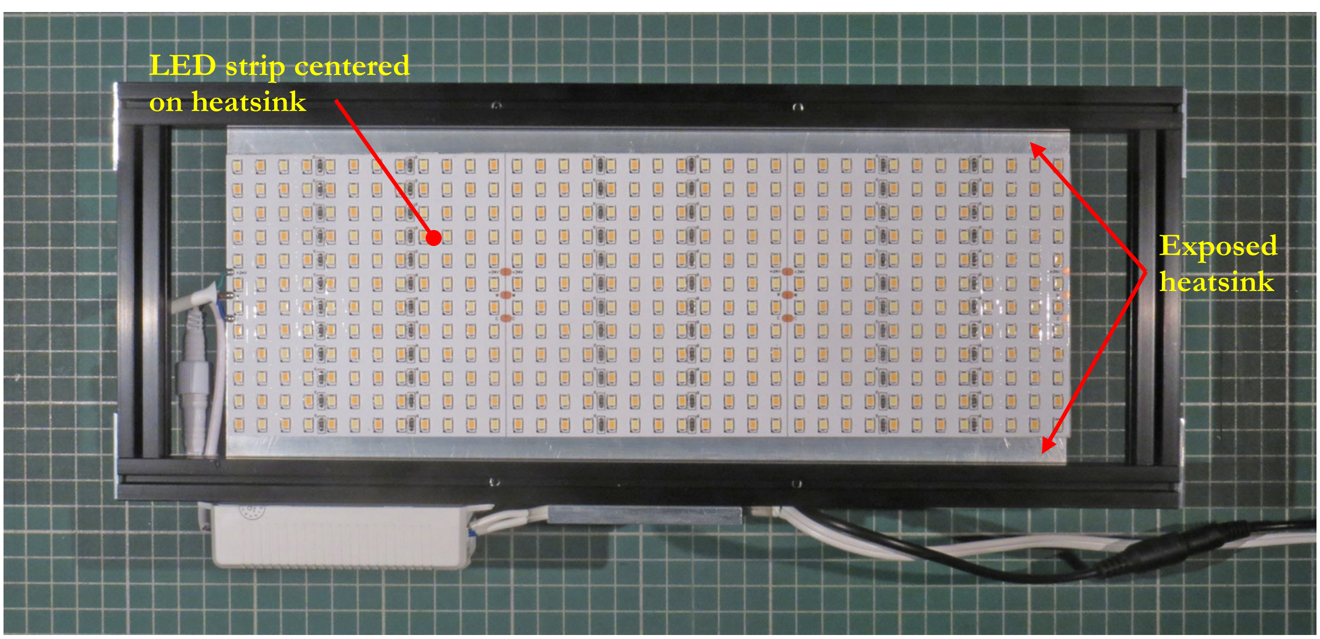
The bracket was (hand) machined from an aluminum bar available at home hardware stores.



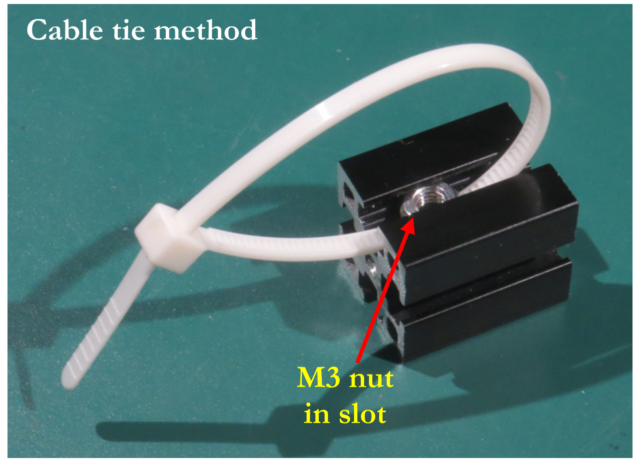
5. Final assembly/Integration

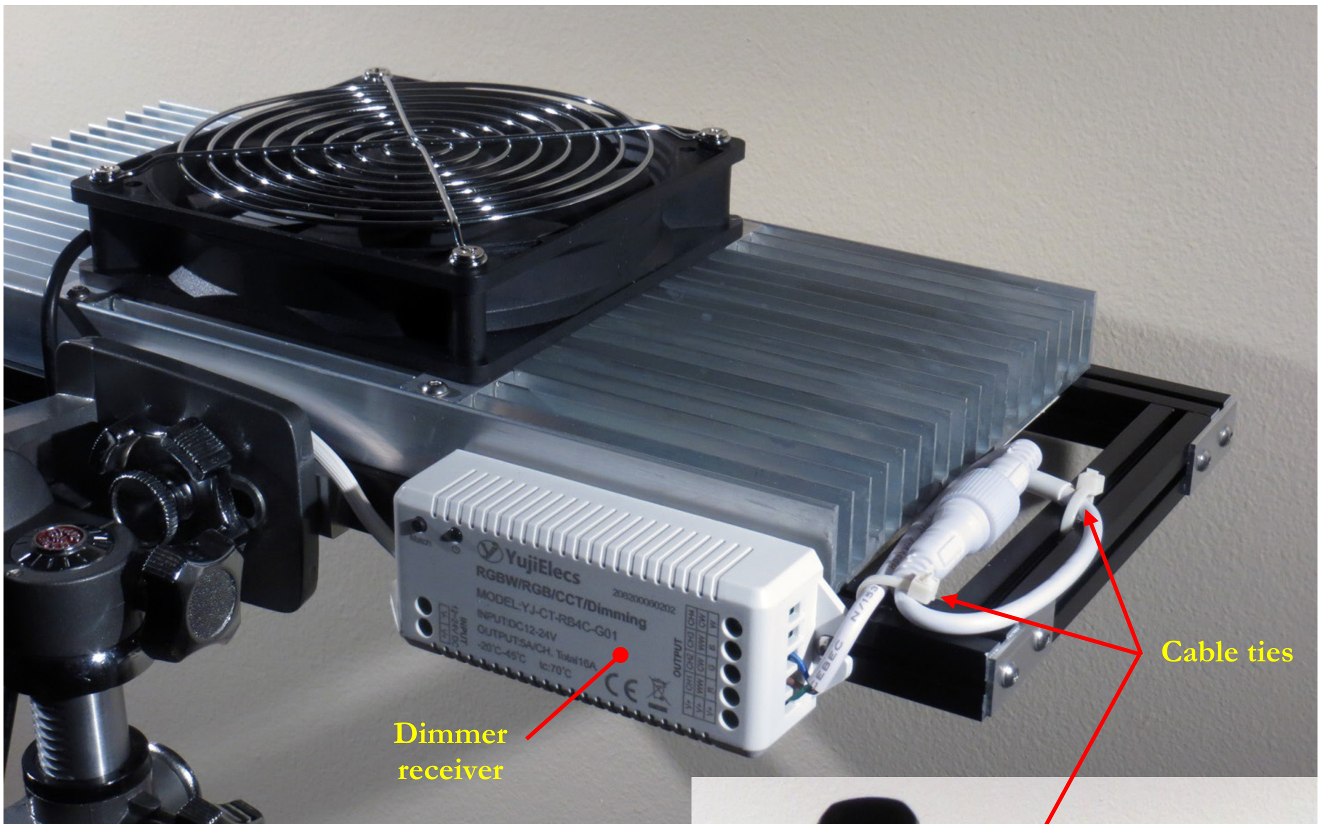
In this section we fix the LED strip on the heatsink and we attach the remote control receiver/dimmer on the bezel. The picture below shows the LED strip just before we removed its backing film which protects the adhesive. You can see where the wires are attached to the strip and in order to prevent an eventual contact between a wire and the heatsink, we placed a small piece of electrical tape on the heatsink surface and edge.



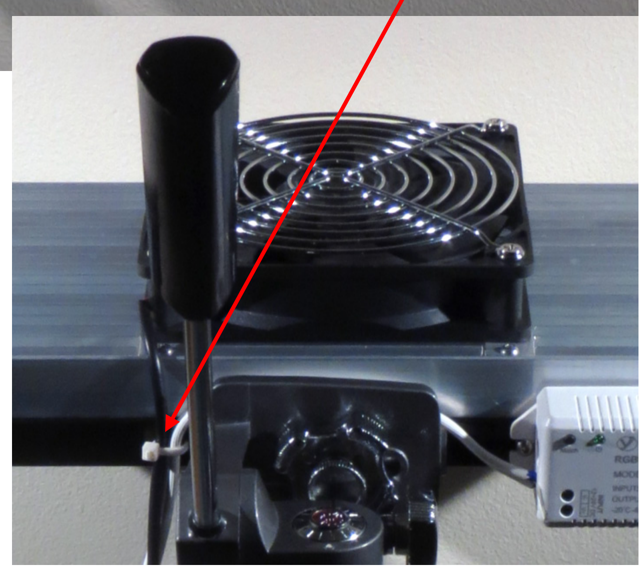


With the LED strip bonded to the heatsink we secured the strip cable to minimize stress and prevent breakage. We used cable ties held by M3 nuts located within the profile slot; this simple "revolutionary" (!) fixation method is illustrated in the picture on the right and examples of its use on the illuminator are shown in the pictures below. Two cable ties secure the LED strip cable while a third cable tie holds the fan and dimmer power supply cables. You will also note that we attached the dimmer receiver to the bezel; we used an M3-6mm screw on each side of the receiver with a matching nut in the profile slot.





This completes the assembly of the illuminator for the purpose of this tutorial. You may wonder what happened with the [dimmer power supply](#) and the [fan speed control](#). Well, since these two components can be located farther away from the lamp head, they could be placed in a dedicated enclosure with a proper ON/OFF switch, or simply left as is, connected to a power bar (with secure electrical connections of course). As many teachers would say when the remainder of the work is not the main subject, I will leave this as an exercise… but you can always have a look at [Appendix E](#) for one possible solution!



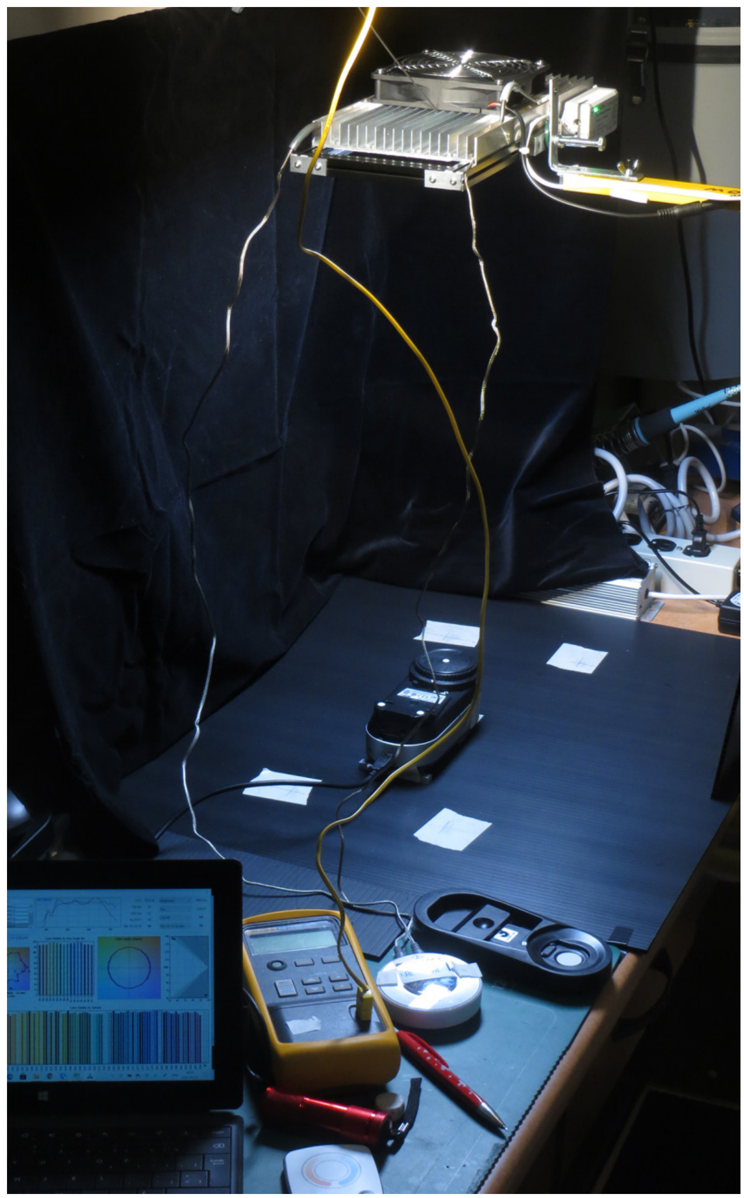
6. Illuminator characterization

This section covers the measurements taken to characterize the illuminator design. It starts with a short description of our test setup. However, before going directly to the colorimetric performance section, we consider it is important to demonstrate the temperature stability of the design since this will affect all subsequent measurements.

This section is separated in five sub-sections:

- Test setup
- Heatsink performance
- Colorimetric performance
- Brightness uniformity
- Dimmer performance

6.1 Test setup



The lamp was tested in a setup where there was no light from an external source, either natural, such as through a window, or artificial, i.e. another lamp. The only other light source in the room was from a laptop whose display was oriented away from the measurement area. An image of the setup is shown on the right.

A black velvet curtain was placed in front of the wall and partially on the sides of the test area. A black Coroplast® sheet was placed at the bottom of the area, under the measuring instrument (an i1Pro 3 spectrocolorimeter from X-Rite®).

The lamp was positioned parallel with the measuring surface and the distance between the LED strip and the ambient diffuser input window on the instrument was set at 500 mm. We "shimmed" the instrument so that its diffuser surface was parallel to the LED strip and measurement area planes.

The presence of potential parasitic reflections was verified using either a white or a black sheet of plastic which was positioned at different locations. For example, we positioned a black sheet on the sides not protected by the velvet and compared measurements with and without the sheet;[15] no variation was seen for the sides and this explains why the setup is opened. We also did a test with a white sheet on the bottom of the area; it did influence the measurements but only slightly since this is a "second order" effect where the light bounces back up to the LED strip circuit board and down again to the detector.

The wires going to the lamp are temperature probes positioned at the center and on the edges of the heatsink.

[15] Be careful with shiny black plastic since it can still reflect light; adjust its orientation so that the reflection of light emitted by the illuminator is directed away from the test area.

6.2 Heatsink performance

As we mentioned in the Heatsink design section, the use of a passive heatsink is absolutely required with an LED strip and active, or forced, cooling was said to bring more stability in light output and spectral characteristics. Here we present the results obtained with and without active cooling.

Experimental method

We measured three parameters: temperature (in °F and °C), brightness (lux), and CCT (kelvin). The LED strip was adjusted for 5000 K using the remote control color ring (5000 K was the goal and we achieved 5022 K according to our spectrocolorimeter). The LED brightness was set at its maximum. The starting conditions are:

i- Temperature: 71°F /22 °C
ii- Brightness: 1880 lux (500 mm distance, in the output field center)
iii- CCT: 5022 K

Fan setting

The fan we selected comes with a variable speed controller with which the voltage can be adjusted between 3 and 12 V DC. According to one source for this fan, it has the following performance in relation to voltage:

Voltage (V DC)	Speed (RPM)	Airflow (CFM)	Noise (dBA)
3	1000	46	18
5	1500	56,8	23
12	3000	114	49

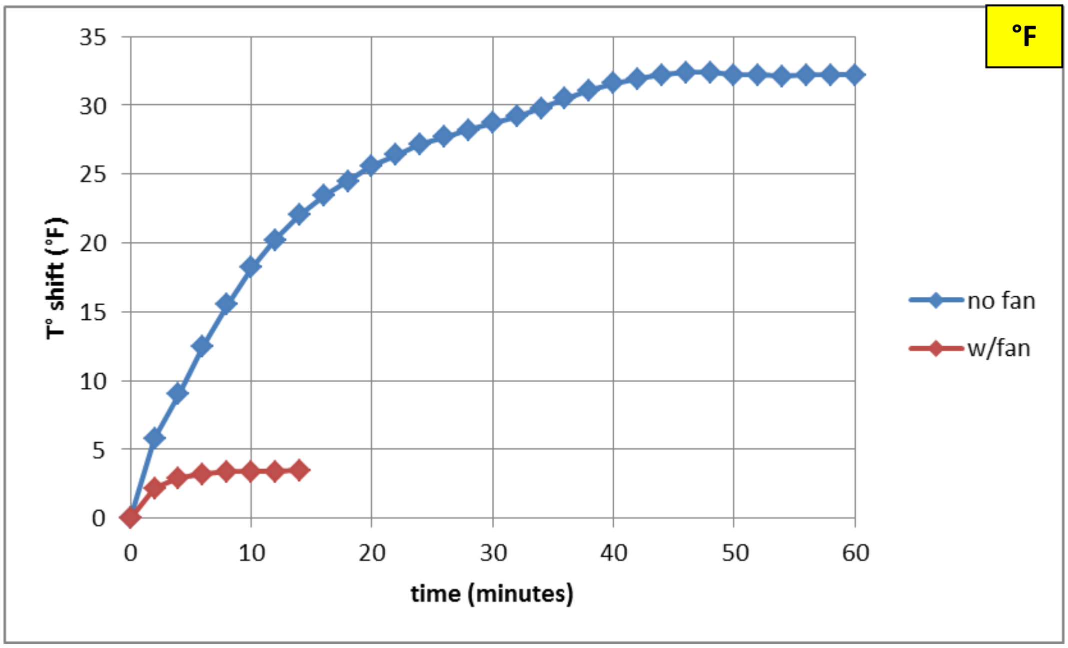
A lot of air is moved at full power and the fan becomes noisy. The maximum speed also appeared excessive for the heat load, even before making measurements, so we made our tests using a rather low setting, as shown on the picture on the right. The output voltage corresponding to this setting is 4,5 V DC. From the specification data table shown above we evaluate this voltage corresponds to a fan speed of about 1400 RPM, a 53 CFM airflow, and a 22 dBA noise level. While we can still hear the fan, we forget its presence quite rapidly; yet, we can easily sense airflow if we place a hand on either side of the lamp, at the heatsink fins level.

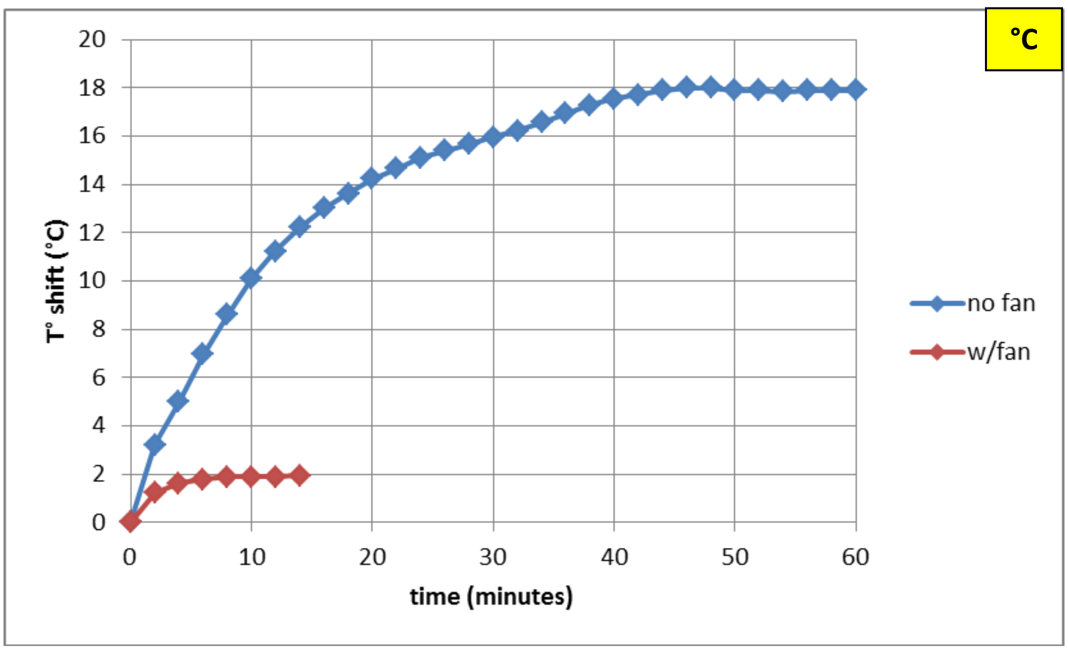
Click on a link to jump to a specific result or for the conclusion:

- Temperature Shift vs Time
- Brightness Shift vs Time
- CCT Shift vs Time
- Heatsink performance conclusion

Heatsink performance: Temperature Shift vs Time

The following graphs show the temperature variation with time, from startup.

