

High Dynamic Range Imaging (HDRI)

Introduction

A High Dynamic Range Image in this documentation (HDRI) is a panoramic 360° image with accurate real world lighting information.

HDRIs are use with the LookDev, see <https://docs.unity3d.com/Manual/LookDev.html>, or as environment lighting in a level.

This documentation aim to describe a method to capture accurate HDRI with full lighting information (i.e no clipped light range) and correctly calibrated. A pack of HDRI capture with the method describe in this documentation is available on the asset store for free:

<https://www.assetstore.unity3d.com/en/#!/content/72511>

HDRI workflow

First step is to gather the equipment required to capture and reconstruct an HDRI

https://docs.google.com/document/d/1xqwASr0BosHjvTec2oiRMd_ZQHPWGZaPGYfifJXKzkg/edit#

The capture workflows can be adapted for any kind of DSLR camera (Unity use Camera 6D).

Second step is to acquire the HDRI

<https://docs.google.com/document/d/1C2KewWHZAEL2QByTgCQR8gmHSJmSUHzChVh9ocjh2IY/edit#>

Third step is to reconstruct the HDRI

https://docs.google.com/document/d/1XRAqVBjefQW-PbV9u0gUWQhoJ9Z67BP57u9d-_y0S0l/edit#

Optionally the HDRI can also be calibrated for luminance:

https://docs.google.com/document/d/1pEGMS3N0aGcGta2uosyc9kV8f73INDV7KifTmBrBw_o/edit#

This is something useful when an analytic sun is simulated in game with a directional light. In this case the measure perform during the capture process allow to setup correctly the directional light intensity without the need of eye-balling it.

Lastly it may be required to remove the Sun from an HDRI to replace it by a directional light like mention above.

https://docs.google.com/document/d/1lcZ_8x_6h3zZbvL1m7akqyfiBsKEiXg6vXtyUghZ4Vo/edit#

Sum up of steps

All the step explained in this documentation are summed up here:

The form to help and track HDRI information is here:

<https://confluence.hq.unity3d.com/download/attachments/23186457/HDRIInformation.pdf?version=1&modificationDate=1489066943806&api=v2>

Capture

With the equipment:

- Setup the tripod, nodal head, CamRanger, and align pivot point. Don't forget to have a clean lens.
- Setup camera to RAW, manual mode, disable all color/contrast enhancing and automatic white balance.
- Fix ISO to 100 and aperture to f/8 with focal length of 0.5m.
- Calculate the EV range of the scene.
- If necessary determine the ND filters to use.
- Use the histogram to check when the darkest and brightest brackets don't clip.
- Calculate the number of brackets required $(EV\ range / EV\ step) + 1$. Recommended 1 EV step.
- Program CamRanger with start value, number of shots and EV step.
- Capture seven views with required number of bracket: horizontal (0, 120, 240) with vertical of 30, horizontal (60, 180, 300) with vertical of -30 and bottom view for tripod removal.
- In the case of a very bright light source there is a first round of shots taken with the ND filter and second round without.
- Perform an extra bracketed bottom view with white balance target.
- (Optional) Use the lux meter to measure the illuminance at the camera position in the up direction.
- Report acquisition information on the HDRI form

Reconstruction

- Extract RAW picture and convert to 16 bit linear TIFF: `dcrw.exe -v -4 -T [file]`.
- (Optional) Correct image artifact.
- Convert to 32 bit TIFF with Adobe Photoshop.
- Create the HDR panorama with and without the ColorChecker with PTGui.
- Correct horizon deformation if needed.
- Perform white balance and (optional) luminance calibration in Adobe Photoshop.
- Remap value if maximum value is above 65504 to be compliant with 16 bit precision.

Equipment

HDRi acquisition requires many pieces of photography equipment. Here, we provide the list of equipment we use to capture HDRIs at Unity. In general, we prefer to rely on affordable devices with a good quality-to-price ratio. Every time we move to a new location for HDRi acquisition, we use this list as a checklist and have found it to be a good practice to adopt.



1. Camera: Canon EOS 6D
2. Lens: Fisheye Sigma 8 mm f/4 EX-DG Circular (include Filter support)
3. Tripod: Manfrotto 475 B.Digital pro tripod black
4. Tripod bag
5. Nodal Ninja Head 4 (highly recommended)
6. Remote: CamRanger + USB cable
7. Mobile: Android or IOS

8. Laptop: Mac Book Pro (optional: dedicated to storage and processing data during long trip)
9. Secondary camera battery
10. Memory Card 256GB (Class 10)
11. Colorchecker Classic (X-rite)
12. Colorchecker Passport Photo (X-rite)
13. (Optional for luminance calibration) Lux meter: Sauter SO 200K (additional battery can be necessary)
14. Unused
15. Spirit level
16. HOYA ND Filter: 16, 32, 64, 500, 1000. Unity use power of 2 ND Filters to simplify the workflow. HOYA are recommended due to their Filters' reduced vignetting and color shift.
17. Bag
18. Screwdriver
19. Lenspen (lens cleaner tools)
20. Notepad and pen to record information about the photographs: location, time, weather, lux, luminance, range, EV step, lens setting
21. Marker
22. Ninja Nodal Nadir Adapter

Note: HDRI processing is an heavy task and we advice to use a computer with a minimum of 32 Go of memory, a SSD, and a good CPU to be comfortable.