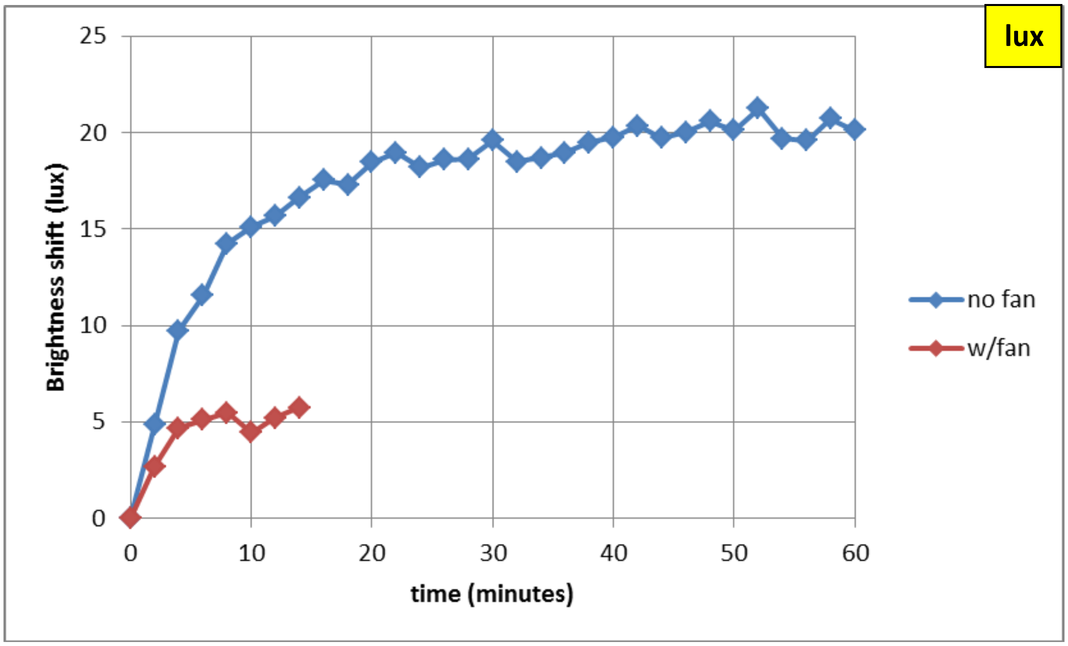


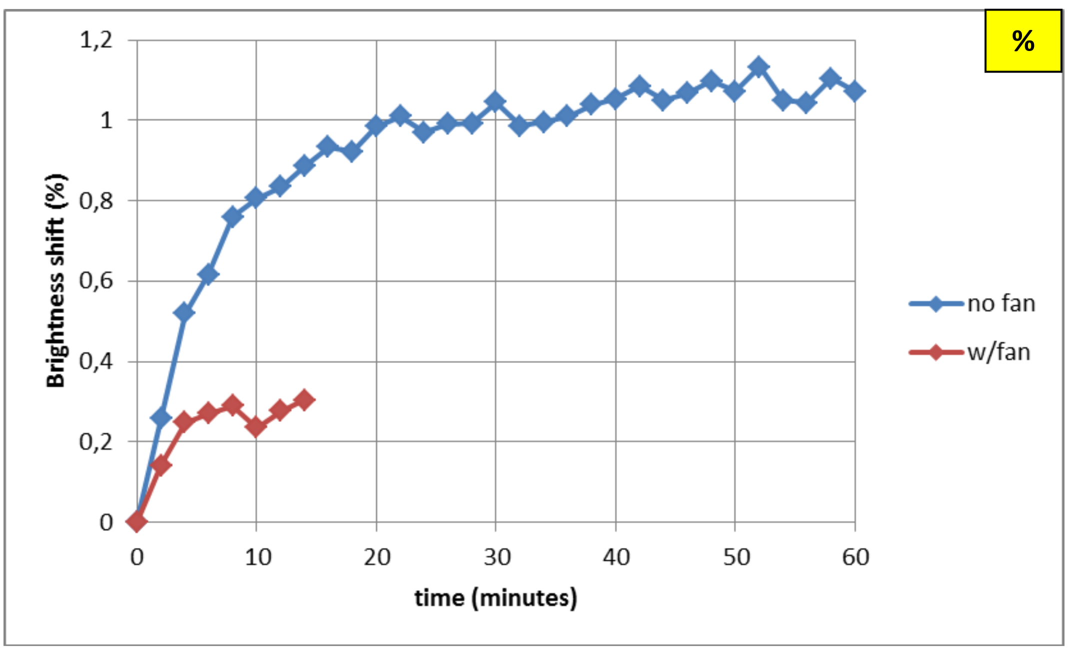


With no fan the temperature stabilizes in about 45 minutes and the LED strip temperature is about 32,5 °F /18 °C above ambient temperature (71°F /22 °C). With a fan the temperature stabilizes in 5 minutes and the LED strip temperature is only 3,5 °F /2 °C above ambient temperature.

Heatsink performance: Brightness Shift vs Time

The following graphs show the brightness variation with time, from startup.

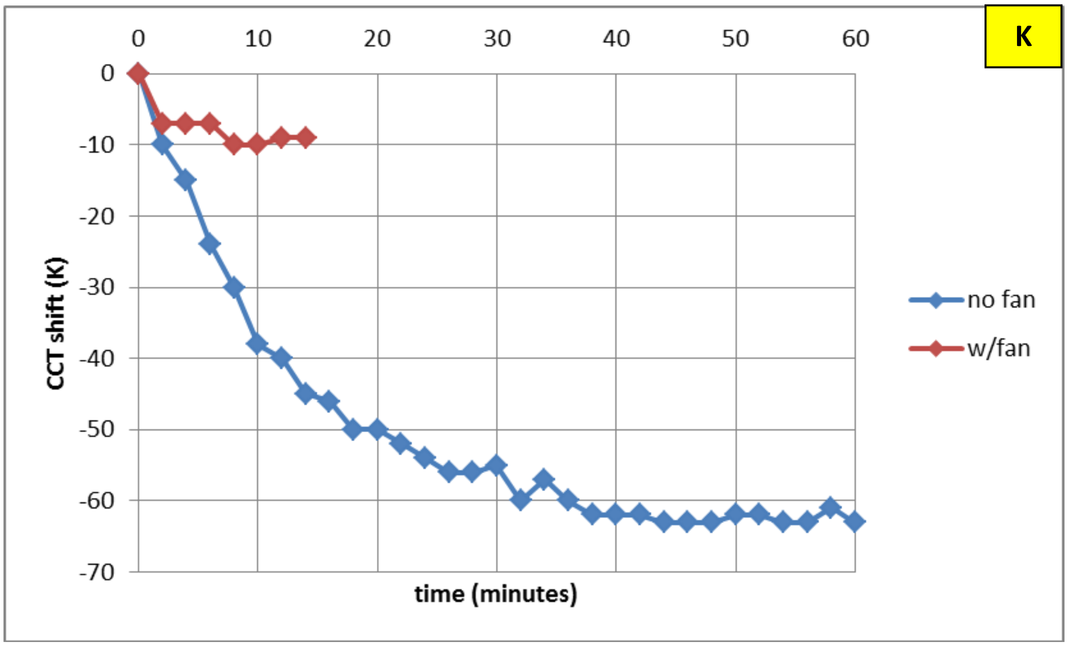




The brightness shift with time closely mimics the temperature stabilization behavior. With no fan the brightness stabilizes in about 45 minutes and shows an increase of 20 lux / 1,05% relative to the brightness at startup (1880 lux). With a fan the brightness stabilizes in 5 minutes to about 5,2 lux / 0,28% above the startup brightness.

Heatsink performance: CCT Shift vs Time

The following graph shows the CCT variation with time, from startup.



The CCT, like the brightness, correlates perfectly with the temperature variation, except that the CCT shift is negative whereas the brightness shift is positive when the temperature increases. With no fan the CCT stabilizes in about 45 minutes with a decrease of about 63 K relative to the CCT at startup (5022 K). With a fan the CCT stabilizes in 5 minutes to about 10 K less than the startup CCT.

Heatsink performance conclusion

The brightness and CCT are both strongly correlated to temperature variations and remain very stable when the temperature reaches an equilibrium point. Without a fan the heatsink becomes warm to the touch, the brightness increases by about 1% and the CCT decreases by 63 K. In all fairness, these changes are not catastrophic per say and could be tolerated for some uses, particularly so when the ambient temperature is not high.

With a fan, the heatsink temperature increase is essentially not noticeable to the touch, the brightness stabilizes to 0,28% of the initial value, and the CCT decreases by about 10 K. The brightness and CCT shifts are so low that, in practice, the illuminator can be used immediately after starting it at full brightness. The improvement brought by even a small amount of forced air is such that it removes any concern related to illuminator stability.

6.3 Colorimetric performance

The LED strip comprises two banks of LEDs, in equal quantity (216 per set), which have a nominal CCT of 2700 K and 6500 K respectively. The actual CCT of each set will vary with production lots. The low temperature set is usually referred to as Warm White (**WW**) and the high temperature set as Cool White (**CW**), a nomenclature which is related to how the light output is perceived and not the CCT value.

It is possible to obtain all CCTs between the WW and CW values by mixing the two banks in varying proportions. The table below shows the colorimetric and color rendering characteristics of the WW and CW banks used alone as well as when mixed to obtain many target CCTs. You will find detailed TM-30 reports for each CCT farther in this section after a description of each parameter in the table and how the luminaire performed relative to it.

Experimental method

Using the color ring on the dimmer to set the CCTs as close as possible to the target ones requires patience! With luck many target values could be obtained in a minute or so but a few took more than five minutes of fiddling with various finger moves on the dimmer color ring.[16] We used the "Tune" mode in the ISO3664+ tool of BabelColor CT&A to make continuous measurements while changing the CCT with the color ring. Once the CCT was set, we used CT&A's CRI tool to get the measurements shown in this section.

CCT stability

Once set, it takes a few seconds to get all the data for a given CCT. Nonetheless, we checked that the CCTs could remain within 10 K for an hour or more, confirming the results presented in the Heatsink performance section.

Experimental results

Target CCT (K)	Meas. CCT (K)	*Duv*	Bright. (lux)*	TM-30-18 / TM-30-20							CIE 13.3		ISO 3664	ISO 23603
				Rf	*Rf,h1*	*Rg*	*Rcs,h1* (%)	Px	Vx	Fx	*Ra*	*R9*	*u'v'* offset	*MIv*
WW	**2841**	**-0,0004**	**1758**	**94,8**	**97**	**99,8**	**0,9**	**P1**	**V3**	**F1**	**94,6**	**94,4**		
3000	3015	-0,0021	1758	95,3	96	101,1	1,4	P1	V3	F1	93,9	89,1	0,0029	
3200	3201	-0,0033	1771	95,4	96	101,9	1,9	P1	V3	F1	93,2	84,1	0,0041	
3500	3499	-0,0044	1789	95,3	95	102,5	2,6	P1	V3	F1	92,5	77,8	0,0053	
4000	3996	-0,0048	1812	95,0	94	102,7	3,3	P1	V3	F1	92,0	71,0	0,0053	
4100	4099	-0,0048	1816	95,1	94	102,7	3,3	P1	V3	F1	92,0	70,0	0,0052	
4700	4711	-0,0038	1863	95,9	94	103,2	3,2	P1	V3	F1	92,4	67,7	0,0035	
5000	5014	-0,0030	1891	96,0	94	103,3	3,3	P1	V3	F1	92,5	68,6	0,0025	B/0,42
5500	5506	-0,0016	1934	95,9	93	102,8	3,4	P1	V3	F1	93,0	68,7	0,0004	B/0,49
6000	5999	0,0000	1974	96,0	94	102,2	3,2	P1	V3	F1	94,0	71,1	0,0016	
6500	6498	0,0017	2014	96,1	94	101,5	2,8	P1	V3	F1	95,2	75,3	0,0036	C/0,65
CW	**6843**	**0,0028**	**2055**	**96,2**	**95**	**101,0**	**2,4**	**P1**	**V3**	**F1**	**96,2**	**79,0**		

*** The brightness and all other measurements were obtained by placing the instrument 500 mm from the LED strip, in the middle of the output beam. The intensity was at the maximum value for all CCTs.**

Results for the individual parameters are discussed next.

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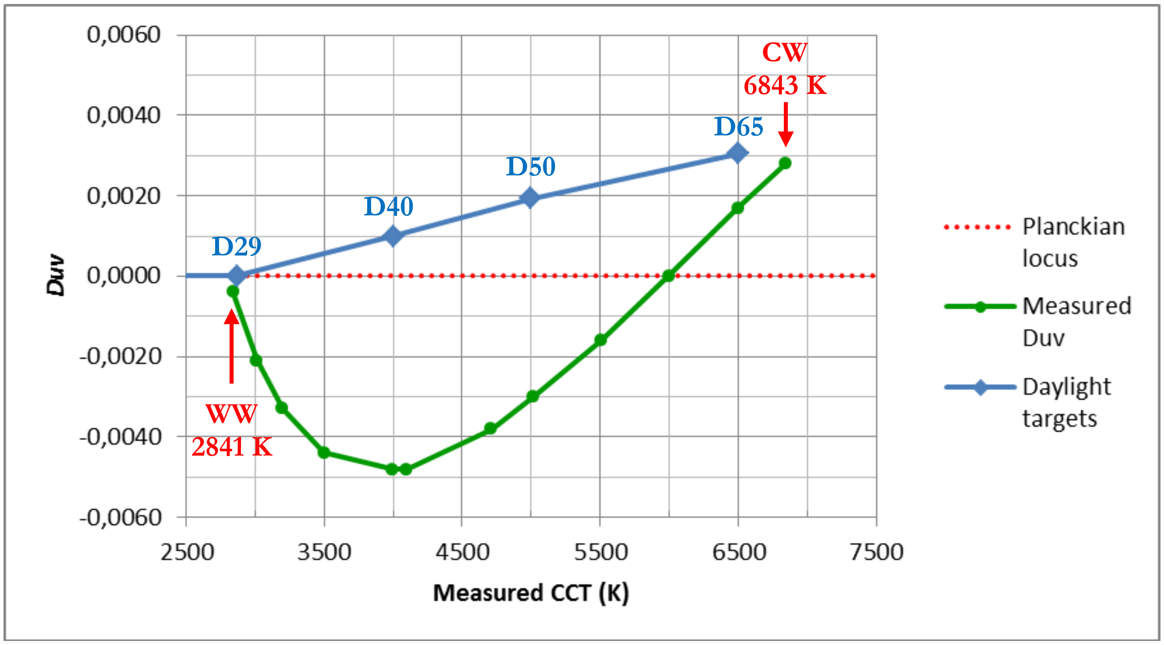
[16] We noticed that the remote control color ring became insensitive if the remote control is not used for 18 seconds; pressing either brightness button makes it responsive again.

Duv

This number is the distance between the chromaticity[17] of the measured light source and a perfect blackbody of the same CCT. The coordinates of the blackbodies at all temperatures define a reference curve called the Planckian locus so, in other words, *Duv* is the distance between the measured source chromaticity and the Planckian locus. For a perfect blackbody, *Duv* is zero; this is represented by the red dotted line in the graph below. When the source chromaticity is higher than the Planckian locus, *Duv* is shown as a positive number, and as a negative number when located below the Planckian locus. In the graph, the green curve represents the measured *Duv* values corresponding to the measured CCTs. The data points associated to the two LED banks, WW and CW, are identified by arrows.



According to **ANSI C78.377-2015**, acceptable *Duv* values should be within ±0,0060 of the **target** chromaticity. Here, since all our targets are specified as **blackbodies** and **not daylight illuminants**, the target *Duv* is zero and we can easily see that the measured values are all within the chromaticity limits.

However, if we had specified daylight illuminants instead of blackbody illuminants, the targets would not be on the Planckian locus but slightly above, with the offset growing as the CCT gets higher.[18] This is illustrated by the blue curve. According to ANSI C78.377 Table 1, the daylight curve is identical to the blackbody curve below 2870 K after which they diverge steadily. In general, we see daylight illuminants starting to be used as a reference somewhere between 4000 K and 5000 K, where the chromaticity difference between the two curves becomes noticeable.

Four points are highlighted on the Daylight curve. The first one is at 2870 K, or D29 if we specify the daylight version; since both illuminants are located on the Planckian locus, they are essentially identical (even though their detailed spectrums will be different). The three other points correspond to target CCTs of 4000 K (D40), 5000 K (D50), and 6500 K (D65). Interestingly, even if we use the blue daylight curve as our target instead of the Planckian curve, our *Duv* results are still within the ±0,0060 tolerance.

---

[17] *Duv* is computed from the coordinates in the **CIE 1960 u-v Chromaticity Diagram**.

[18] In ANSI C78.377-2015 Table 1 the equation for the **target** *Duv* of Daylight illuminants for $T \geq 2870$ K is
$Duv = 57700 \times (1/T)^2 - 44{,}6 \times (1/T) + 0{,}00854$.

TM-30-20 (IES, 2020)

The analysis of a light source using TM-30-20 (identical to TM-30-18) should not be associated with a single parameter, *Rf* for instance, but should consider combinations of two or three of these parameters:

- the Fidelity Index (*Rf*);
- the Fidelity Index of the first hue bin (*Rf, h1*);
- the Gamut Index (*Rg*);
- the Chroma Shift of the first hue bin (*Rcs,h1*).

The TM-30-20 Fidelity Index (*Rf*) is similar in scaling to the legacy CRI (*Ra*) of CIE 13.3 but more robust in terms of sensitivity to variations in the spectral structure of the test source. It is computed from 99 Color Evaluation Samples (CES) which, on average, cover the visual spectrum uniformly.

The 99 samples are grouped in 16 hue bins covering 22,5 degrees each in the chromaticity diagram; the fidelity index of each bin is labeled *Rf,h1* to *Rf,h16*. It was found that the red chroma which characterizes the patches of Hue Bins 1 and 16 (i.e. *h1* and *h16*), *is the strongest single predictor of subjective evaluations* i.e. it correlates well with the overall visual assessment of the test subjects. It is interesting to note the similarity in the importance of Hue Bin #1 and sample *R9* of CIE 13.3, with the difference that this Hue Bin is always included when computing the overall fidelity whereas *R9* was generally discarded.

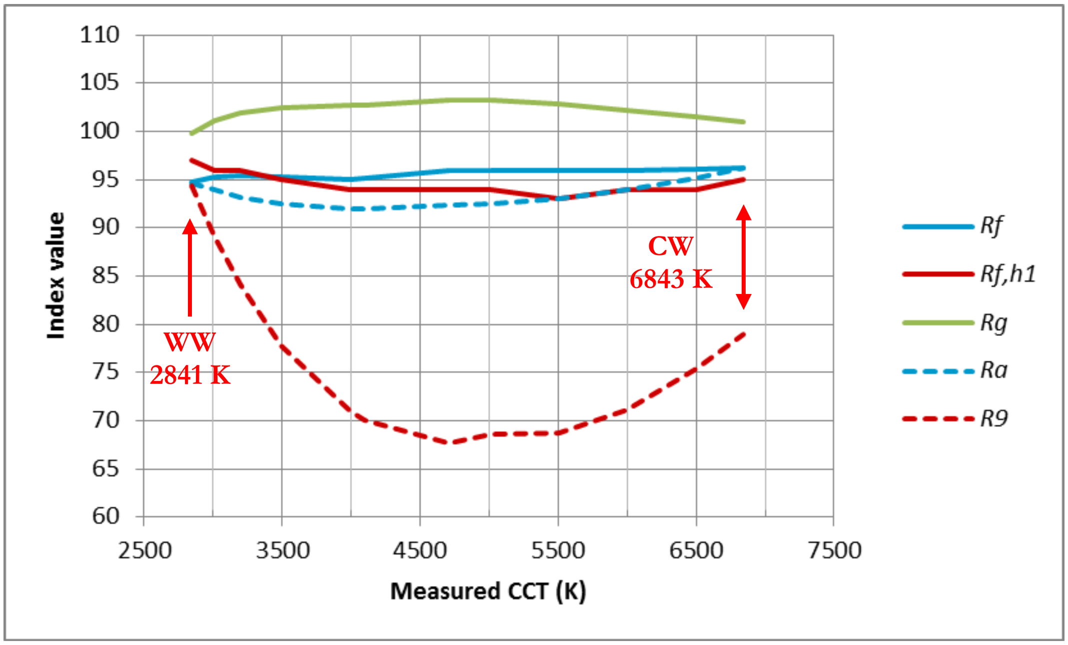
The gamut index, *Rg*, is the ratio of the gamut area of the Test source samples relative to the area covered by the Reference source samples. The areas are computed from the hue bins chromaticities in the CAM02UCS $a'_M b'_M$ plane. Finally, the Chroma Shift of the first hue bin, *Rcs,h1*, is also computed in the CAM02UCS $a'_M b'_M$ plane.

The four TM-30-20 parameters described above are then analyzed according to the required design intent of the light source. Three **Design Intents** are suggested in TM-30-20 Annex E: **Preference** (**P**), **Vividness** (**V**), and **Fidelity** (**F**). In addition, three **Priority Levels** are defined for each Design Intent, with "Level 1" being the most stringent. An analysis grid with the thresholds for each intent and level is presented in Appendix D. The analysis results for each source are presented in the table, in the Px, Vx, and Fx columns. In our case we are concerned only by the fidelity result since our application is critical color assessment. All CCTs meet the highest fidelity level (**F1**).

CIE 13.3:1995

The table shows *Ra*, the "good old" Color Rendering Index (CRI) computed with 8 color samples, as well as the more problematic *R9* special index, corresponding to a saturated red sample, which is not used in computing *Ra* since it can be really bad (and is often not provided by lamp manufacturers). Here the minimum *Ra* is 92, which is excellent, and the minimum *R9* is 67,7, which is not great but not a show stopper. The good *Ra* results are not surprising here since the TM-30-20 are excellent; the reverse is not always true and good *Ra* results are not a predictor of good TM-30-20 results.

(TM-30 and CRI 13.3) vs CCT
Now that we have looked at the TM-30 and CIE 13.3 indices numbers individually, let's see how they vary in relation to CCT. This is illustrated in the graph below.



We note that *Rf*, *Rf,h1*, *Ra* and *R9* are never higher than the maximum value from WW or CW.[19] For example, *Rf* is never higher than 96,2, the index for CW, and *Rf,h1* is never higher than 97, the index for WW. The behavior of the red hue bin, expressed by the *Rf,h1* index correlates somewhat with the *R9* special index of CRI 13.3 by showing a dip between WW and CW; however, the smaller extent of the dip conveys less of a potential issue than what *R9* seems to indicate. If you look at the fidelity of the 99 TM-30 samples in the 4700 K Color Rendition Report, you will not see a dramatic dip for any sample, including the reds, so we should be careful not to place too much emphasis to the *R9* results.

Overall these curves show that the colorimetric performance remains stable for CCTs obtained by mixing the WW and CW LED banks.

ISO 3664 *u'v'* offset
This is the distance between the targets and the measured chromaticities in the CIE 1976 *u'v'* chromaticity plane. The coordinates are computed using the 10 degree Standard Observer (CIE 1964). A tolerance of 0,0050 is specified in ISO 3664;[20] while it is specified for D50, we use it for all CCTs. Here we see that the measurements meet the requirement for most CCTs and, where they fail, in the 3500 K to 4100 K range, it is not by much. Please note that a blackbody was assumed as the reference for all CTTs and not a Daylight illuminant. If a Daylight illuminant had been specified for CCTs of 5000 K and above, i.e. as D50, D55, D60, and D65, the offset requirement would still be met for D55 ($\Delta u'v'$=0,0049), D60 ($\Delta u'v'$=0,0028), and D65 ($\Delta u'v'$=0,0008), but not for D50 ($\Delta u'v'$=0,0070). It should be noted that the measured 5000 K CCT spectrum is compared to a D50 reference spectrum when computing the color rendering and metameric indices (see next page), and these results are nonetheless excellent.

[19] Interestingly, the gamut index (*Rg*) values for the CCTs obtained by mixing (i.e. NOT WW and CW) are always higher than the maximum value between WW and CW (*Rg*=101,0 for CW).
[20] ISO 3664:2009: "Graphic technology and photography — Viewing conditions"

ISO 23603 (CIE S 012) Metameric Index (Visible)
This test assigns a Quality Grade to the measured illumination relative to an "ideal" daylight illuminant. This grade is expressed by a letter from "A" to "E", with "A" being the best grade. The grade is based on the average color difference between L*a*b* data obtained with a set of virtual metamers (i.e. theoretical reflection samples) and the measured ambient light, which is compared to the data obtained with the ideal illuminant. The relation between the Quality Grade and the MI value is shown in the table.

Quality Grade (QG)	MI
A	≤ 0,25
B	> 0,25 to 0,50
C	> 0,50 to 1,00
D	> 1,00 to 2,00
E	> 2,00

The standard contains reference metamers for D50, D55, D65, and D75. Both a visible and a UV MI are specified in ISO 3664 but only the visible MI (*MIv*) can be computed with an i1Pro series instrument.[21] ISO 3664 also specifies that illumination in the plane of viewing **shall** have a visible range metamerism index of less than 1,00 (QG "C" or better) and **should** have a visible range metamerism index of less than 0,50 (QG "B" or better).

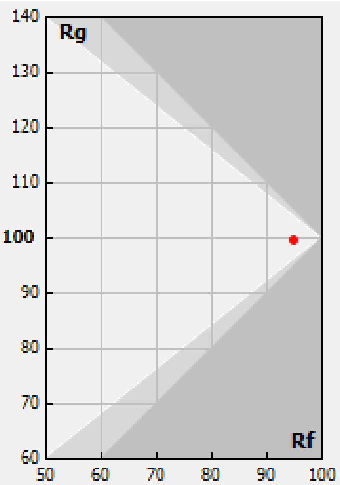
Using the LED strip, we were able to set the CCT close to 5000 K, 5500 K, and 6500 K. The spectrum for each CCTs was exported from the CT&A CRI tool and imported in the CT&A ISO 3664+ tools where we selected the "**P1: Prints: CRITICAL comparison**" viewing condition.[22] A "B" grade was obtained for both 5000 K and 5500 K, with a *MIv* value of 0,42 and 0,49 respectively, and a "C" grade was obtained for 6500 K (*MIv*=0,65). These *MIv* values surpass the performance of many light booths designed with fluorescent tubes, and easily meet the specification of the modern JUST LED moduLight color proofing luminaire (which is *MIv* ≤ 0,8).

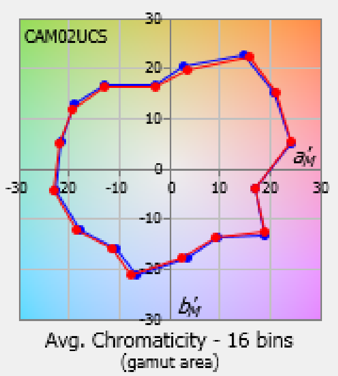
TM-30 reports
Click on a link to jump to a specific TM-30-18/TM-30-20 report. You will notice that all spectral graphs in our measurements clearly show light content in the violet range above 400 nm.

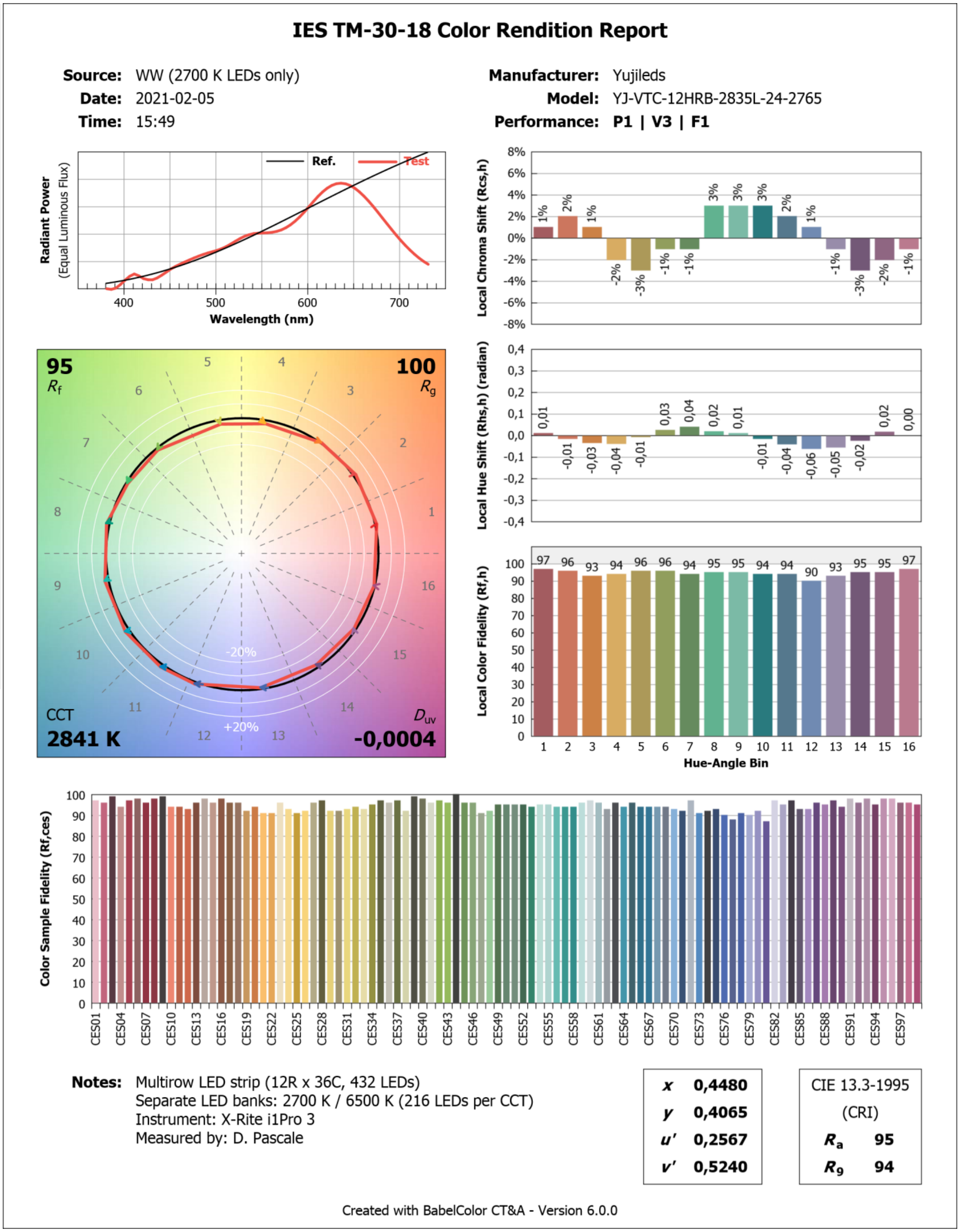
- WW (2700 K LEDs only)
- 3000 K
- 3200 K
- 3500 K
- 4000 K
- 4100 K
- 4700 K
- 5000 K
- 5500 K
- 6000 K
- 6500 K
- CW (6500 K LEDs only)

[21] The LED strip does not emit UV light so there is also no need to measure a UV MI.
[22] See the ISO 3664 standard or the CT&A Help manual for more information on the viewing conditions.

LED strip CCT setting: WW (2700 K LEDs only)

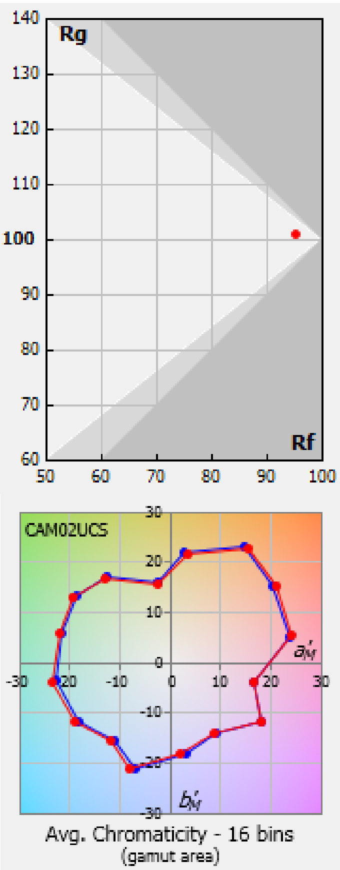


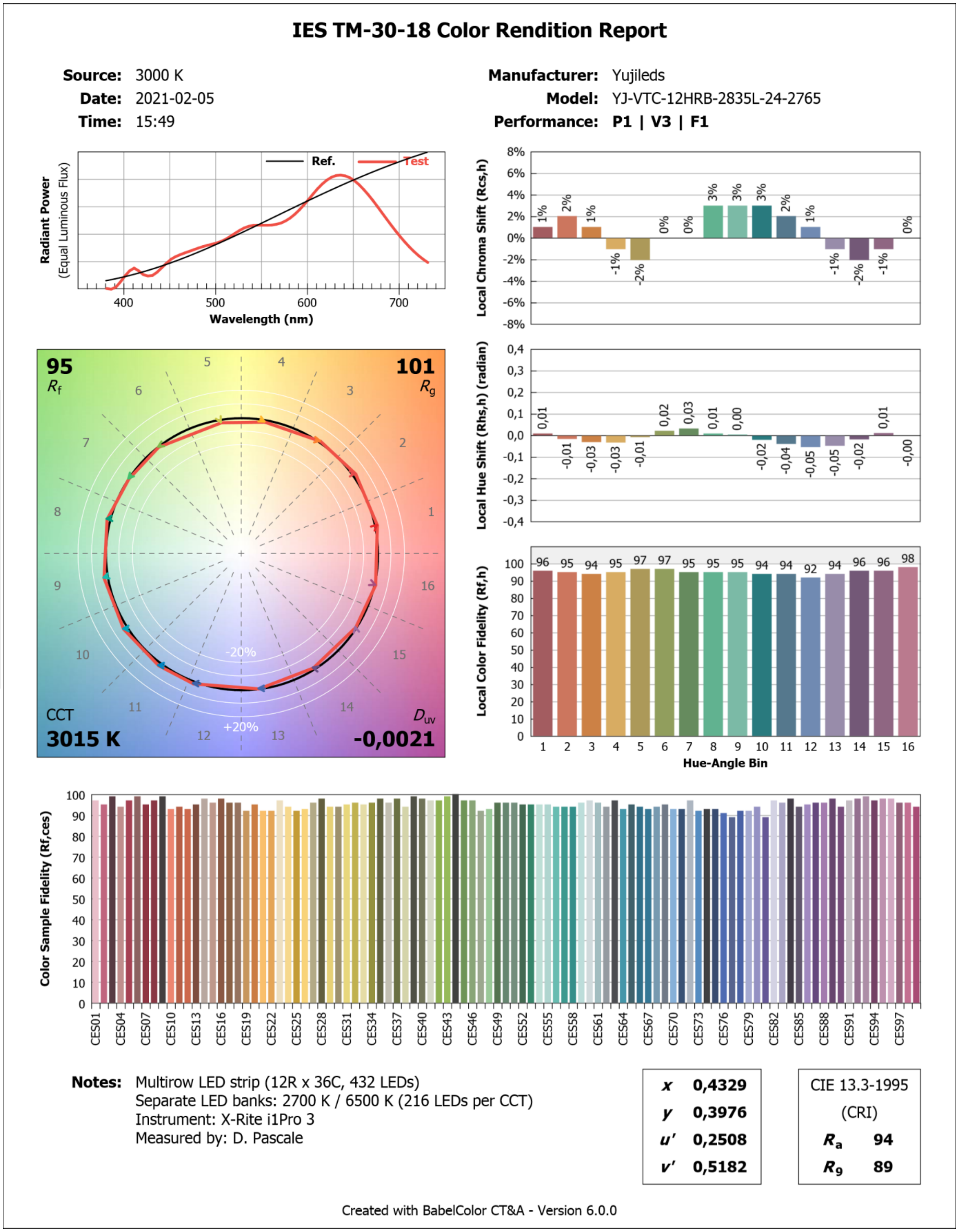




Return to the report selection list

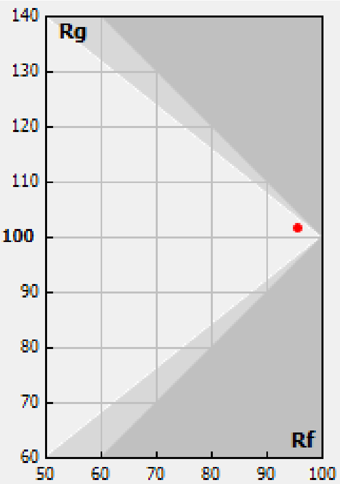
LED strip CCT setting: 3000 K

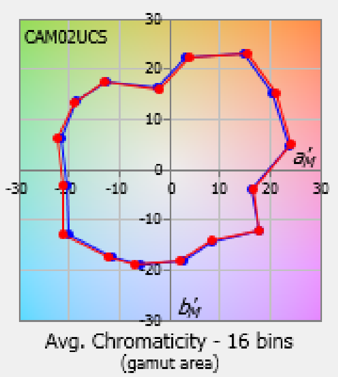


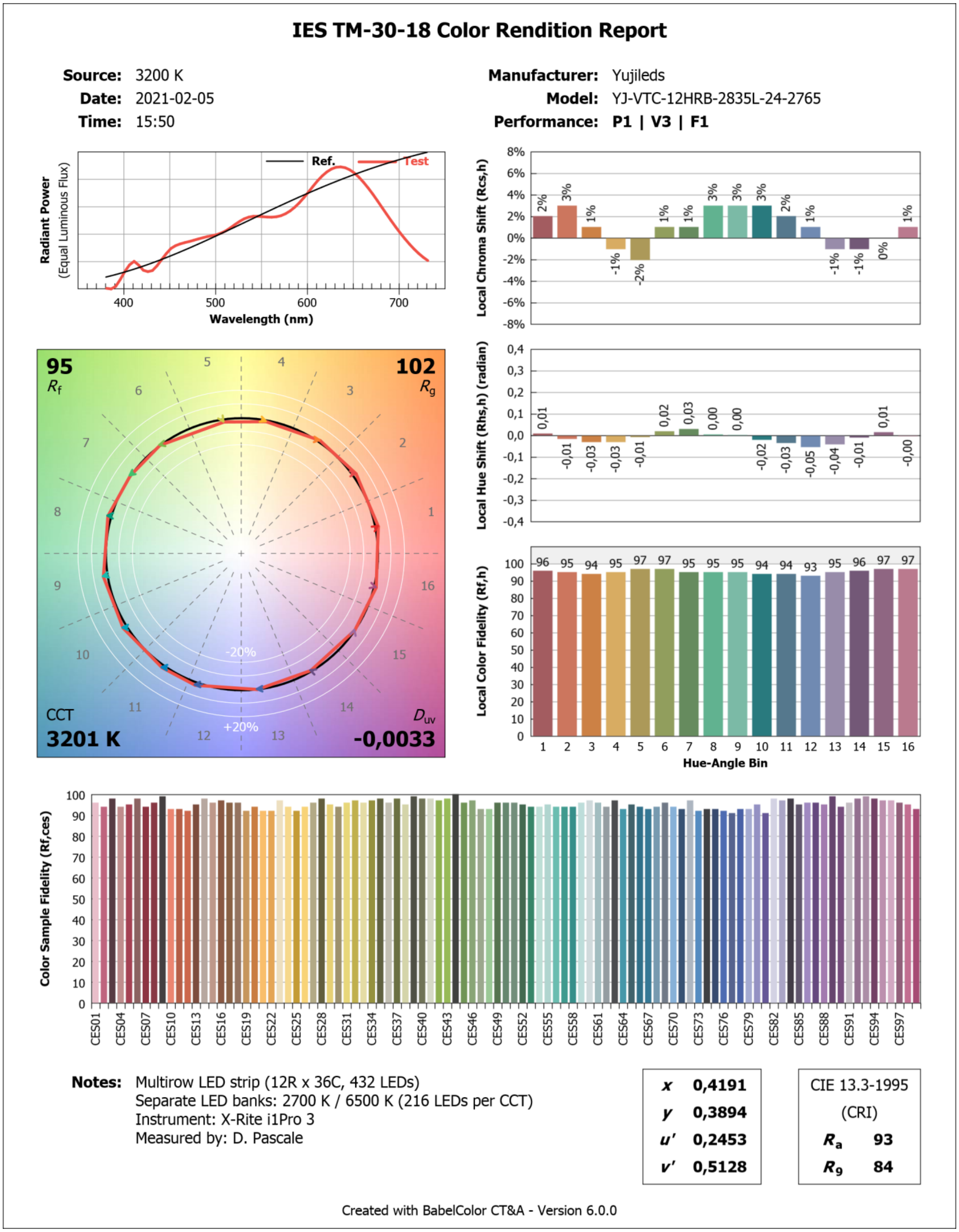


[Return to the report selection list](#)

LED strip CCT setting: 3200 K

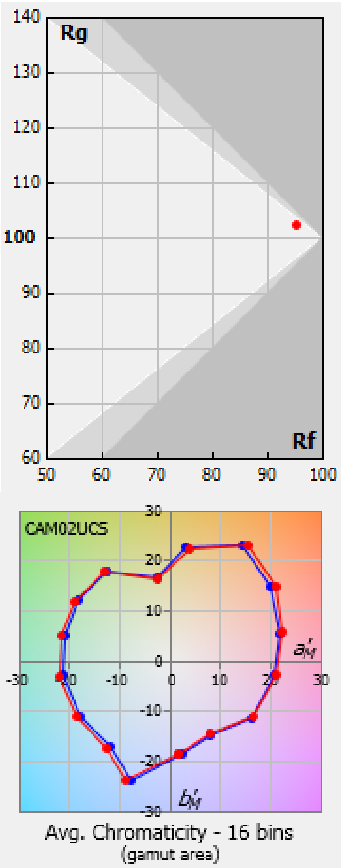


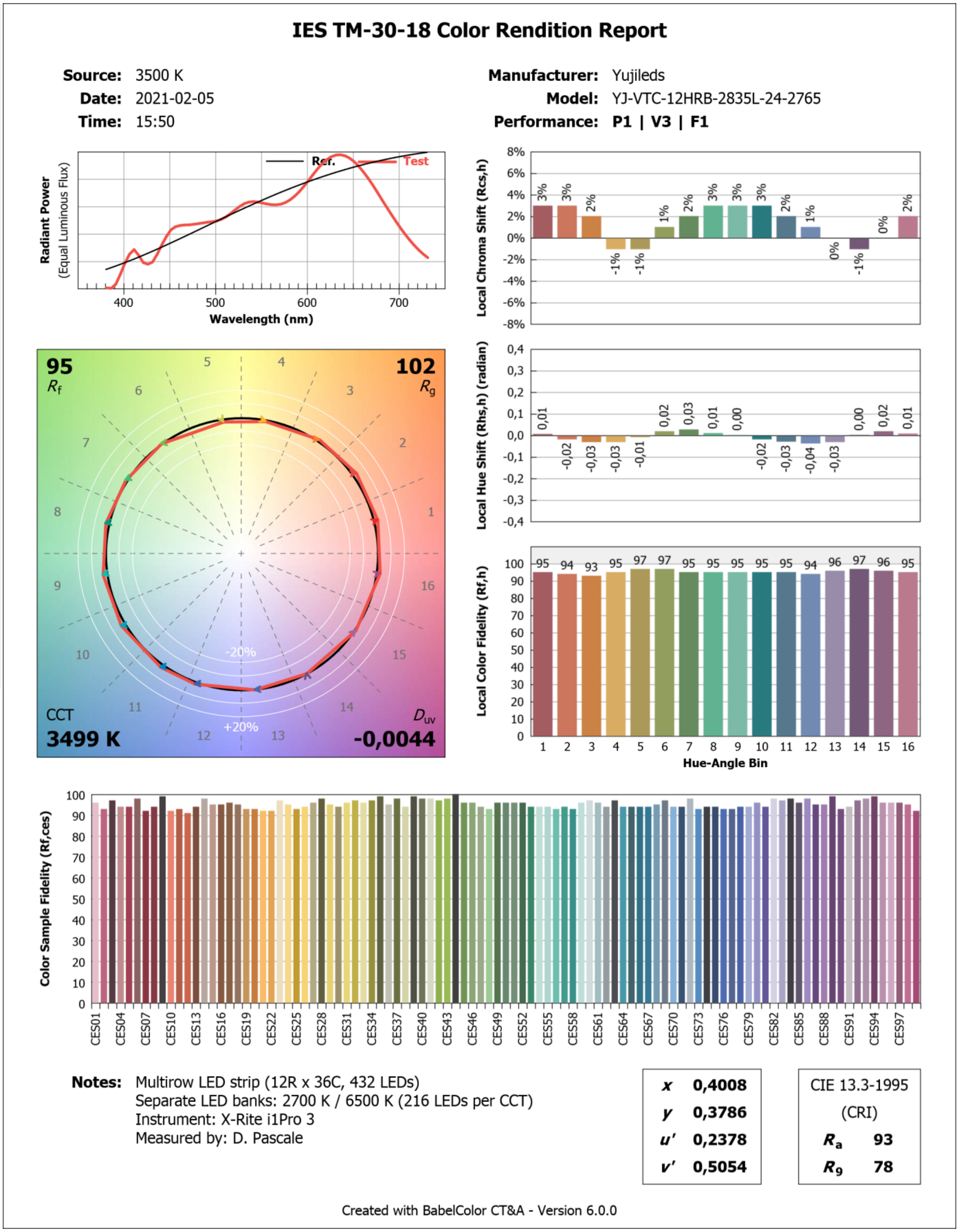




Return to the report selection list

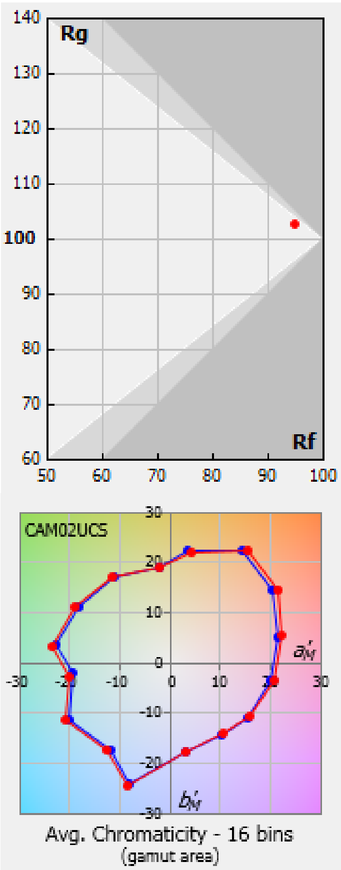
LED strip CCT setting: 3500 K

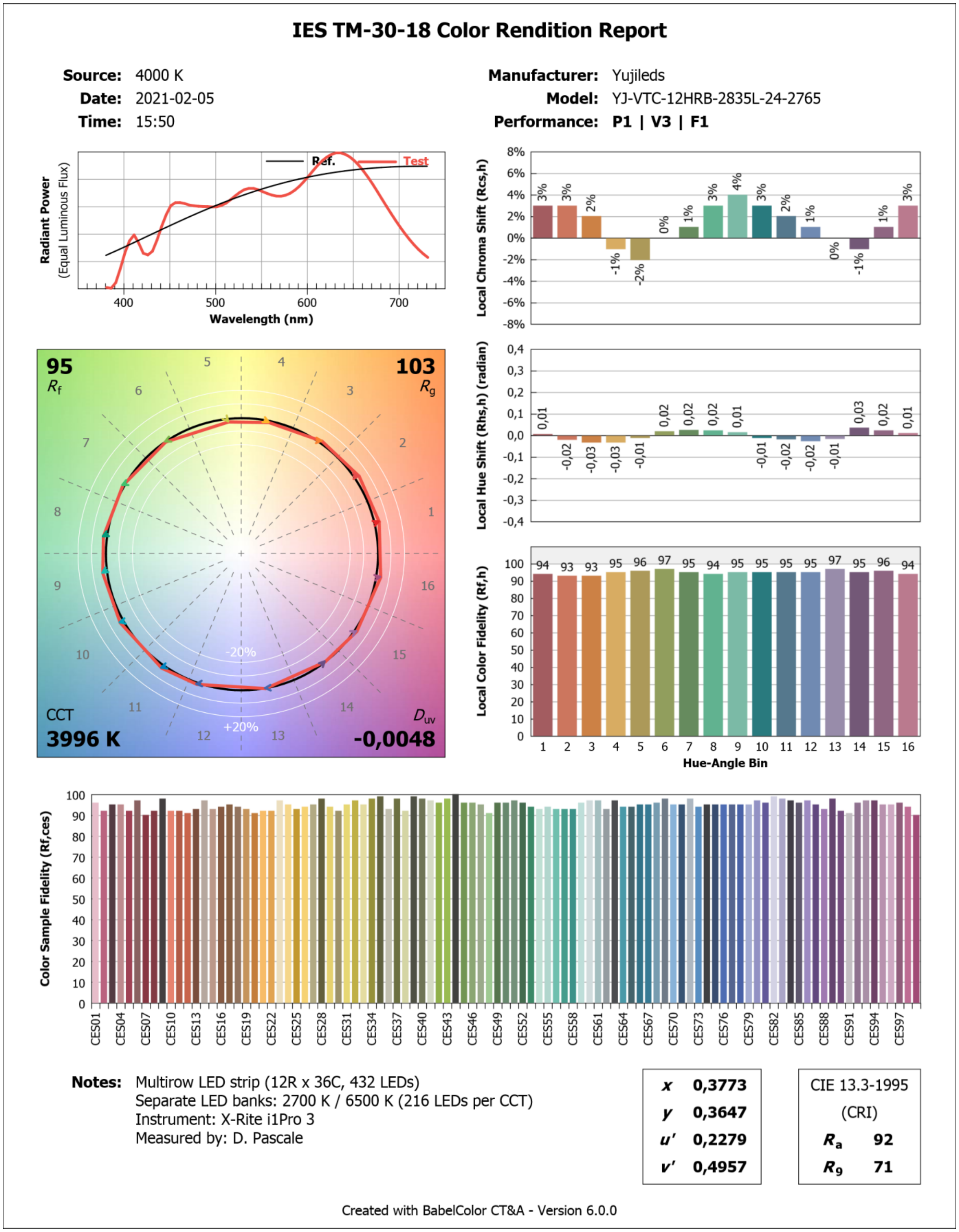




[Return to the report selection list](#)