During long shooting sessions, be aware of the amount of data that can be captured. Additional batteries and hard drives are important to avoid interrupting the shooting session. Also, it is good practice to take a picture of the notepad before shooting to identify which pictures belong to which HDRI. When planning a trip, be aware of the size of the equipment. The Manfrotto tripod and head are heavy, so moving to a lot of locations without a car is difficult. Nevertheless, such heavy devices are very stable in case of wind (stability allows easier HDRI reconstruction) and important for low shutter speed. At Unity we decided to deal with this restriction.

Neutral density Filters

The equipment list includes neutral density (ND) Filter. An ND Filter reduces the amount of light entering the lens by reducing the intensity of all wavelengths of light equally, giving no changes in hue or color rendition. Applying an appropriate ND Filter is equivalent to stepping down one or more additional EVs.



The strength of an ND Filter depends on its ND number notation, which is mostly a power of two.

Decreasing light intensity by 1 EV requires doubling the ND number. Table below gathers information from various ND Filters.

NDnumber notation	EV reduction	Transmittance
	0	100%
ND2	1	50%
ND4	2	25%
ND8	3	12.5%
ND16	4	6.25%
ND32	5	3.125%
ND64	6	1.563%
ND100	6.64	1%
ND128	7	0.781%
ND256	8	0.391%
ND400	8.64	0.25%
ND512	9	0.195%
ND1024 (also called ND1000)	10	0.098%
ND2048	11	0.049%
ND4096	12	0.024%
ND8192	13	0.012%

An ND Filter cannot be mounted directly on a fisheye lens due to its curvature. Fisheye lenses require a Filter support to do so (that will crop the field of view). It is always provided with the fisheye lens.

ND Filters can be mounted on top of each other. In this case, their EV reduction is additive:

An ND32 on top of an ND1000 produces an EV reduction of 15. We recommend having various power of 2 ND Filters to be able to deal with a variety of high intensities.

Software

1- **Cam ranger** application (Camera remote)

Windows: <http://camranger.com/windows-downloads/>

Mac OS: <http://camranger.com/mac-downloads/>

Android: <http://camranger.com/android-downloads/> or use Playstore

IOS: <http://camranger.com/ios-downloads/> or use Applestore

2- **DCRaw**: Convert RAW to TIFF

Windows: <http://www.centrostudiprogressofotografico.it/en/dcraw/>

Mac OS: <http://www.cybercom.net/~dcoffin/dcraw/>

3- **Adobe Photoshop CC**: Lateral chromatic aberration correction, white balance

<http://www.photoshop.com/products/photoshop>

4 - **PTGui**: Create HDR panorama - PTGui Pro is required

<https://www.ptgui.com/download.html>

5 - **Unity (LookDev)**: Viewer

Panoramic HDRI acquisition

What to capture?

Captured HDRIs are mainly used to author an asset in the context of look development. It is not necessary that the HDRI looks beautiful, but it should be as close as possible to the game environment and create interesting lighting conditions. Typical examples are the Star Wars games that have clearly identified environments (sequoia forest, sand desert, snow desert, etc.) where the best option is to capture the HDRI at the same location used for the movie.

Example of an HDRI that can be used for asset authoring in the context of a game level located on Endor in the movie Star Wars: Return of the Jedi:



Artists tend to author their assets with an HDRI that includes a bright light source like the sun because it creates good highlights. They later use other HDRIs with different lighting conditions (overcast sky, night, dramatic, indoor, etc.) to check the correct behavior of the asset.

Equipment setup

The following section describes how we setup the equipment to capture the HDRI at Unity. The tripod and nodal head are mandatory as various shots need to be perfectly aligned for a sharper final image at potentially low shutter speeds.

Tripod and panoramic head

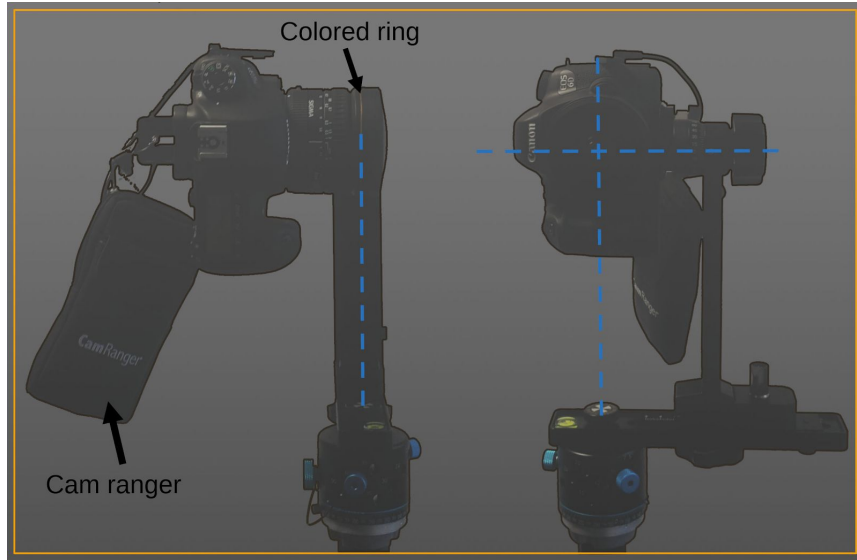
First, install the Nadir Adapter on the nodal head. Then mount the camera on the tripod with the nodal head. The camera should be at around eye level. With this setting, the 360 panorama looks as if you were in the scene.



Camera alignment and remote controller with nodal head

The nodal head gives 360° freedom of movement. To achieve perfect stitching without wasting time on the computer for the alignment task, you should take the time to level and align the camera to find the no-parallax pivot point.

- Level the tripod.
- Use the nodal head to put the lens center at the pivot point. Use a level to center the camera.
- The colored ring on the lens is the center.
- Attach the CamRanger on the back side of the head to follow the camera rotation.



Lens cleaning

Before any shot, the lens must be cleaned as dust on the lens produces a lot of artifacts.

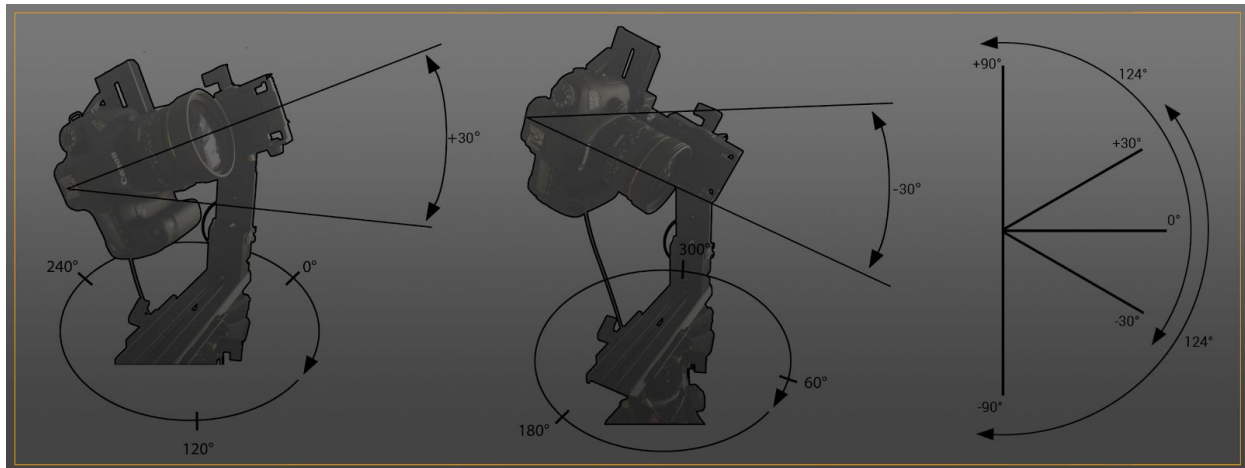


Camera orientation and number of views

To build a 360° panorama with a fisheye lens, we use the following settings:

- 3 views (horizontal 0°, 120°, 240°) at +30° vertical
- 3 views (horizontal 60°, 180°, 300°) at -30° vertical

We found that this setting gives fast and good quality results in practice. Note that 30° is easy to set up with the Ninja head. With an angle of +30°, the sky/top side is completely captured. With an angle of -30°, the tripod is barely visible.



Choosing 30° instead of 45° gives more detail at the horizon as artifacts increase proportionally to the distance to lens center. The horizon often contains a lot of detail that helps to match overlapping shots and it often includes moving objects that need to be detected correctly to be removed. Moreover, with 30° and a field of view of 124° it covers the range -32° to +92°, so it correctly includes the whole sky.

Note: the fisheye lens has a field of view of 180° but distortion, vignetting and chromatic aberration appears at the edge of the lens (> 120°). It is better to use more views with some of them overlapping, in order to discard the faulty region during postprocessing. The stitching also needs overlapped areas to match images together. Lastly, the ND Filter used to capture very bright light sources causes the effective field of view to be 124° (40° for the support, plus 16° for the ND Filter) and not 180°.

To have a snap during the rotation for faster shooting, we set the head to a 60° rotation step.



An extra bottom view is captured to remove the tripod entirely:



- Put a marker under the tripod at the center point. (1)
- Place the camera at the bottom orientation. (1)
- Turn the Nadir Adapter to 180. (2)
- Move the tripod until the focus is on the marker and ensure that the tripod feet do not cover the same places. (2)
- Lock the head to avoid movement during the bottom shot.
- Remove the marker.
- Do the bottom view. (3)

To sum up, we use seven views to cover the 360° panorama.