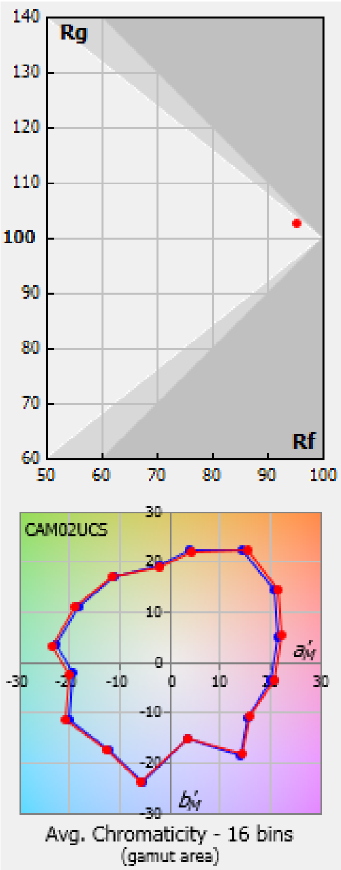
LED strip CCT setting: 4000 K

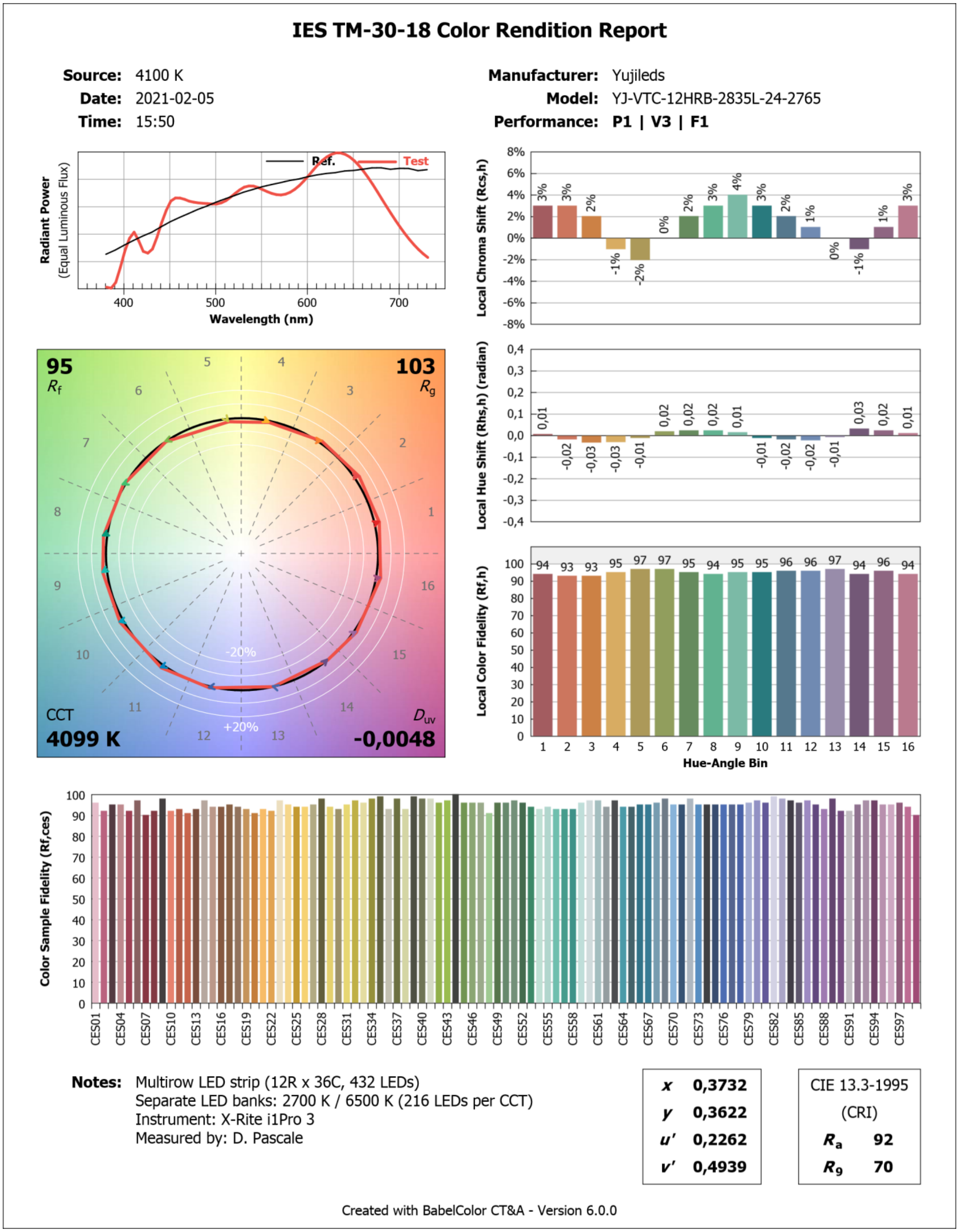




[Return to the report selection list](#)

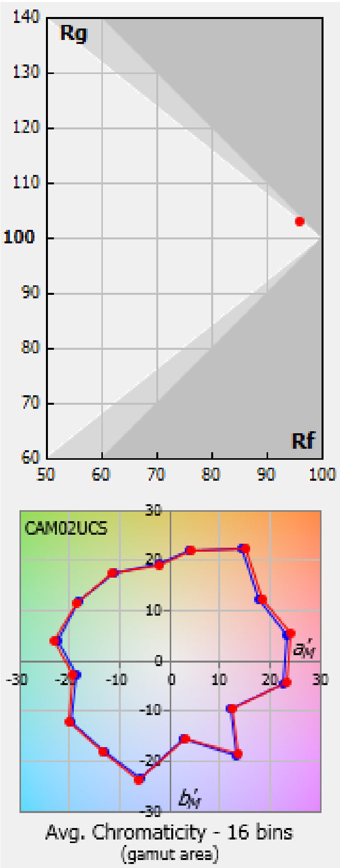
LED strip CCT setting: 4100 K

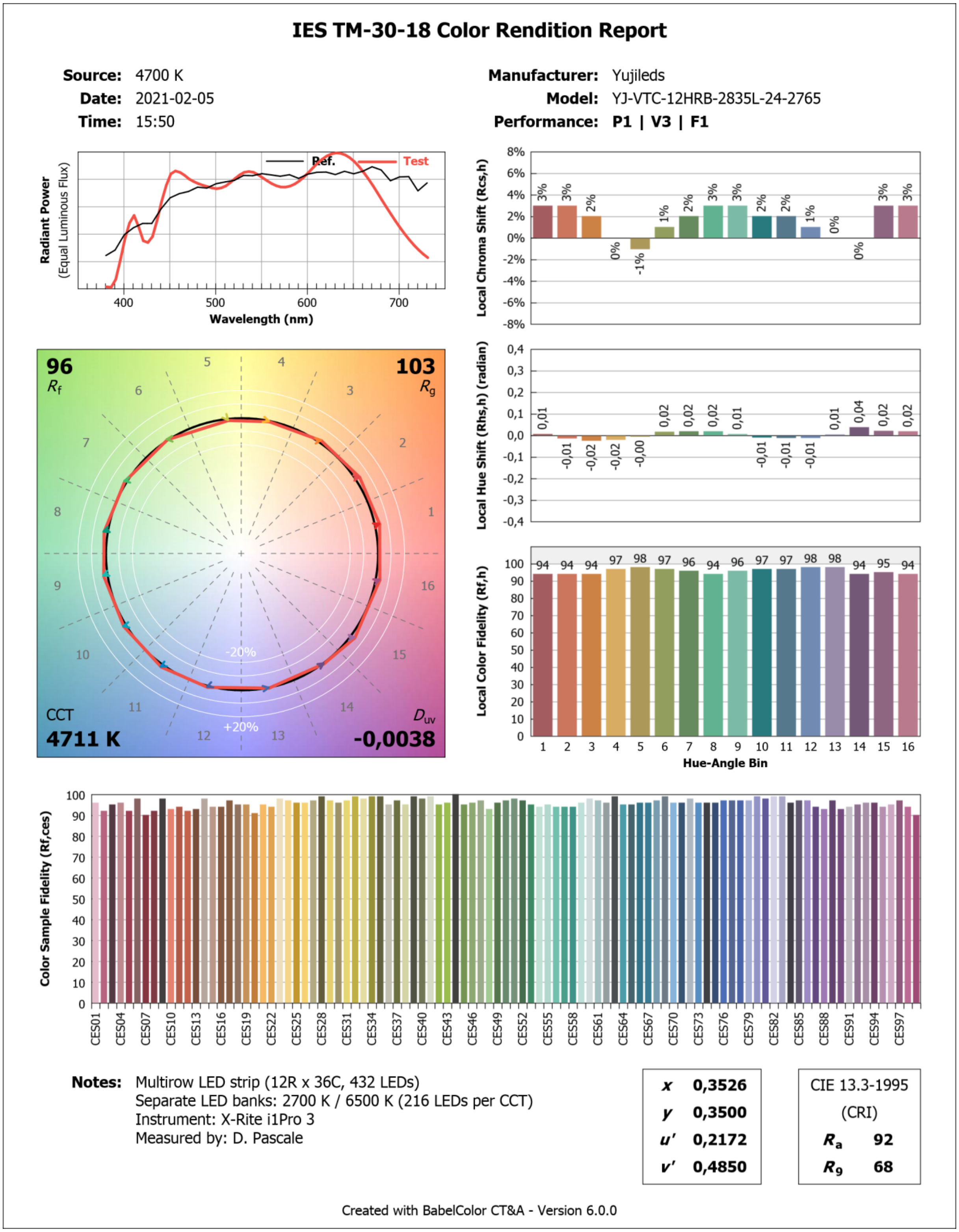




Return to the report selection list

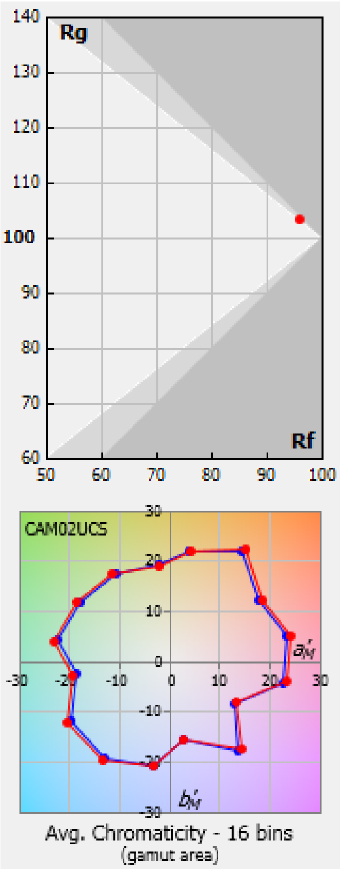
LED strip CCT setting: 4700 K

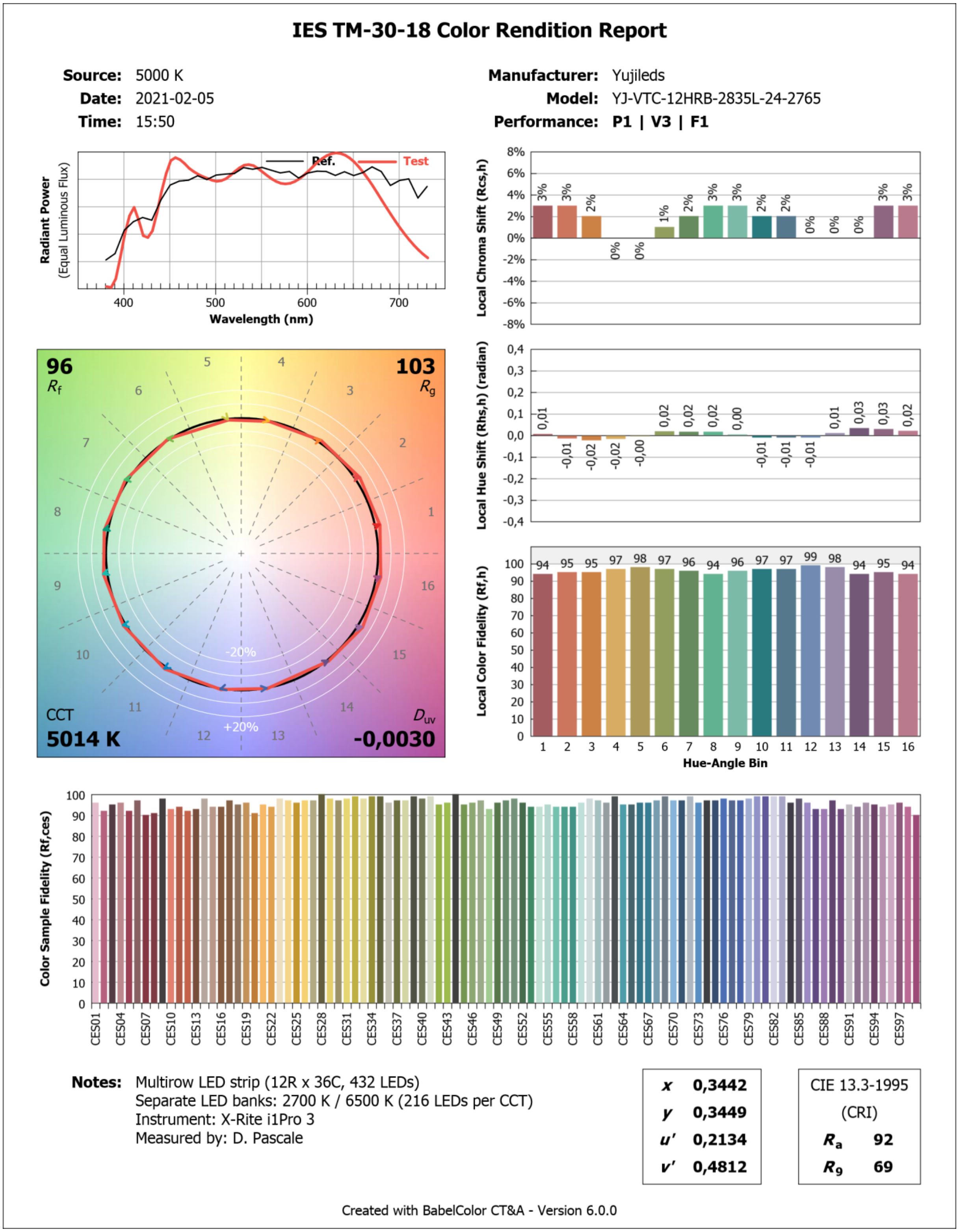




[Return to the report selection list]

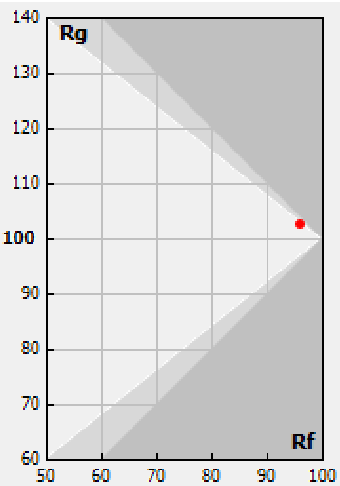
LED strip CCT setting: 5000 K

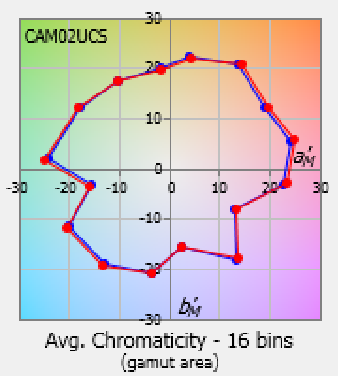




Return to the report selection list

LED strip CCT setting: 5500 K

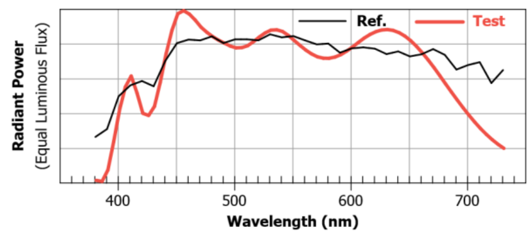


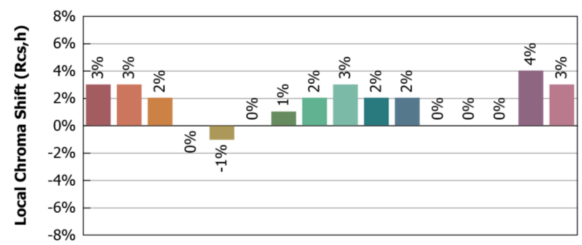


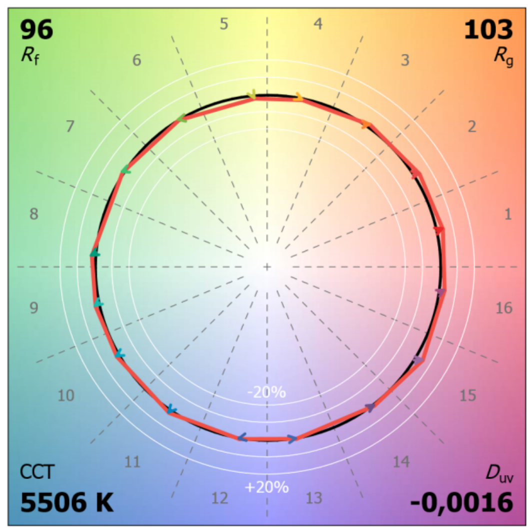
IES TM-30-18 Color Rendition Report

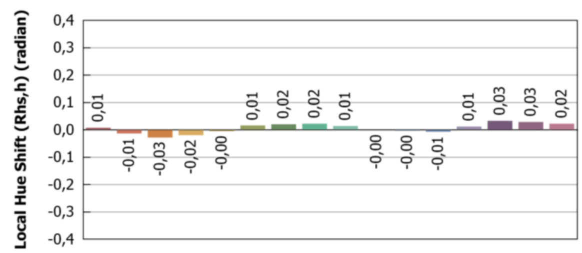
Source: 5500 K
Date: 2021-02-05
Time: 15:51

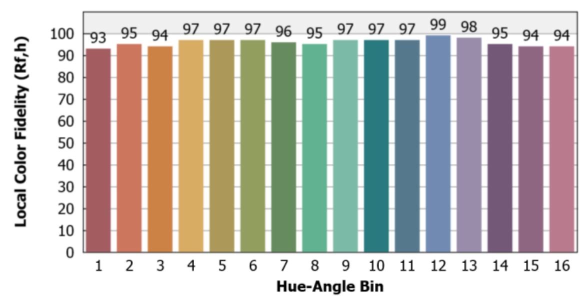
Manufacturer: Yujileds
Model: YJ-VTC-12HRB-2835L-24-2765
Performance: **P1 | V3 | F1**

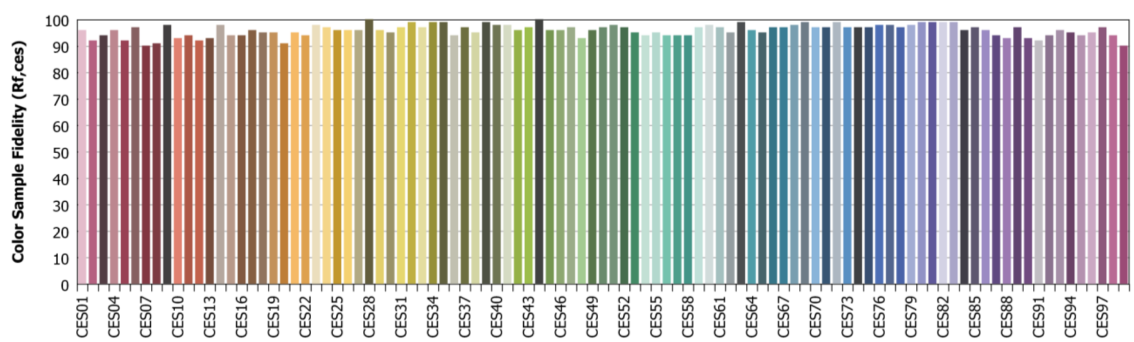












Notes: Multirow LED strip (12R x 36C, 432 LEDs)
Separate LED banks: 2700 K / 6500 K (216 LEDs per CCT)
Instrument: X-Rite i1Pro 3
Measured by: D. Pascale

x	0,3323
y	0,3378
u'	0,2080
v'	0,4759

CIE 13.3-1995 (CRI)	
R_a	93
R_9	69

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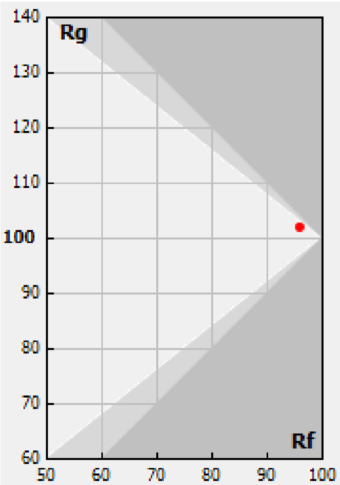
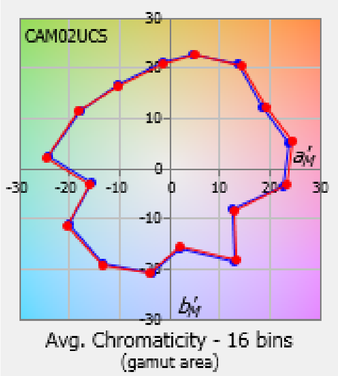
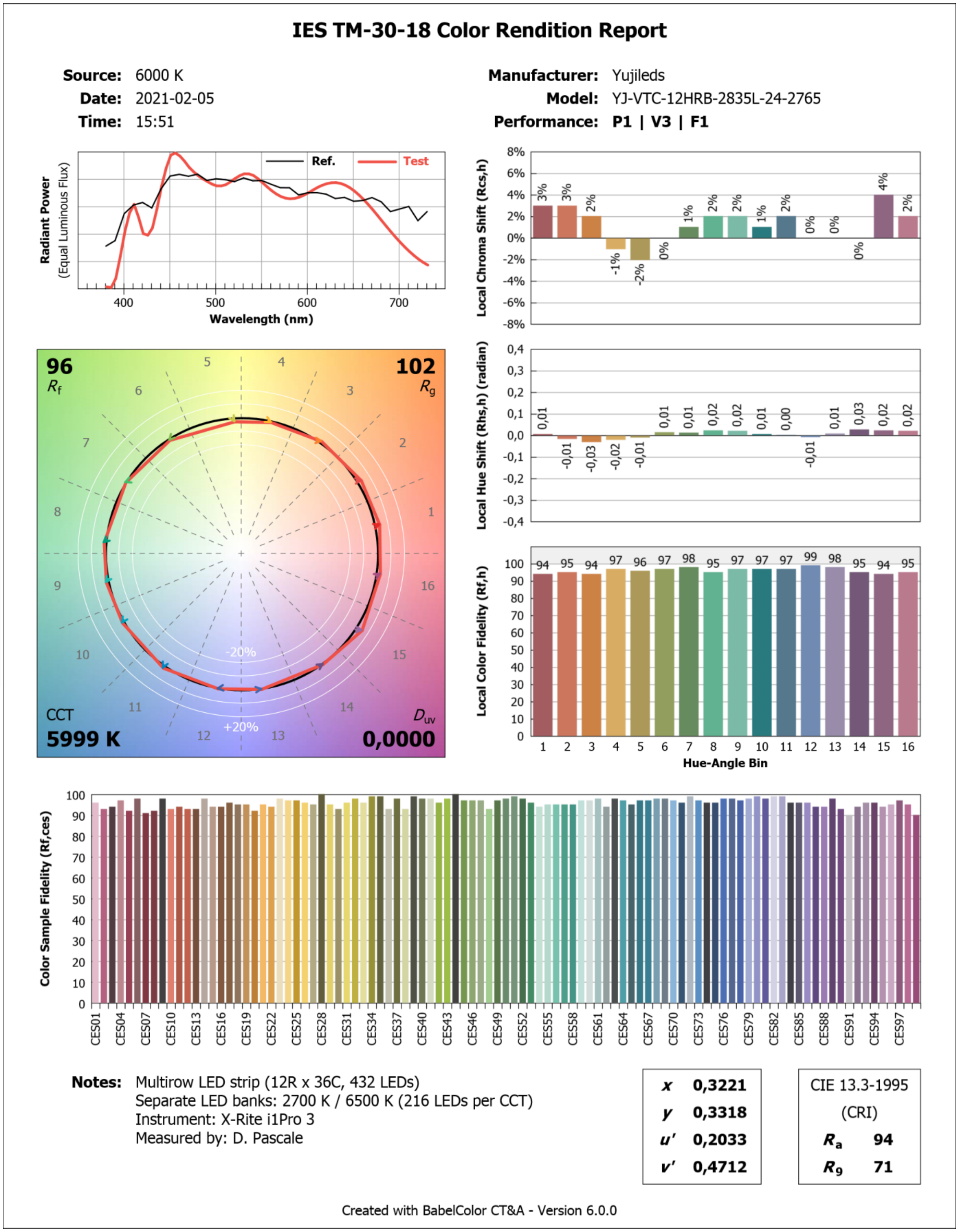
Return to the report selection list

LED strip CCT setting: 6000 K







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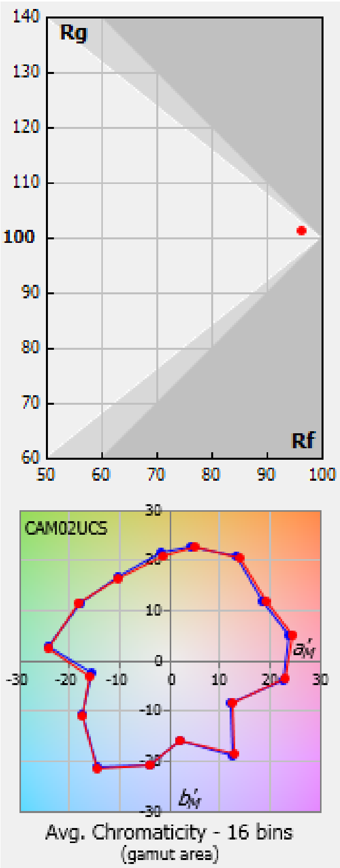
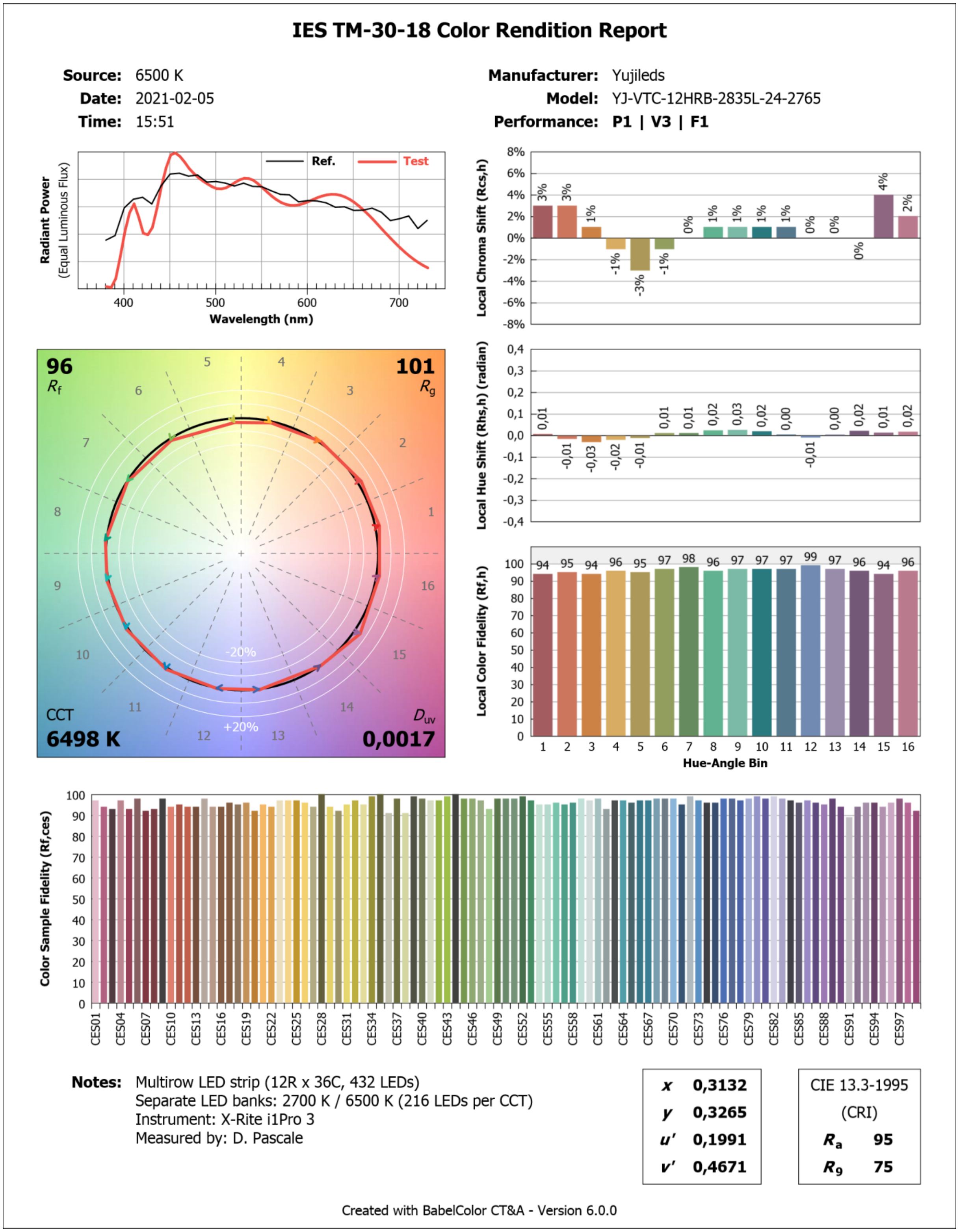
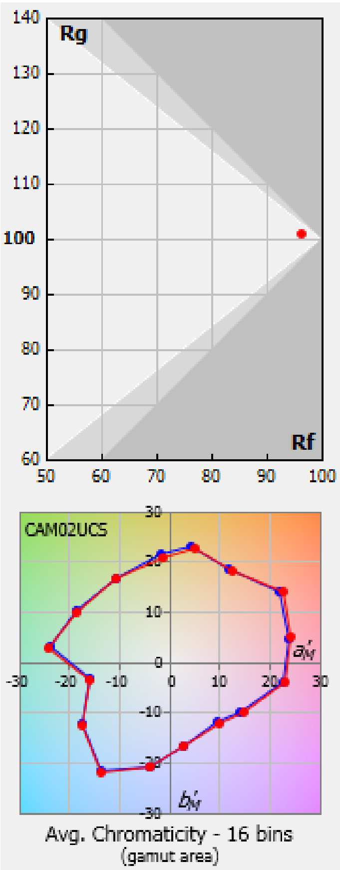
LED strip CCT setting: 6500 K

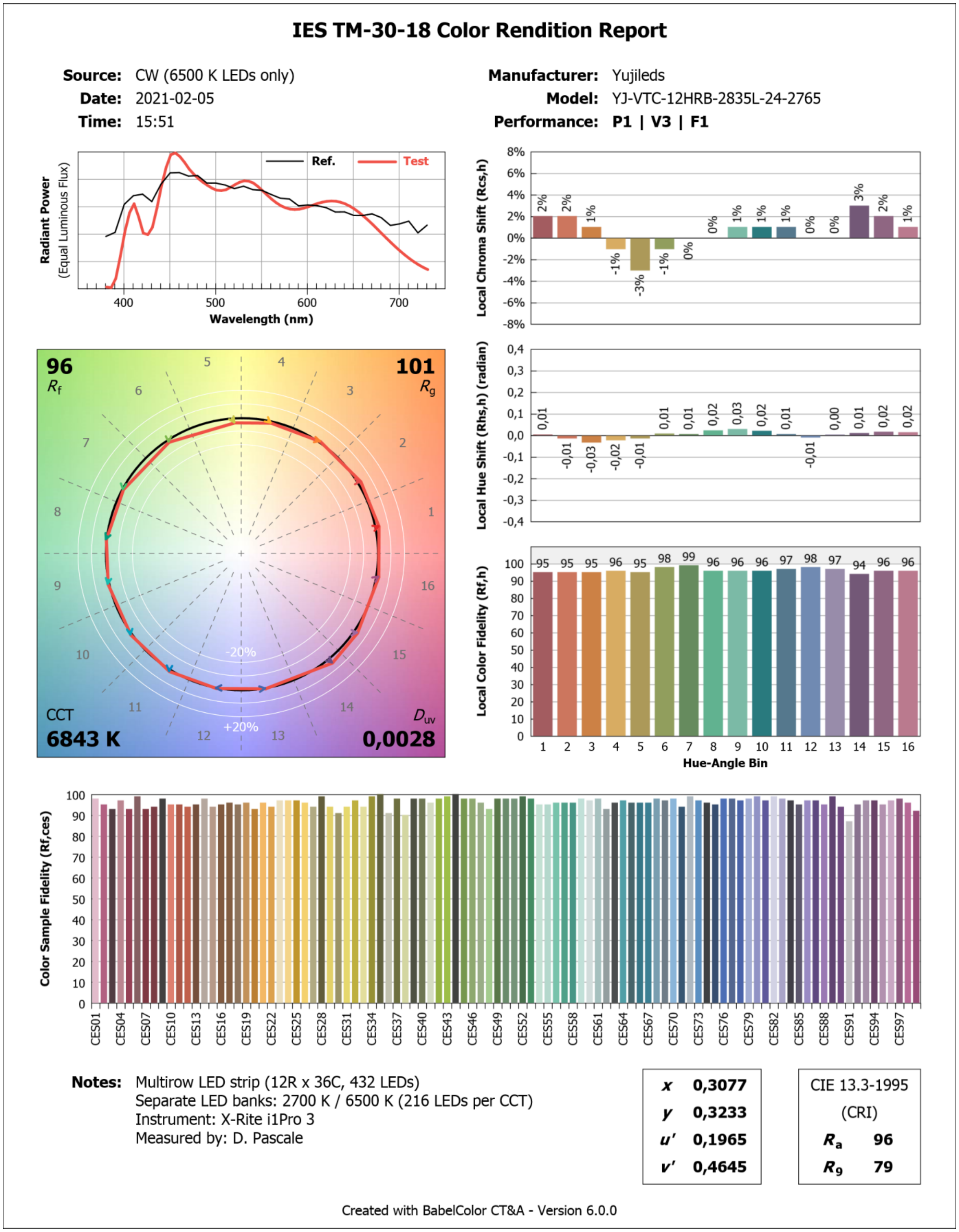




Return to the report selection list

LED strip CCT setting: CW (6500 K LEDs only)





Return to the report selection list

6.4 Brightness uniformity

There are many ways to measure brightness uniformity. Our goal was to find the zone where the brightness is within 75% of the brightness in the center of the illumination beam. We evaluated three options, of which we selected the third one:

i- Define a grid in the illumination plane with sufficient measurement positions to enable the creation of a level map. This method can require many measurements and will require interpolation to find the 75% brightness locations.

ii- Use the brightness uniformity criteria of ISO 3664 where nine (9) positions are measured on a rectangular working area. The problem here is that the size of the work area is not defined but is what we seek to measure; there is in effect an infinity of rectangles with different width and height that can match this requirement.

iii- Use a "hybrid" approach with nine points where we first move the spectrocolorimeter horizontally each side from the center position until we obtain 75% of the center position brightness. We then repeat the process vertically after which we have five points defining a cross. Four other points are found by scanning the instrument vertically up and down after positioning it midway between the center and the horizontal side points. What we find here are points located on an ellipse where the output falls at 75% of the center brightness. Also, because we have a grid of nine points, even if irregular, we can use the same software tools used in measuring ISO 3664 compliance.

Brightness uniformity standards such as ISO 3664 also have specific brightness goals. ISO 3664 defines two viewing conditions for illumination:

- "**P1: Prints: CRITICAL comparison**" : the goal is 2000 lux (±500 lux accepted, ±250 lux preferred)
- "**P2: Prints: PRACTICAL appraisal**" : the goal is 500 lux (±125 lux accepted)

Here we did all our measurements with the illuminator at 500 mm from the working area. As we saw in the Colorimetric performance section, the center brightness varied from 1758 lux at 3000 K to 2014 lux at 6500 K. For the 3000 K CCT, since the brightness was set at its maximum, we would need to reduce the illuminator height in order to get 2000 lux for the P1 condition. This revised height can be determined with the following equation:

$$Dnew = Dold \,/\, (Ynew \,/\, Yold)^{1/2} \qquad \text{(Eq. 1)}$$

where *Dnew* is the new distance corresponding to the new Illuminance goal (*Ynew*) and *Dold* is the current distance corresponding to the current Illuminance (*Yold*).

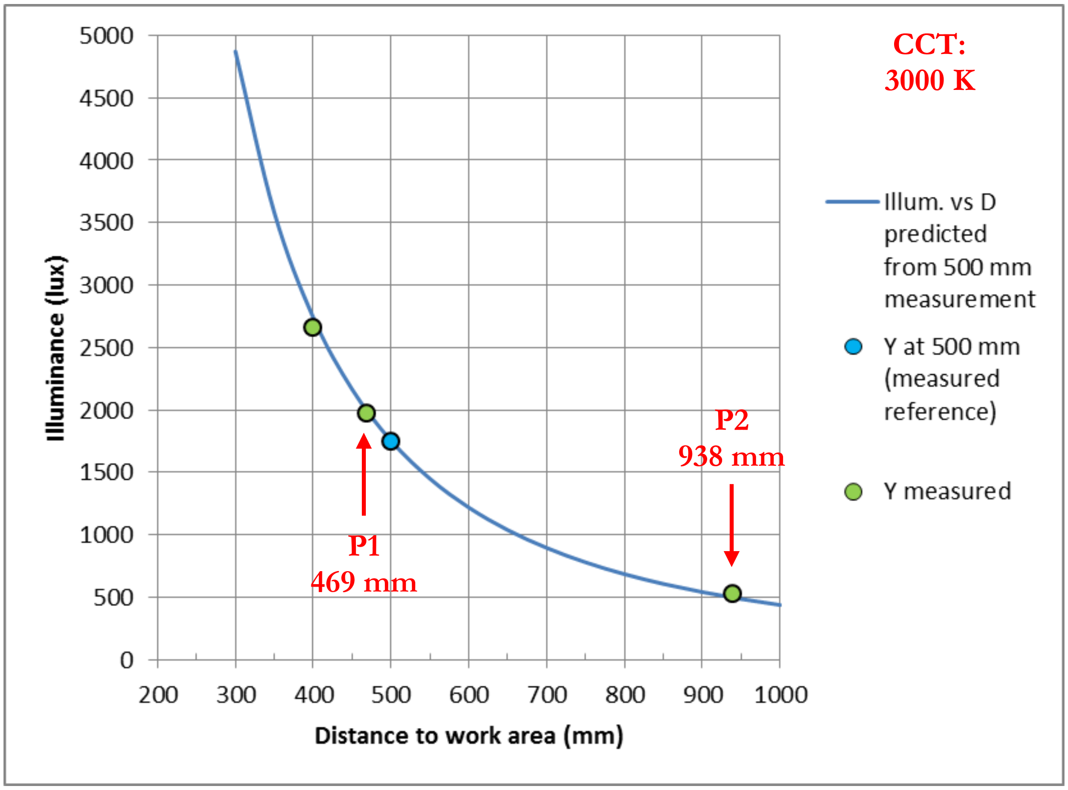
Let's use this equation with our 3000 K measurements. We measured an Illuminance *Yold* =1758 lux at a distance *Dold*=500 mm; our goal is to find the distance for *Ynew*=2000 lux. With these values Eq. 1 gives *Dnew*=469 mm. We have actually moved the illuminator to the calculated distance and measured an illuminance of 1977 lux, quite close considering the errors in measuring the working distance. This measurement and a few others done with the same setup are shown on the graph on the next page.

We can also predict the Illuminance we will get (*Ynew*) for a new distance (*Dnew*) from the current distance (*Dold*) and the current Illuminance (*Yold*):

$$Ynew = Yold \times (Dold \,/\, Dnew)^{2} \qquad \text{(Eq. 2)}$$

Now, let's assume that you are positioned to get about 2000 lux for the P1 condition; you may then want to set your illuminator for the P2 condition, with a center illumination of 500 lux. We can either dim the illuminator or increase its height with less or no dimming. Since the brightness follows an inverse square law with distance, as represented in Eq. 1 and 2, and starting with 2000 lux, we would just need to double the working distance to lower the brightness by a factor of 4 (to get 500 lux). This can easily be verified with Eq. 2 and demonstrated by the graph on the next page.

The graph below[23] shows, as a blue line, the Illuminance predicted when changing the distance between the illuminator and the work area **based on a single measurement** at 500 mm (the blue dot) when the CCT was set at 3000 K. As mentioned before, the measured Illuminance at 500 mm was 1758 lux and we determined with Eq. 1 that the working distance should be reduced to 469 mm in order to get (or a least get closer to!) a 2000 lux Illuminance. Also as mentioned previously, we did measure an Illuminance of 1977 lux at the closer position; this measurement is shown by the green dot close to the 2000 lux line, and well within tolerances for the P1 condition.