Camera settings

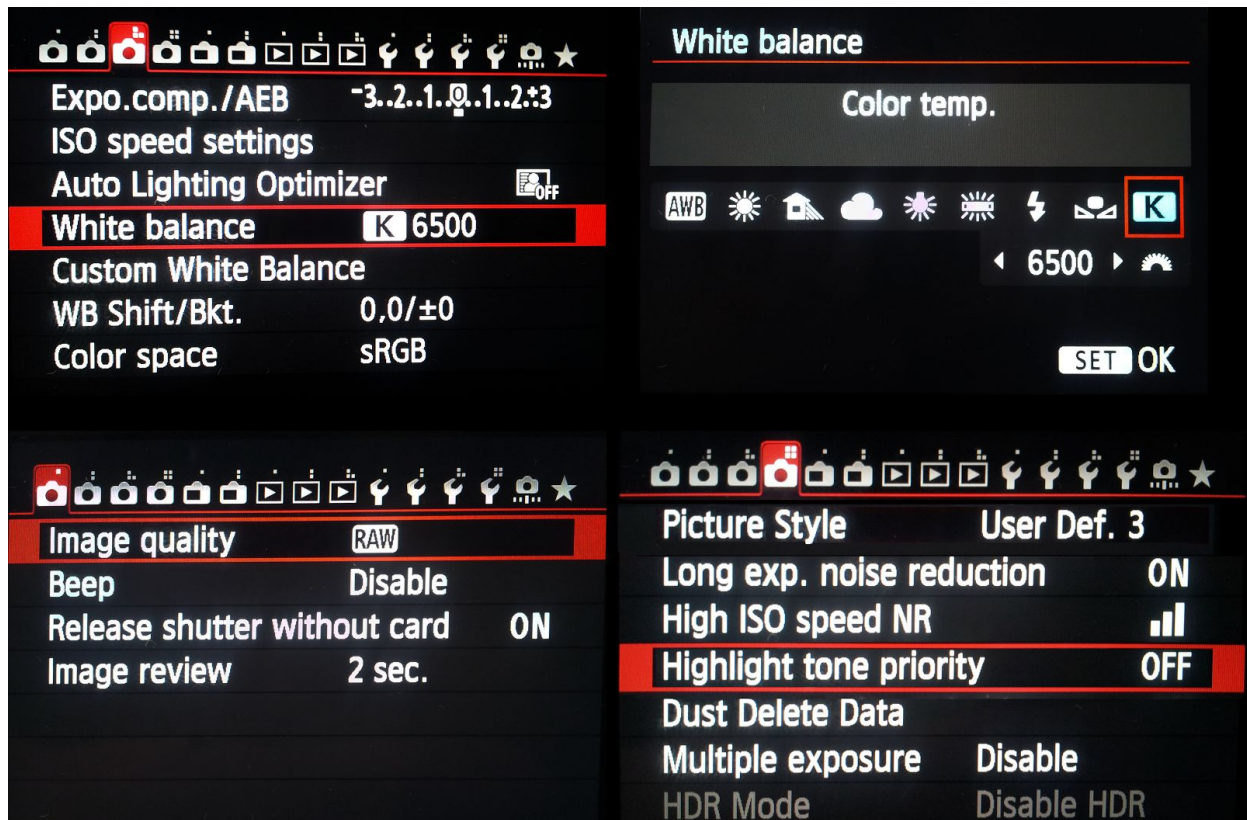
An HDRI is a combination of shots taken with different exposures (brackets). HDRI acquisition requires taking several shots of varying exposure of each view. The exposure is based on three parameters: shutter speed (t), aperture (N) and ISO (S). A given combination of these parameters can be summarized as an exposure value (EV).

Unity's HDRIs are acquired with fixed aperture value f/8 at 0.5m, that seems to provide the best result for a panorama, and fixed ISO value 100 to minimize noise. If at the maximum shutter speed (30s on Canon 6D) the darkest area is not covered, it is necessary to increase the ISO to capture the full range. Also, in some specific cases where shooting speed is crucial - a sunrise, for instance - we find it useful to increase ISO despite the resulting noise.

Constant EV step increments/decrements provide the best result when reconstructing an HDRI. The Unity team decided to use 1 EV step.

Remember to:

- Setup camera to use RAW format.
- Place camera in manual mode.
- Disable automatic white balancing and set the white balance to 6500K. RAW files are not white balanced and we do not apply any white balancing to them in our current workflow, but we use the setting to make sure that camera previews all use the same white balancing.
- Disable all color and contrast enhancing features.



More details about Unity settings for HDRI can be find in this presentation:

http://blog.selfshadow.com/publications/s2016-shading-course/unity/s2016_pbs_unity_hdri_notes.pdf

Shutter speed

The shutter speed controls the amount of time that the sensor is exposed to light. Each time the shutter speed is doubled, the quantity of light on the sensor is doubled.

This parameter is the only varying parameter for panoramic shooting and is thus used to control the exposure of the various shots. Several brackets are necessary to capture the dynamic range (i.e. contrast) of the scene in order to correctly reconstruct the HDRI. Finding the full range depends on the scene's context (indoor, outdoor, day, night, ...) and weather conditions (sunny, cloudy, ...). We recommended determining the range before each scene acquisition to avoid wasting time on unnecessary shots or useless results (e.g. clipped lighting). To get the full range of the scene, we use the preview mode:

- Fix ISO and aperture with the values provided in the previous section - we usually use ISO 100 and aperture f/8 with a focal distance of 0.5m.
- Orient the camera so its direction is parallel to the ground, turn on preview mode with the histogram activated and rotate the camera on the tripod to cover the whole panorama. During the process, identify the darkest and brightest areas of the scene.

- Use the main dial to adjust the shutter speed in the darkest and brightest areas until the histogram is not clamped. The brightest areas are the most difficult to capture completely. The histogram can look correct but the highlights are still bloomed. To address this, we increase the shutter speed until bloom completely disappears around the bright region.