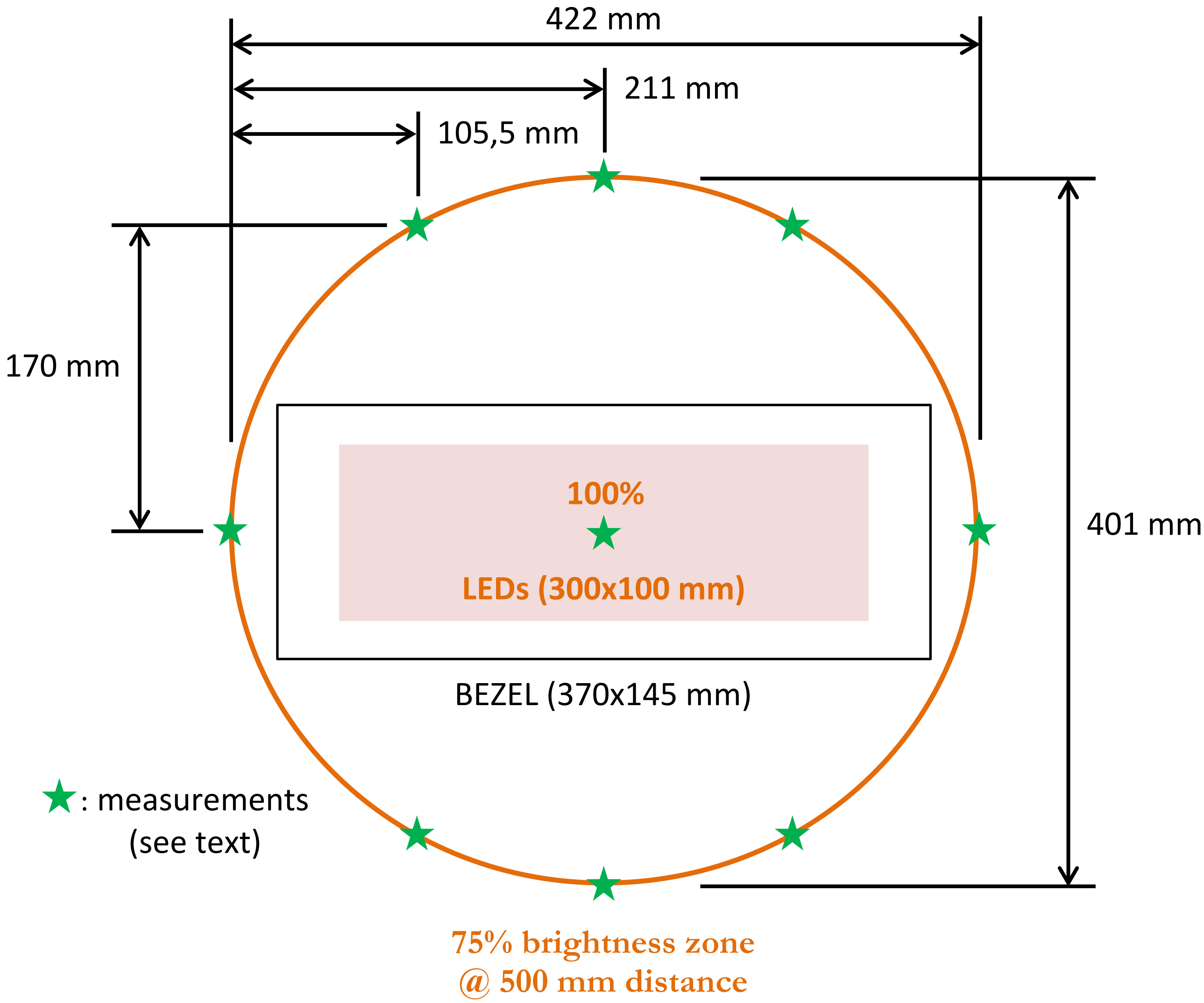
Following this measurement, we doubled the working distance, at 938 mm, with the goal of meeting the 500 lux requirement of the P2 condition. At 938 mm the measured Illuminance was 533 lux, just above the requirement and also well within tolerance for the P2 condition.

The point at the 400 mm working distance was just tested to see how the graph was reliable at a closer range. In fact, you should not expect the graph to be reliable at very close range (300 mm and less) since the lamp is not a point source but a large extended source with a size of 300x100 mm.

Now that we know how to adjust the center Illuminance, we can measure its uniformity in the work area plane. We did nine measurements as we described in the beginning of this section and the results are shown in the following illustration.

[23] The graph blue line coordinates were determined using Eq. 2. Please note that there is no need to trace a graph when you are looking for a revised viewing distance since just using Eq. 1 will provide the answer.

The illustration below shows nine measurements (the **green** stars) taken on the work area plane located 500 mm from the illuminator. The maximum output is in the center and the eight other positions have an Illuminance which is 75% of the center value. The emission pattern approximates the shape of a slightly flattened circle, an ellipse with a major horizontal axis of 422 mm and a minor vertical axis of 401 mm. The larger horizontal pattern dimension is explained by the shape of the LED strip whose size is shown to scale (colored rectangle).



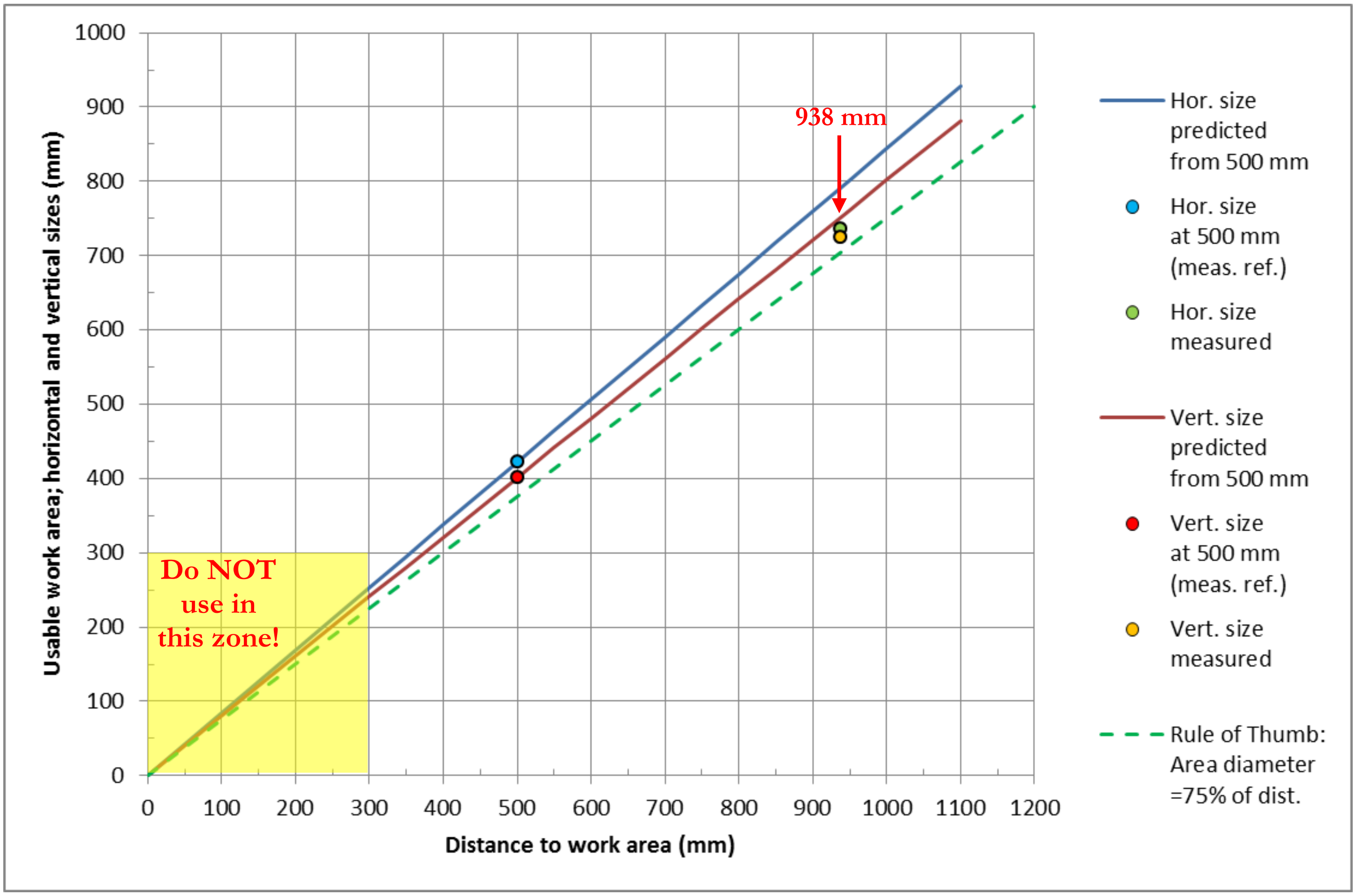
Because of the LED strip size, you should expect a more elongated (and squarish!) emission pattern as you get closer to the illuminator and a more uniform, eventually circular, pattern as you get farther away. Of course, as we increase the working distance we also increase the size of the 75% uniformity zone. Here, as a first approximation, we expect a linear relation where doubling the distance doubles the horizontal and vertical sizes of the work area.[24]

The graph on the next page presents the 75% uniformity zone in relation to working distance.

[24] The work **area** does follow a power law since doubling the distance increases the area by four.

The graph below shows, as a blue line, the horizontal size of the elliptical emission pattern predicted when changing the distance between the illuminator and the work area **based on measurements at 500 mm** (the blue dot). The red line, similarly derived for the vertical size of the pattern, is also based on measurements at 500 mm (the red dot). The green and orange dots are measurements done with a 968 mm working distance. The major (Hor.) and minor (Vert.) axes were 736 mm and 725 mm respectively; this is a more circular ellipse than the one measured at 500 mm.

Note: The emission pattern is the same at all CCTs.



The pattern size prediction lines assume that the lamp is a point source, which explains why the curves go to zero. This is not possible here since the LED strip has a 300x100 mm rectangular size. You should thus disregard the graph for working distances which are less than 300 mm. The effect of the large LED strip, likely still present at 500 mm, should also diminish as we get away from the lamp and this is suggested by our measurements at 938 mm.

As a Rule of Thumb, we propose the following:

The usable work area is a circle with a diameter equal to 75% of the working distance.

The dashed green line on the graph shows the usable viewing area according to the above rule. For example, at a 1000 mm range, the usable viewing area is 750 mm. While one may argue that the "real" viewing area is slightly larger than the rule, look at the extra space as a tolerance in locating the area under the illuminator. And as we discussed previously, the emission pattern was measured as the contour corresponding to 75% of the center Illuminance. So you just need to remember one number, 75%!

On the next pages you will find two versions an **ISO 3664 Test Report** made with BabelColor CT&A. The illuminator was set at a CCT of 5000 K, with a 500 mm working distance, and a center brightness reduced to 559 lux using the remote control. The measurement locations are those shown on the emission pattern illustration presented earlier in this section. The brightness meets the requirements of the P2 condition (500 lux ±125 lux).

The first report version uses 5000 K as the reference for the chromaticity error and the second one uses D50 as the reference. As we have seen in the Colorimetric performance section, the illuminator *u'v'* chromaticity error is within the ISO 3664 requirements (of 0,0050) when compared to a 5000 K blackbody but is slightly off when compared to the D50 reference chromaticity.[25]

In this section not only have we seen measured data on brightness uniformity, but it was shown how to set the working distance for a required Illuminance level and how to determine the size of the usable working area for a given working distance.

[25] As also mentioned in the Colorimetric performance section, the measured chromaticity is within requirements for the D55, D60, and D65 settings.

BabelColor®

ISO 3664 Test Report: Prints - Practical Appraisal (P2)

Illuminance (lux)

409	412	411
410	549	410
410	410	410

PASS

Goal: 500 lux

Tolerance: +/- 125 lux

Brightness uniformity

75%	75%	75%
75%	100%	75%
75%	75%	75%

PASS

Goal: Up to 1m x 1m: 75% +, relative to center

For larger areas: 60% +, relative to center

CCT (kelvin) / u'v' error

4988 K 0,0018	4994 K 0,0021	4982 K 0,0020
4997 K 0,0020	5018 K 0,0025	4999 K 0,0021
4994 K 0,0020	4987 K 0,0018	4980 K 0,0019

PASS

u'v': Chromaticity in CIE 1976 UCS units

CCT ref.: 5000 K (NOT D50 as per ISO 3664)

u'v' ref.: 5000 K (NOT D50 as per ISO 3664)

u'v' tolerance: 0.0050 radius

See text →

CRI / Special Indices

93 SI min: 88	93 SI min: 88	93 SI min: 88
93 SI min: 88	93 SI min: 88	93 SI min: 88
93 SI min: 88	93 SI min: 88	93 SI min: 88

PASS

CRI as per CIE 13

CRI ref.: 5000 K (NOT D50 as per ISO 3664)

CRI goal: 90+

Special Indices (SI) goal: 80+

MI Quality Grade / Value

'B' 0,45	'B' 0,45	'B' 0,46
'B' 0,45	'B' 0,43	'B' 0,45
'B' 0,45	'B' 0,45	'B' 0,46

PASS

MI (Visible) as per ISO 23603 / CIE S 012

MI ref.: D50

QG goal: 'C' or better (MI ≤ 1)

Preferred goal: 'B' or better (MI ≤ 0.5)

Customer: BabelColor

Lightbooth: BabelColor prototype

Lamp(s): YUJILEDS YJ-VTC-12HRB-2835L-24V-G02-2765

Measuring instrument: i1Pro 3 (XRGA) (S/N: 2000033)

Test performed by: Danny Pascale

Test location:

Nominal White Point: 5000 K

Lamps usage (hours): < 40

Date / Time: 2021-01-26 / 13:23:44

Signature:

BabelColor CT&A Version 6.0.0 b398

BabelColor®

ISO 3664 Test Report: Prints - Practical Appraisal (P2)

Illuminance (lux)

409	412	411
410	549	410
410	410	410

PASS

Goal: 500 lux

Tolerance: +/- 125 lux

Brightness uniformity

75%	75%	75%
75%	100%	75%
75%	75%	75%

PASS

Goal: Up to 1m x 1m: 75% +, relative to center

For larger areas: 60% +, relative to center

CCT (kelvin) / u'v' error

4988 K 0,0064	4994 K 0,0067	4982 K 0,0066
4997 K 0,0066	5018 K 0,0071	4999 K 0,0067
4994 K 0,0066	4987 K 0,0064	4980 K 0,0065

FAIL

u'v': Chromaticity in CIE 1976 UCS units

See text →

CCT ref.: D50

u'v' ref.: D50

u'v' tolerance: 0.0050 radius

CRI / Special Indices

93 SI min: 88	92 SI min: 88	92 SI min: 88
92 SI min: 88	93 SI min: 89	93 SI min: 88
92 SI min: 88	92 SI min: 88	92 SI min: 88

PASS

CRI as per CIE 13

Ref.: D50

CRI goal: 90+

Special Indices (SI) goal: 80+

MI Quality Grade / Value

'B' 0,45	'B' 0,45	'B' 0,46
'B' 0,45	'B' 0,43	'B' 0,45
'B' 0,45	'B' 0,45	'B' 0,46

PASS

MI (Visible) as per ISO 23603 / CIE S 012

MI ref.: D50

QG goal: 'C' or better (MI ≤ 1)

Preferred goal: 'B' or better (MI ≤ 0.5)

Customer: BabelColor

Lightbooth: BabelColor prototype

Lamp(s): YUJILEDS YJ-VTC-12HRB-2835L-24V-G02-2765

Measuring instrument: i1Pro 3 (XRGA) (S/N: 2000033)

Test performed by: Danny Pascale

Test location:

Nominal White Point: 5000 K

Lamps usage (hours): < 40

Date / Time: 2021-01-26 / 13:24:51

Signature:

BabelColor CT&A Version 6.0.0 b398

6.5 Dimmer performance

The output level can be adjusted with the remote control. Starting with maximum output, there are 10 levels of dimming where the difference is approximately 10% per level. The last level does not go to zero but to about 4% of the max value; it cannot be reached with a single button push and you must leave your finger on the "brightness-down" button.

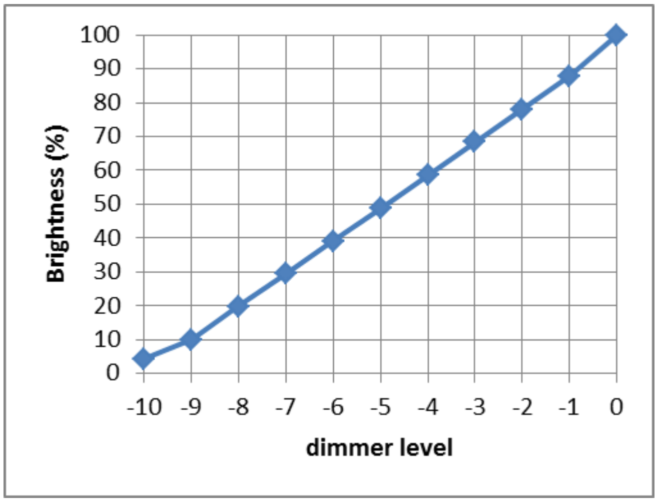
The following pages present how the light output is affected by the dimmer for different CCT settings. You will find graphs of the Brightness, the CCT, *Duv*, TM-30-18/TM-30-20 *Rf* and *Rg*, and CIE 13.3 *Ra* and *R9* at all output levels.

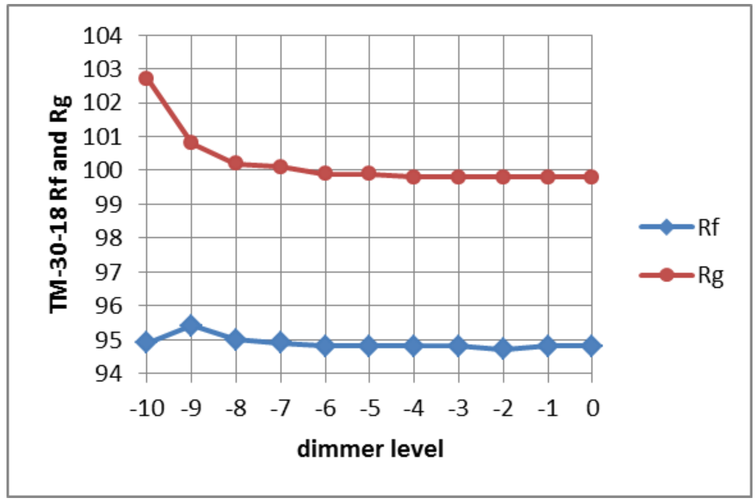
Experimental method
All measurements were made in the center of the emission pattern; see the Brightness uniformity section for more information on the shape of the pattern. The distance between the LED strip plane and the detector head was 500 mm. As mentioned in a Colorimetric performance section, setting the CCTs as close as possible to the target CCTs can take time. Again we used the "Tune" mode in the ISO3664+ tool of BabelColor CT&A to make continuous measurements while changing the CCT with the color ring. Once the CCT was set, we used CT&A's CRI tool to get the measurements shown here.

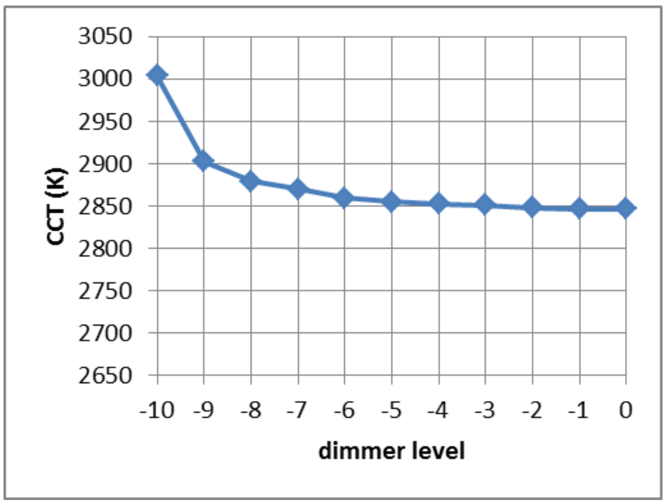
Detailed results
Click on a link to jump to dimmer results specific to a CCT setting:

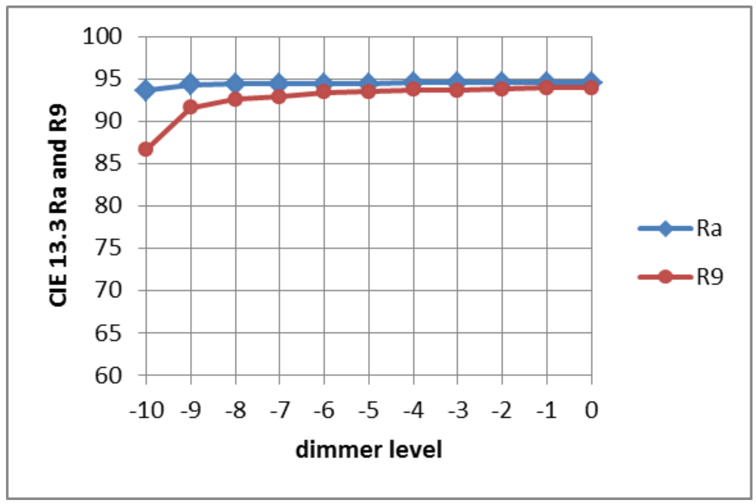
- WW
- 3000 K
- 4000 K
- 5000 K
- 6500 K
- CW
- Dimmer performance discussion

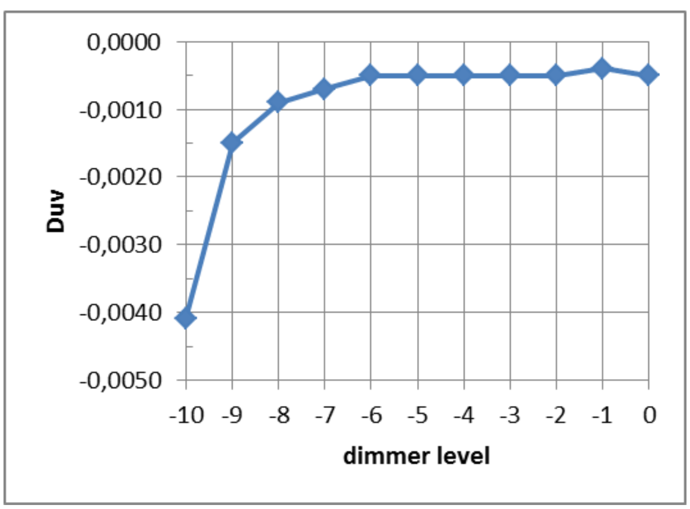
Dimmer performance: WW (2700 K LEDs only)





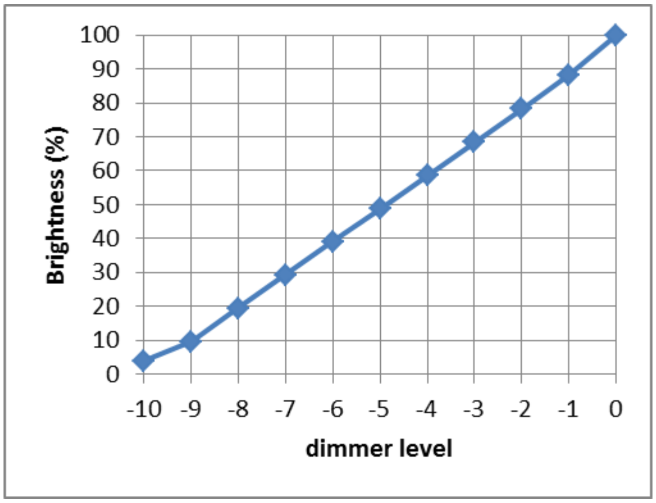


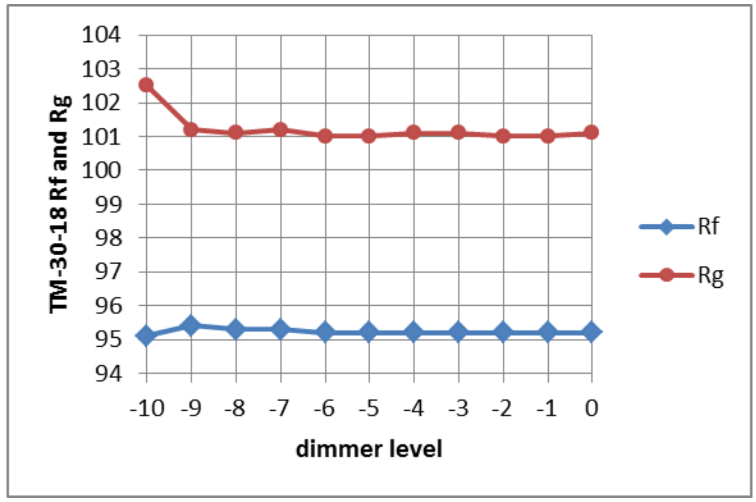


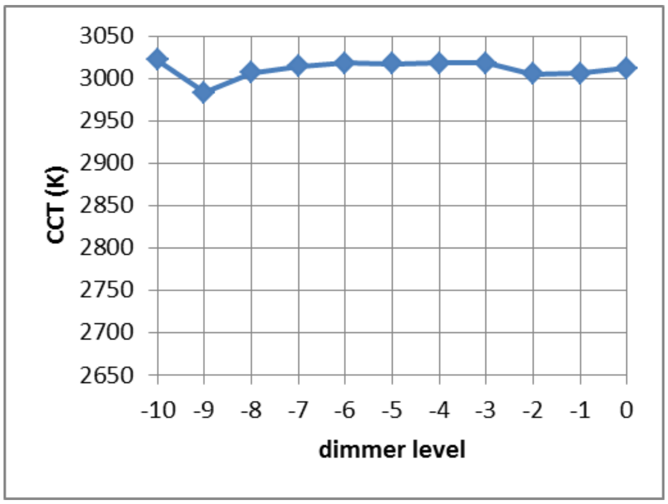


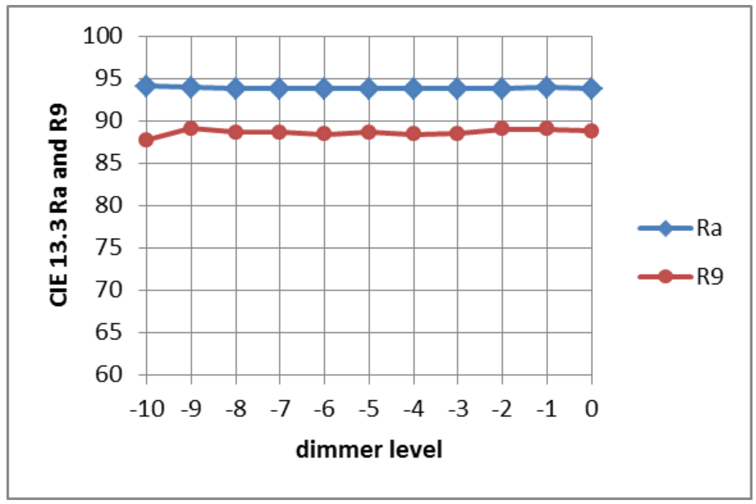
Return to the dimmer report selection list

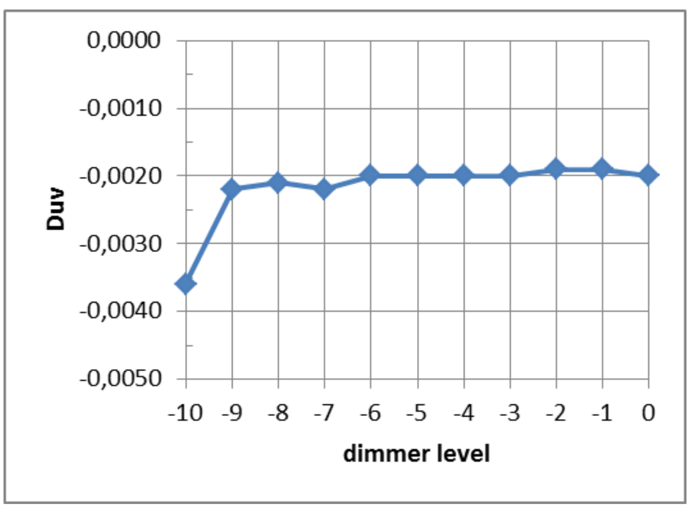
Dimmer performance: 3000 K





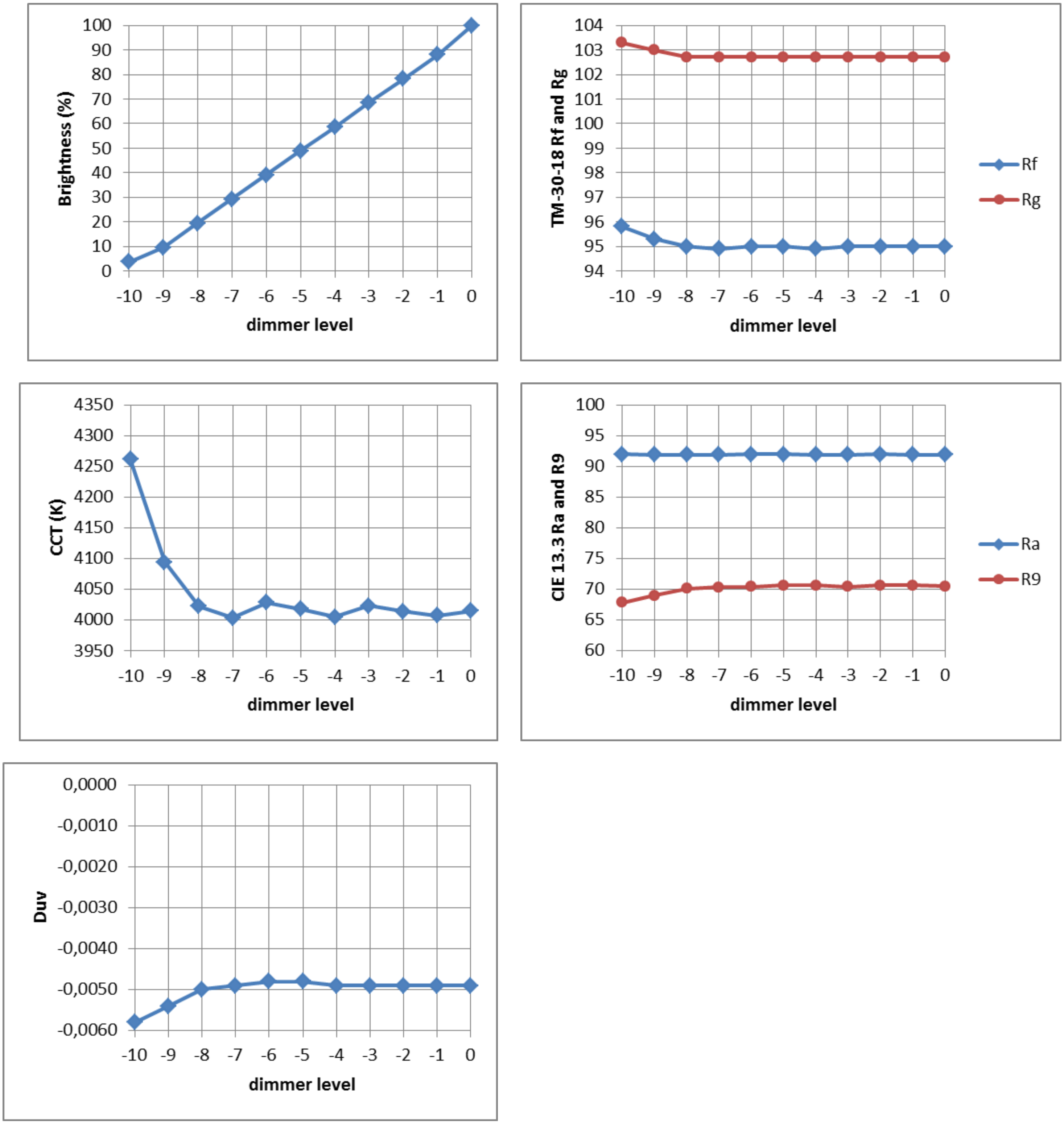






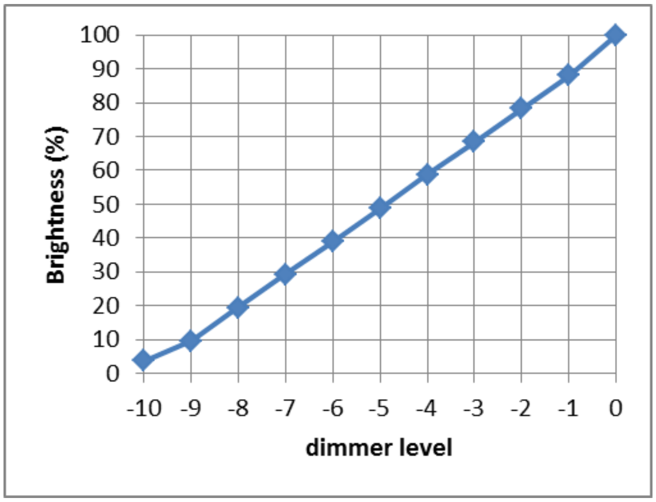
Return to the dimmer report selection list

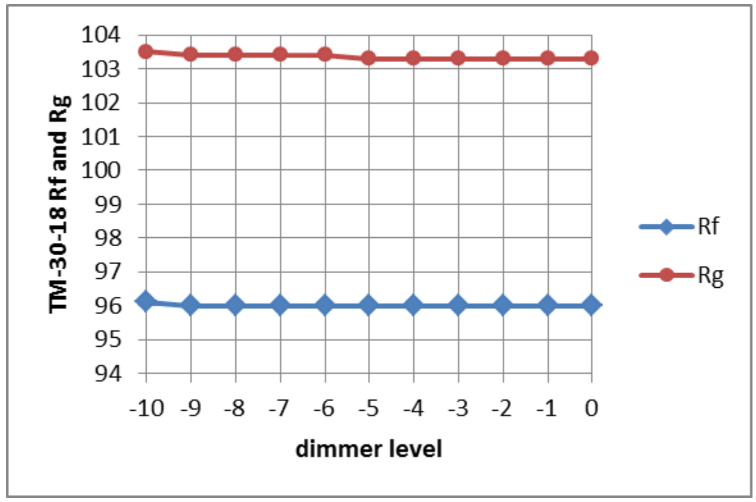
Dimmer performance: 4000 K

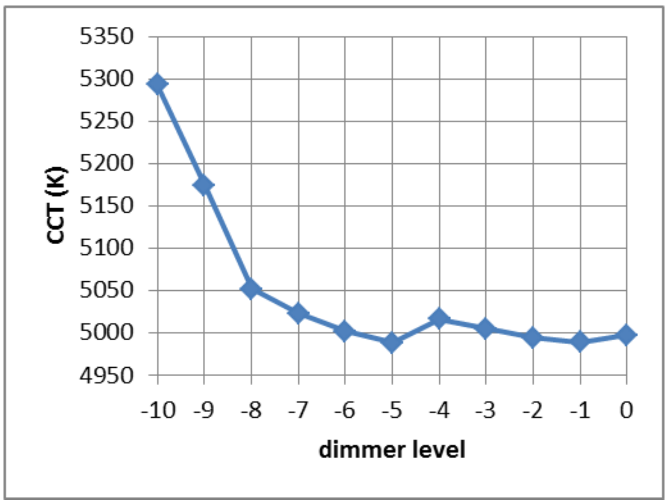


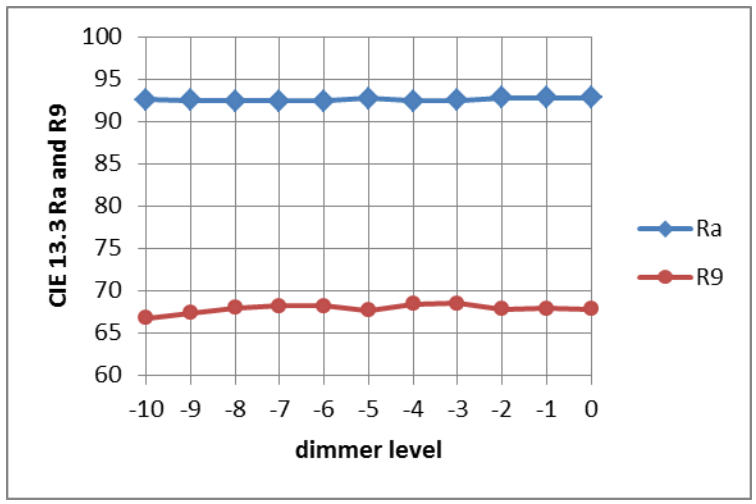
Return to the dimmer report selection list

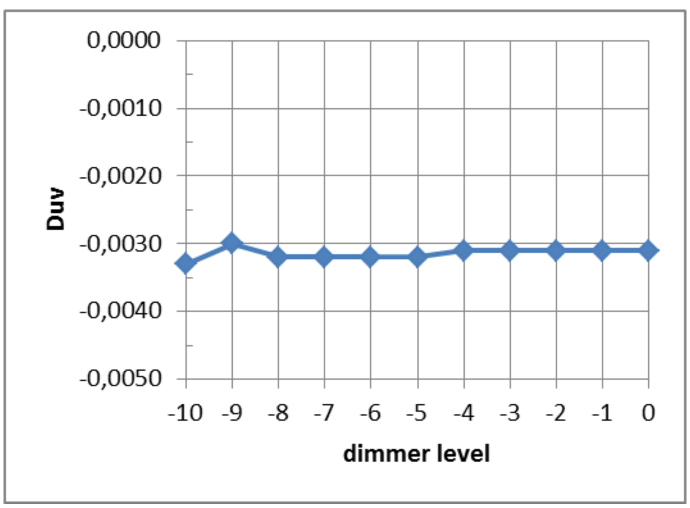
Dimmer performance: 5000 K





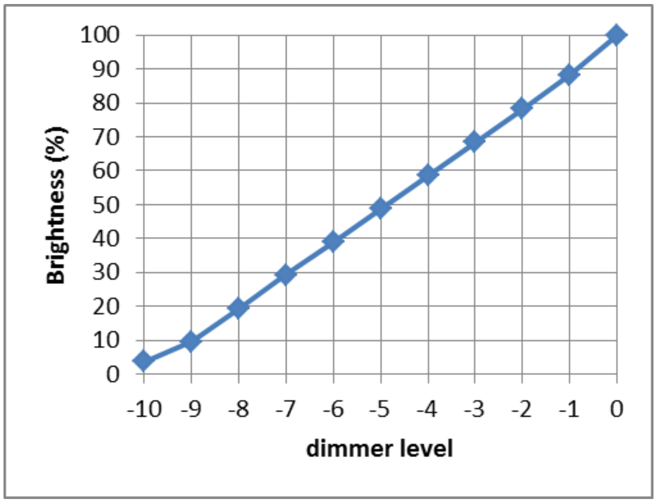


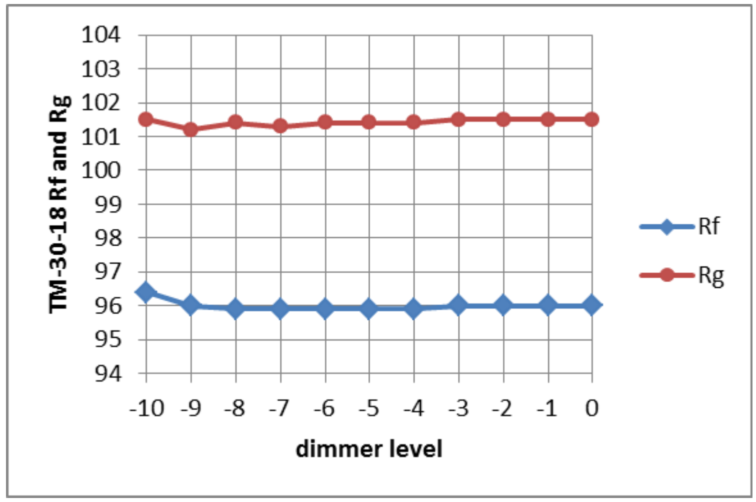


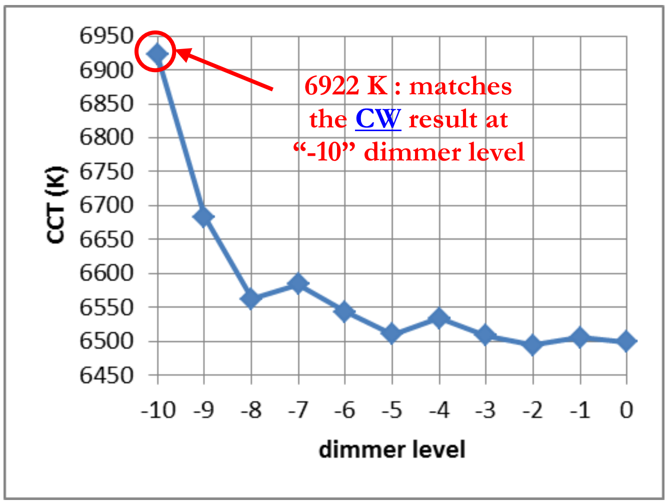


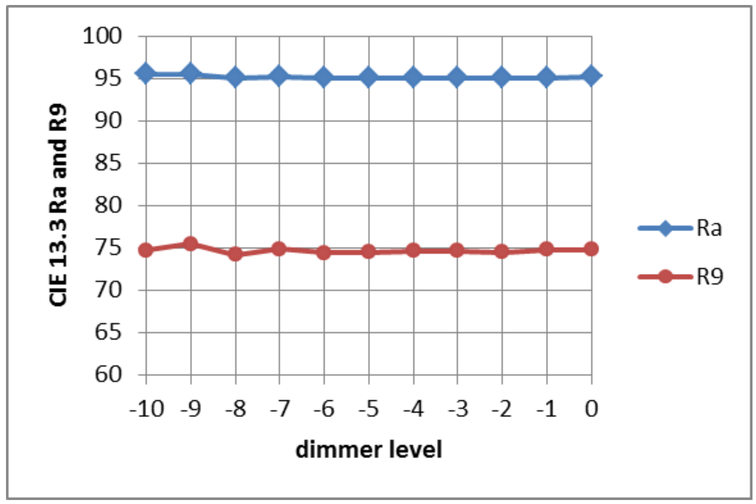
[Return to the dimmer report selection list]

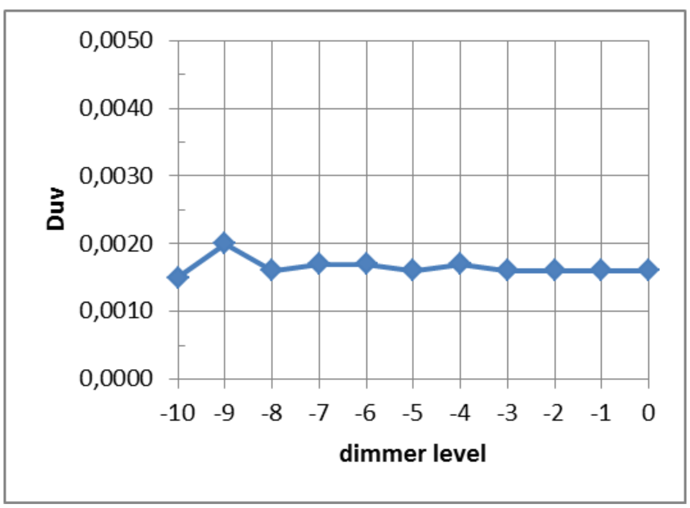
Dimmer performance: 6500 K





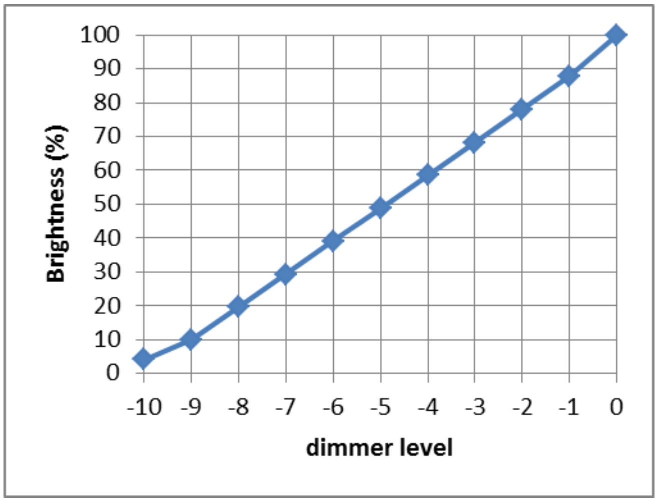


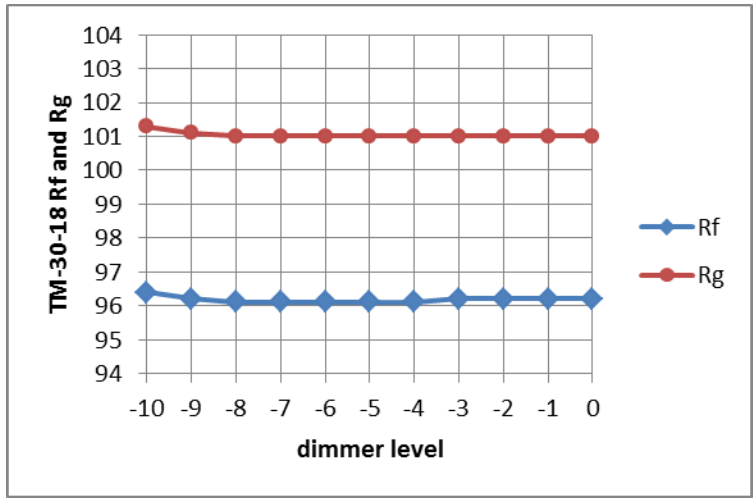


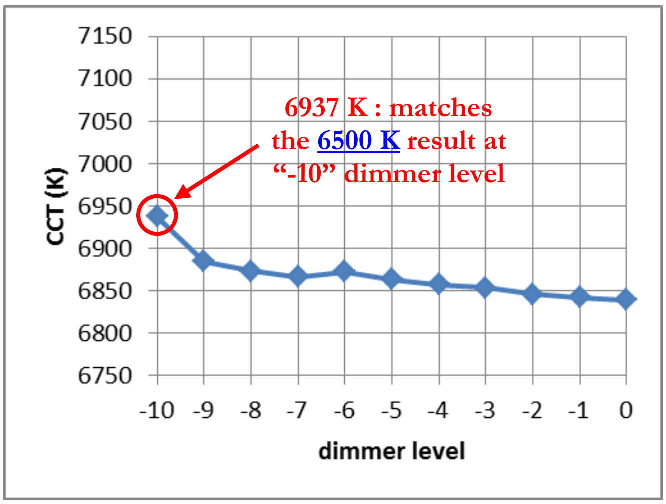


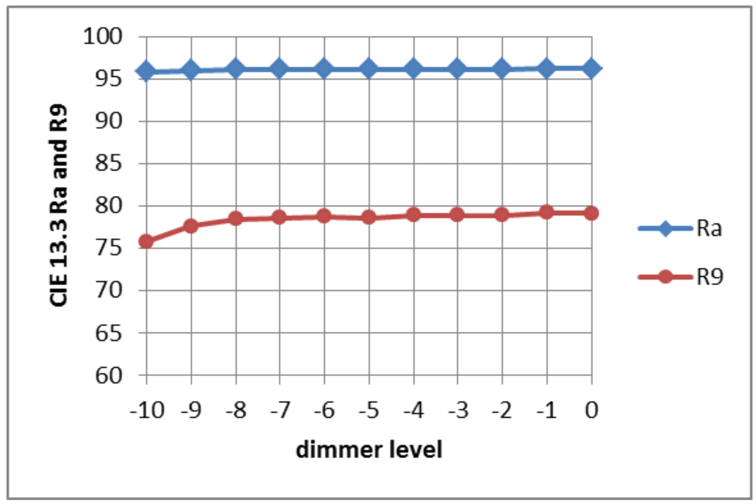
Return to the dimmer report selection list