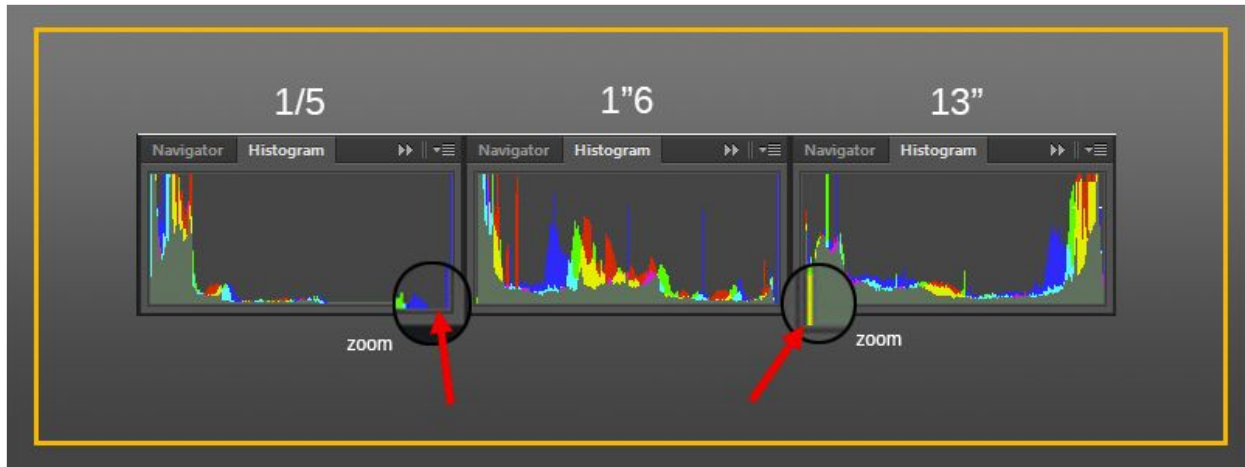


1. Preview button
2. Dark areas not clamped
3. Bright areas not clamped
4. Highlight checking

- The previous information provides the set of shutter speed values to use and the EV range of the scene.

Note: the start value in the CamRanger application must be set to *shadows point* (lower exposure). This range determination process is valid for overcast skies or interiors. On sunny days or in the presence of very bright light sources, the camera cannot capture high ranges without an ND Filter. We describe the specific setup and how to determine ranges for capturing very bright light sources in “Sun and other bright light sources” section.

Image clipping detection with histogram



The first histogram (1/5) does not clamp the brightest values. The last histogram (13") does not clamp the darkest values (1 pixel empty from the left). It is important to note that with a fisheye lens, the dark part of the histogram will exhibit a weird pattern due to the circular fisheye format.

Number of brackets and set of shutter speed values

The EV range is dened by the difference between the shutter speed to capture the brightest and darkest areas. Every time the shutter speed is doubled, an EV is added. The number of brackets to do by view is $(EV\ range / EV\ step) + 1$. If the number of shots is not an integer, it should be rounded up.

At Unity, we use following table to easily find the number of brackets to do and with which shutter speed values.

1/4000	1/2000	1/1000	1/500	1/250	1/125	1/60	1/30	1/15	1/8	1/4	1/2	1	2	4	8	15	30
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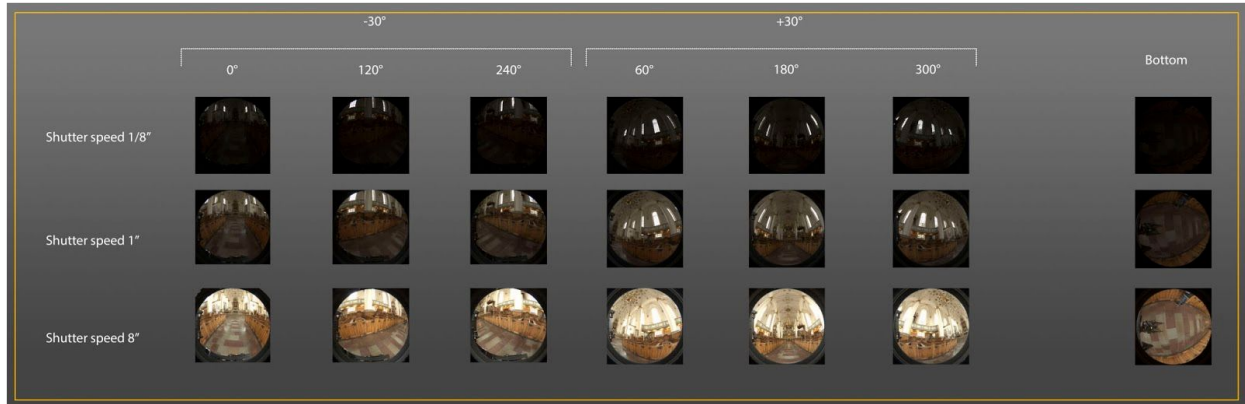
Check the table for the longest and shortest shutter speed values needed based on the bright and dark areas seen before. The number of columns in between the two values is the number of shots to do.

Each value between the two values is the shutter speed to use for the bracket.

Here is an example for a scene with brightest value not clamped at 1/8" and darkest value not clamped at 8". Fixed camera settings is ISO 100 and aperture f8. And Step of 3 EVs.

- Between 1/8" and 8", there is a difference of 6 EVs (7 different settings in the table): 1/8" - 1/4" - 1/2" - 1" - 2" - 4"- 8".
- The number of shots to take is $(6 / 3) + 1 = 3$. With 1/8", 1", and 8".
- In CamRanger, define the shadow point to 1/8", step to 3 EV and number of shots to 3.