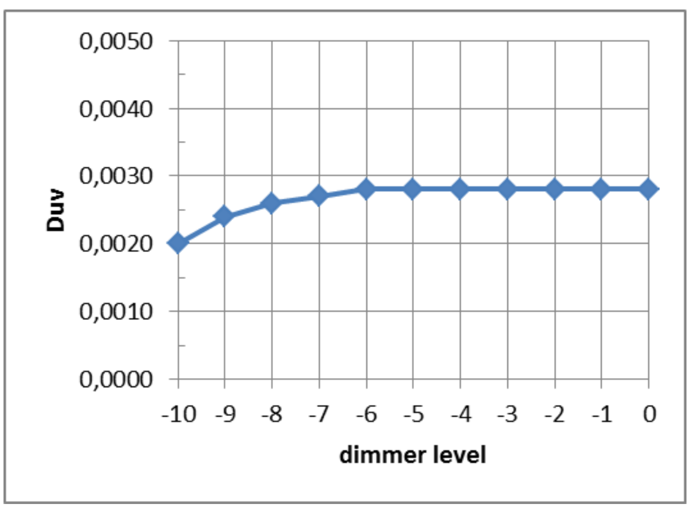
Dimmer performance: CW (6500 K LEDs only)











Return to the dimmer report selection list

Dimmer performance discussion

Here are a few observations from the dimmer measurements presented in this section.

Brightness vs dimmer level
The behavior is identical for all CCTs. Looking at it in details, the first step down is about -12% lower than the maximum output and the other steps somewhere between 9% and 10% lower, down to the "-9" level. For practical use, each step can thus be considered 10% of the max brightness.

The tenth step below maximum output (the "-10" level) is not zero but provides about 4% of the maximum brightness. It cannot be set with a single push on the lower-brightness button and you need to keep your finger on the button for a second or so.

(CCT and *Duv*) vs dimmer level
The CCT and *Duv* are stable down to the "-8" level, i.e. 20% of maximum brightness. These parameters can change significantly for the two lower levels, "-9" and "-10", i.e. 10% and 4% of maximum brightness, which are not used much in practice. Interestingly, the large *Duv* changes at lower output levels have minimal or no effect on the rendering results (*Rf*, *Rg*, *Ra*, *R9*).

We noticed something interesting with the CCT of the lowest level ("-10") of the 6500 K data (set with the color ring; this is not the default CW setting). While the measured CCT of 6922 K at the "-10" level significantly differs from the CCTs at higher output, it is nearly equal to the 6937 K CCT measured at the "-10" level of the "CW" setting (when only the CW LEDs are energized). Please note that the exact CCT obtained by pressing the "CW" button will vary between manufacturing lots; in our case the CCT was measured at 6843 K (maximum output level). The CW CCT is thus not very far from 6500 K and when we use the color ring to set the illuminator CCT at 6500 K, the proportion of the output coming from the WW LEDs is small.[26] So, when we dim the output once set to 6500 K, the amount of WW becomes even smaller and what we see is that it effectively was zero at the "-10" level.

(TM-30 *Rf* and *Rg* and CIE 13.3 *Ra* and *R9*) vs dimmer level
The color rendering indices remain essentially stable at all dimming levels. The most noticeable variations are seen for *Rg* and *R9* at the lowest dimming level ("-10") of the "WW" setting (2700 K LEDs only). While these variations are noticeable on a graph, I doubt that they will be noticeable in practice since they remain close to the indices at maximum output.

In conclusion, for the dimmer performance:

- Each push on the dimmer controls will change the output by about 10% (between 100% and 10%).
- At 10% output, if you keep your finger on the lower-brightness button, output goes down to 4%.
- The CCT and *Duv* are stable down to 20%. Use of the 10% and 4% levels (levels "-9" and "-10") is not recommended if the CCT is critical.
- The color rendering performance (*Rf*, *Rg*, *Ra*, *R9*) is excellent and stable at all dimmer levels (100% to 4%).

[26] This may also explain why we found it more difficult to adjust the CCT using the remote control color ring at values near the two extremes, i.e. WW and CW. In other words, at high CCTs near the CW point, the CCT is very sensitive to small changes in the amount of WW, thus making the adjustment more delicate. The same is true for low CCTs near the WW point.

7. Conclusion

We have seen that a high quality illuminator with adjustable color temperature (CCT) can be built from a commercially available LED strip. An affinity with manual work is a prerequisite to assemble and build the mechanical components and a spectrocolorimeter is required to set the illuminator CCT.

Instead of a "wordy" conclusion, the illuminator performance will be presented in the form of a specification. The criteria selected correspond to those seen in commercial illuminator and if you take the time to compare the respective performance numbers, you will realize that this illuminator is in the top tier of what you can get commercially, at a fraction of the price. The only thing missing is a separate UV content control. However, the spectrums do show broad violet content down to 405 nm, the wavelength of the exciter LED used in the strip we tested, content not present in illuminators based on blue light exciters.

Warning: This is not to be interpreted as guaranteed performances but as a snapshot of what we obtained with the specific components.

Parameter	Specification
CCT range	Based on LED banks: adjustable between 2841 K (WW) and 6843 K (CW)
Work Distance @ 2000 lux (ISO 3664 P1) (max brightness)	469 mm to 500 mm (depending on CCT)
Work Distance @ 500 lux (ISO 3664 P2) (max brightness)	938 mm to 1000 mm (depending on CCT)
Work area (75% of central brightness)	Circle with a diameter equal to 75% of the work distance
TM-30-18 / TM-30-20 *Rf*	Min.: 94,8, Max.: 96,2
TM-30-18 / TM-30-20 *Rg*	Min.: 99,8, Max.: 103,3
TM-30-18 / TM-30-20 Fidelity level (see Appendix D)	F1
CIE 13.3 *Ra*	Min.: 92,0, Max.: 96,2
CIE 13.3 *R9*	Min.: 67,7, Max.: 94,4
ISO 3664 - *u'v'* offset	Min.: 0,0004, Max.: 0,0053 (relative to blackbody)
ISO 23603 - Metameric Index (visible) Shown as: Quality Grade / *MIv*	@ 5000 K (using D50 ref. data): B / 0,42 @ 5500 K (using D55 ref. data): B / 0,49 @ 6500 K (using D65 ref. data): C / 0,65
Dimmer range	CCT, *Duv*, *Rf*, *Rg*, *Ra*, *R9* stable between max output (100%) and 20% of max output
Temperature stability (with heatsink)	5 minutes with low speed heatsink fan (usable from startup) 45 minutes without fan

You will find additional information in these appendices:

- Appendix A: Nuts and bolts
- Appendix B: Drill bits and taps
- Appendix C: Components info and cost breakdown
- Appendix D: TM-30-20 analysis grid
- Appendix E: Lamp base example

Appendix A

Nuts and bolts

The picture below shows the nuts and bolts used in this project and the quantities required for each part.

Note: Except for the MakerBeam T-slot nut XL, you may be able to find these parts in a large hardware store. In some cases where the load applied to the attached components is low you could use a standard M3 nut instead of a T-slot nut.

Note: For some fasteners we decided to buy multi-parts kits since this can be a cost-effective solution (if you intend to use them in other projects!).

Note: Except for the M4 size mounting screws which came with the fan kit, all other screws in the project are **M3** size with a **0,5 mm thread** and **Allen key, i.e. hex key, driven**. The screws should have either a **button head** or a **flat head** depending on usage.

The table on the next page indicates where each part is used. Price and seller info can be found in the Components info and cost breakdown appendix.

Part	Usage
T-slot nut	i- To attach the long section MakerBeamXL profiles on the heatsink (4X). ii- To attach the tripod adapter on a MakerBeamXL profile (4X).
M3-10mm flat head	To hold the tripod adapter on a MakerBeamXL profile (4X).
M3-6mm button head	i- To attach the long section MakerBeamXL profiles on the heatsink (4X). ii- To attach the short section profiles on the long section profiles (4X). iii- To attach the flat brackets on the bezel (8X). iv- To hold the LED dimmer on the bezel (final assembly) (2X).
M3-10mm button head	Used for the fan holder bracket (8X).
M3-12mm standoff FF	Used for the fan holder bracket (4X).
M3 nut	i- To attach the flat brackets on the bezel (4X). ii- To attach the LED dimmer on the bezel (final assembly) (2X). iii- To attach the cable ties on the bezel (final assembly) (3X).

Appendix B

Drill bits and taps

The picture below shows the drill bits and taps used in this project.

The drill bits to use for a given tap are shown below the taps. The 3/32” drill bit was not used since all M3-0,5mm threads were done in the already present center hole at both ends of all MakerBeamXL profiles.

Note: When tapping a thread you should use lubricating/cutting oil. We found that 3-IN-ONE® oil was adequate for aluminum.

The table on the next page indicates where each tool is used.

Tool	Usage
M3-0,5mm tap	Both ends of all MakerBeamXL profiles (see profile machining).
M4-0,7mm tap	fan holder bracket
1/4-20 UNC tap	tripod adapter
1/8" (or 3,3 mm) drill bit	heatsink, fan holder bracket, flat bracket, tripod adapter
13/64" drill bit	tripod adapter
7/64" drill bit	Long profile sections (see profile machining).
1/4" drill bit	tripod adapter countersinks

Appendix C

Components info and cost breakdown

LED ASSEMBLY							
Item	**Description – see https://store.yujiintl.com/**	**Vendor**	**Store**	**QTY**	**Pkg. price**	**Parts/Pkg.**	**Part(s) price**
YJ-VTC-12HRB-2835L-24-2765	Full Spectrum CRI 98 Dynamic Tunable White Multirow LED Strip	Yujileds	Yujileds	1	219,92	1	219,92
YJ-RCT-RB2C-G01	Remote Control Dimmer Kit for Single Color/Bi-color LED Strips	Yujileds	Yujileds	1	40,07	1	40,07
YJ-DPS-120-24V-G01	IP67 Waterproof Power Supply for LED Strips, 120W, 24V	Yujileds	Yujileds	1	62,34	1	62,34
							322,34
HEATSINK ASSEMBLY							
Item	**Description**	**Vendor**	**Store**	**QTY**	**Pkg. price**	**Parts/Pkg.**	**Part(s) price**
fan kit	120mm AC 110V 220V DC 12V Fan w/Speed Control (alt. source)	GDSTIME	Amazon	1	17,50	1	17,50
heatsink	Aluminum Heatsink 300x140x20 mm (alternate source)	Yae First Trading	Amazon	1	17,99	1	17,99
M3-12 standoffs	M3 Brass Standoffs Hex Female-Female (from a kit)	tanus	Amazon	4	24,49	300	0,33
M3-10mm screw-button	Stainless Steel-Hex Drive **Button Head**	Em/woah Inc.	Amazon	8	10,88	100	0,87
fan holder (Aluminum)	21.2x15x6.7 mm	custom-made		4			
							36,69
BEZEL ASSEMBLY							
Item	**Description**	**Vendor**	**Store**	**QTY**	**Pkg. price**	**Parts/Pkg.**	**Part(s) price**
beam (Aluminum)	MakerBeam XL black anodized beams 1000x15x15 mm	Capital Affiliated	Amazon	1	116,27	4	29,07
T-slot nuts	MakerBeam XL T-Slot Nuts	GETALLDAY LLC	Amazon	4	43,18	50	3,45
M3 nut	flat brackets (4), cable ties (3), dimmer (2), Stainless Steel, from M3 M4 M5 Phillips Pan Head Screw Bolt Nut Washer Kit	Dongguan Lanqi Jewelry Co.,Ltd.	Amazon	9	15,88	240	0,60
M3-6mm screw-button	Stainless Steel-Hex Drive **Button Head**	Em/woah Inc.	Amazon	18	10,88	100	1,96
flat bracket (Aluminum)	30x13 mm; 1/16" th.	custom-made		4			
							35,08
TRIPOD ADAPTER							
Item	**Description**	**Vendor**	**Store**	**QTY**	**Pkg. price**	**Parts/Pkg.**	**Part(s) price**
T-slot nuts	MakerBeam XL T-Slot Nuts	GETALLDAY LLC	Amazon	4	43,18	50	3,45
M3-10mm screw-flat	Stainless Steel-Hex Drive **Flat Head** by Fullerkreg	kunshan dongfluo hardware co.,ltd	Amazon	4	18,99	100	0,76
plate (Aluminum)	67x15x6.7 mm	custom-made		1			
							4,21
					Pkg. Total 598,40 $	CAN $	**Fixture Total 398,32 $**

Appendix D

TM-30-20 analysis grid

Recommended Color Rendition Specification Criteria

The recommendations for specifying light source color rendition from TM-30-20 can be found in its Annex E of which **Table E2** is reproduced below (Note :This table is identical to the one of TM-30-18 Annex E). TM-30-20 Annex F provides additional background and evidence to support the recommendations. Reading of Annex E is strongly recommended for those who want to better understand the subtleties of color rendition analysis.

TM-30-20 Annex E – Table E-2 (used by permission)

Priority Level (The balance between allowing for tradeoffs and increasing the likelihood of meeting the design intent)	**Design Intent** (The desired effect of color rendition on the illuminated environment)		
	Preference (P)	**Vividness (V)**	**Fidelity (F)**
1	**P1** $R_f \geq 78$ $R_g \geq 95$ $-1\% \leq R_{cs,h1} \leq 15\%$	**V1** $R_g \geq 118$ $R_{cs,h1} \geq 15\%$	**F1** $R_f \geq 95$
2	**P2** $R_f \geq 75$ $R_g \geq 92$ $-7\% \leq R_{cs,h1} \leq 19\%$	**V2** $R_g \geq 110$ $R_{cs,h1} \geq 6\%$	**F2** $R_f \geq 90$ $R_{f,h1} \geq 90$
3	**P3** $R_f \geq 70$ $R_g \geq 89$ $-12\% \leq R_{cs,h1} \leq 23\%$	**V3** $R_g \geq 100$ $R_{cs,h1} \geq 0\%$	**F3** $R_f \geq 85$ $R_{f,h1} \geq 85$

Table note: All criteria assume a polychromatic environment with average horizontal illuminance between 200 and 700 lux and uniform chromaticity.

The **Design Intents'** typical usages suggested in Annex E are:

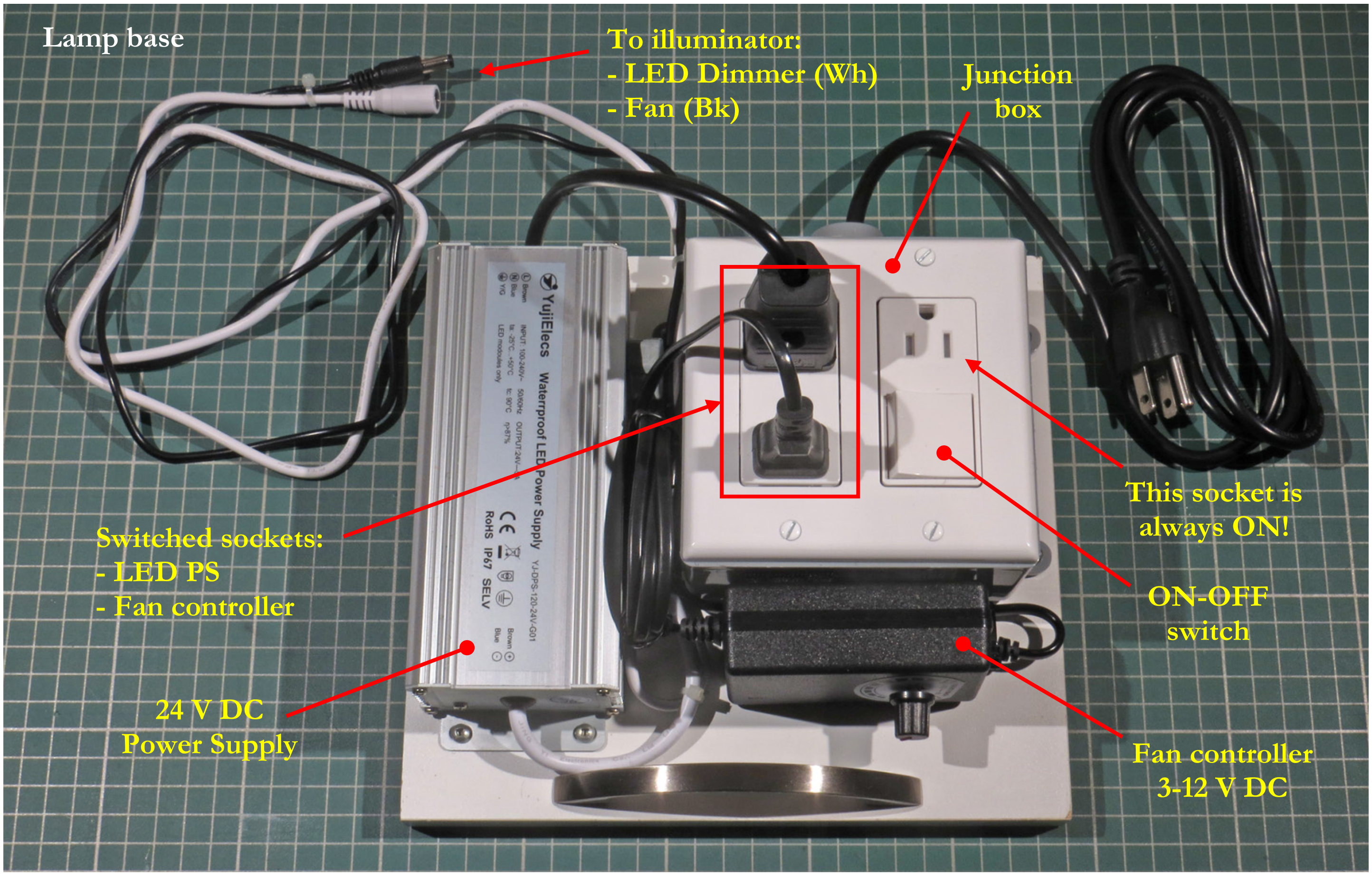
- **Preference (P)**: retail, office, hospitality, and residential lighting applications
- **Vividness (V)**: entertainment, display, and retail applications
- **Fidelity (F)**: manufacturing, medical, color matching, and color reproduction applications

Three **Priority Levels** are defined for each Design Intent, with "**Level 1**" being the most stringent. Because of how the design constraints were defined and how the parameters are computed, it is not possible to find a light source which reaches a "Level 1" for all three intents. However, a **test** source which is **identical** to a **reference** source will exhibit a Level 1 for Preference (**P1**) and Fidelity (**F1**), and a Level 3 for Vividness (**V3**). These results are usually presented in the form "**P1 | V3 | F1**".

Appendix E

Lamp base example

As mentioned in the Final assembly/Integration section, we do not present in details how to package the dimmer power supply and the fan speed control since this is not essential to the design of the illuminator. Nonetheless, as soon as your illuminator will light up, you will be looking for ways to facilitate transport and connection of **all** components. The picture below shows a lamp base that meets "our" requirements; yours may vary!



We have mounted all the components on a melamine covered wood board; we even added a cabinet handle for transport and to give it a nice "recycled" look! The components are held by screws, cable-ties, WAGO® splicing connectors, and even VELCRO® Brand[27] fasteners (for the fan controller). The base is powered with a single standard AC power cord. AC is distributed inside a PVC junction box with a switch and three AC sockets. The two sockets on the left are switched and the socket above the switch is always ON (when the cord is connected!). The switched sockets are used to energize the 24 V DC LED power supply and the 12 V DC fan controller. The always ON socket is dedicated, in our case, to a laptop on which the spectrocolorimeter is connected.

Two DC-power cables exit from the base; the one in black is for the fan while the white cable is connected to the LED Dimmer. These two cables are fitted with the same connector type so, to prevent errors, the cable ends are mismatched; one cable ends with a female connector and the other with a male connector. Since the maximum current required to power the LED strip can be relatively high (≈2 A), the LED strip cable should be made of wires with a gage of at least 20 AWG. Here are links to two such cables (search for "*DC power cable 12V 20AWG*"):

- Amazon: QTY-2 12ft/3,6m 5,5mm*2,1mm Male to Female Power DC cable, 20 AWG
- Amazon: QTY-1 10ft/3m 5,5mm*2,1mm Male to Female Power DC cable, 18 AWG

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The BabelColor Company

Founded in 2003, *The BabelColor Company* develops and sells software dedicated to the measurement and analysis of color.

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Revision History

First release (2021-02-20)

Rev. a (2021-03-05): "Duv vs CCT" and "(TM-30 and CRI 13.3) vs CCT" graphs added in the Colorimetric performance section. Addition of the fan specification table. Addition of Appendix E (Lamp base example).