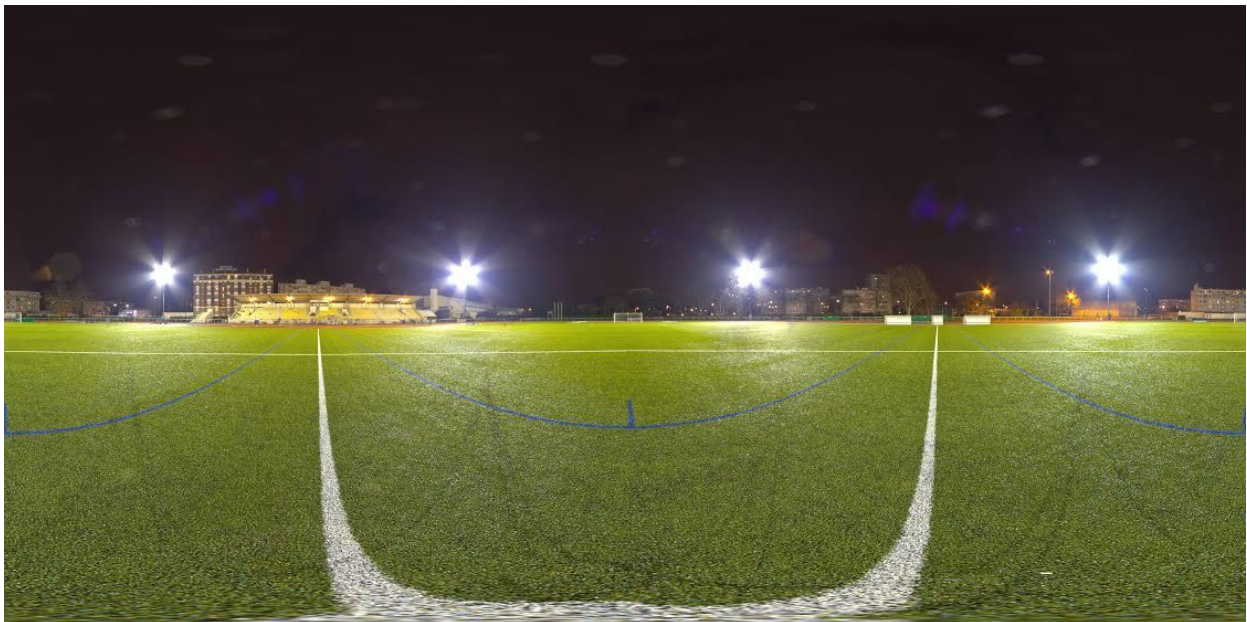
This will produce the following brackets:



Sun and other bright light sources

Dealing with high intensity

Creating an HDRI requires taking shots at various exposures, and shutter speed is the only varying parameter in Unity's HDRI capture process to control this exposure. Note however that shutter speed control is bounded. On a Canon 6D for example, shutter speed can vary from 30s to 1/4000". For scenes with very bright light sources such as spot lights in a football stadium or the sun, which can emit up to 30 EV, such settings are insufficient and the intensity of the lights will be clipped as well as highlights on objects.



In order to capture such high intensity values without clipping, it is required to use ND Filters.

Estimate which Filter is needed

- Face the camera towards the very bright light source. The light should be in the middle of the view and it will be the first view position (0) of the Unity capture process described earlier. Use the zoom button to t the brightest area in preview mode.
- Set the shutter speed to the minimum allowed (1/4000" for Canon 6D). Install one or more ND Filters in front of the lens (from lower to higher EV reduction) until the light source disappears. Then decrease the shutter speed until the range limit of the scene is found, like in the regular process. The histogram is not always helpful for this step as the bright source area can be really small, so simply control the preview until the bright light source disappears.
- When shooting a clear sky with sun scene ND1000+ND500 is the default ND Filters choice.

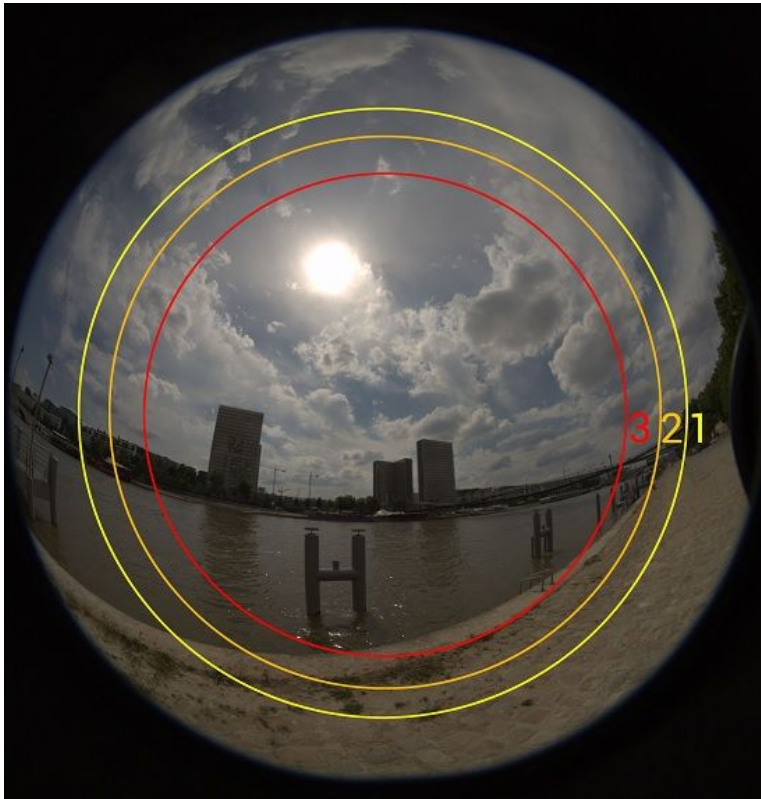
Camera facing the light source:



Different filters are installed until the bright light source disappears:



It is important to use as few ND Filters as possible as they reduce the field of view available to the camera:



1- Filter support crops at 139°.

2- One ND Filter crops at 124°.

3- Two ND Filters crop at 110°.

Determine EV range, number of shots and start shutter speed

ND Filters allow us to emulate a decrease of EV without changing the camera settings. It can be helpful to think about it as if we were able to decrease the shutter speed below the camera's limit, generating a *virtual* shutter speed value. The shooting is split in two parts. The first part is performed with the ND Filters for all *virtual* shutter speed below the camera's shutter speed limit. The second part is done with the usual process.

The number of brackets with ND Filter to capture can be retrieve in the below "Sun" table by following a similar process than with regular (non sun) table presented previously (TODO: put a link here):

EV	Virtual	No filter	ND16	ND32	ND64	ND500	ND1000	ND500 + ND1000
0	1/4096	1/4000	1/250	1/125	1/60	1/8	1/4	
-1	1/8192		1/500	1/250	1/125	1/15	1/8	
-2	1/16384		1/1000	1/500	1/250	1/30	1/15	
-3	1/32768		1/2000	1/1000	1/500	1/60	1/30	
-4	1/65536		1/4000	1/2000	1/1000	1/125	1/60	
-5	1/131072			1/4000	1/2000	1/250	1/125	
-6	1/262144				1/4000	1/500	1/250	
-7	1/524288					1/1000	1/500	
-8	1/1048576					1/2000	1/1000	
-9	1/2097152					1/4000	1/2000	
-10	1/4194304						1/4000	1/8
-11	1/8388608							1/15
-12	1/16777216							1/30
-13	1/33554432							1/60
-14	1/67108864							1/125
-15	1/134217728							1/250
-16	1/268435456							1/500
-17	1/536870912							1/1000
-18	1/1073741824							1/2000
-19	1/2147483648							1/4000

The table list of the ND Filter use at Unity. From previous step (Estimate which Filter is needed) we have the shutter speed that clip the bright light for a given ND Filter. The number of row between row EV-1 and this bright clip' shutter speed is the number of brackets to perform with which shutter speed. EV 0 is redundant with the 1/4000" shutter speed without ND Filters and is not required. If ever equivalent exposures are captured due to the CamRanger software, they should be deleted. Brackets without ND Filters are preferred because they are less cropped. Non power of 2 ND Filters (ND100, ND400) should be avoided to simplify the capture process. The EV range of the scene is the number of brackets with ND Filters added to the number of brackets without minus one.

Example: An ND32 Filter with shutter speed 1/4000 is needed to capture the bright light source. The dark area is not clip with 1/8 shutter speed without ND Filter. We use 1 EV constant step. Looking into regular and Sun tables:

- 5 brackets with an ND32 Filter will be captured with shutter speeds: 1/4000", 1/2000", 1/1000", 1/500", 1/250".

- 10 brackets without ND Filter will be capture with shutter speeds: 1/4000", 1/2000", 1/1000", 1/500", 1/250", 1/125", 1/60", 1/30", 1/15", 1/8".
- Scene EV range is 14 (15 bracket - 1).

The sun without clouds can require up to EV -19, thus the limit of the reference table. To capture the sun an ND1000000 Filter can be used, but such a Filter is not easy to find. Moreover, a long exposure time can be a problem in case of such intense lighting because of movement (for example, clouds). It is best to do more series with few ND Filters in order to use faster shutter speed settings. This is the case highlighted with ND1000 + ND500 (19 EV reduction) in the table. The first series of brackets are captured with both Filters from 1/4000" to 1/15", then a second series with ND1000 only is captured from 1/4000" to 1/8", and lastly the usual process is performed.

In this case, it is very important to place the sun at the center of the view at 0. Two ND Filters crop the image up to 1100. This is a problem because three views do not add up to 3600. However, in the range capture with two Filters (-19 to -11 EV) only the sun is visible, the rest of the image (not the sun) is black so there is no impact to cropping at 124° instead of 110° when performing the stitching. An alternative could be to capture four views instead of three in case of highlights in the missing area.

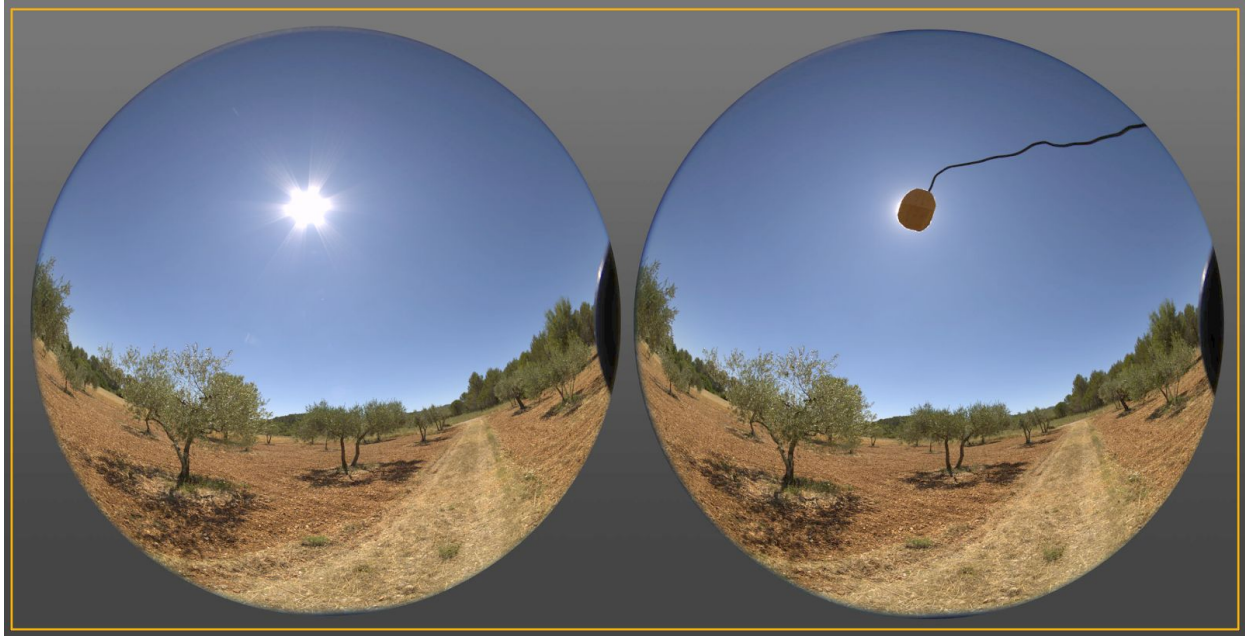
Shooting session

For each of the seven views of our HDRI capture, there are two (or three) brackets series to capture with: one with and one without the ND Filter. It is simpler to do the same numbers of brackets by series to ease the stitching step. Where brackets with the ND Filter are totally black, they can be replaced by black images and shooting time can be saved. Often the bottom view does not need brackets with ND Filters. It is however not recommended for other views, because some low lighting could be lost.

For a view, begin by the series of bracket with the ND Filters, then remove the support where the ND Filters are screwed. The following figure shows an example of such a bracket series.



In case of presence of big lens flares, the first view with the sun is doubled with a cardboard to cover the sun. Then HDRI is composed at after reconstruction.



Acquired calibration data

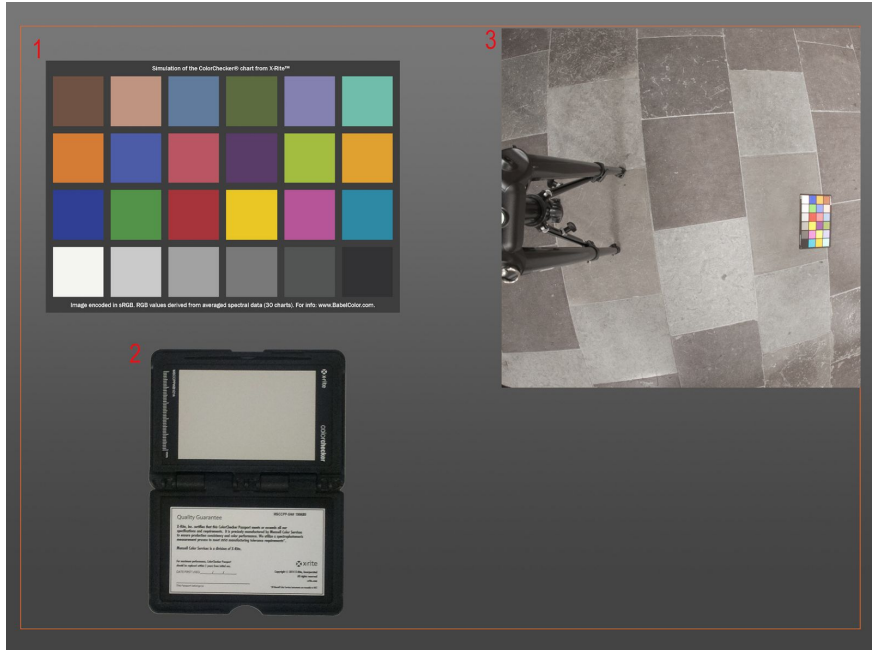
In order to calibrate an HDRI for both chrominance (white balance) and luminance it is necessary to acquire some extra information.

White balance data

During acquisition automatic white balance is disabled. Then during the reconstruction a manual white balance is performed.

To acquire white balanced data, during the acquisition process after the bottom view, recapture the bottom view (for all bracketed exposures) but this time with an Xrite chart: either the white balance chart, ColorChecker or ColorChecker Passport. The Xrite white balance chart is recommended compared to the ColorChecker for white balancing because it is more neutral.

There is no correct location to put the white balance chart. Setting the chart on the bottom view is an option to average all the lighting sources. Try to have it perpendicular to the lens and avoid tilting it. To avoid occlusion from the tripod, the chart is set at 1 meter from the camera.



1- Color checker

2- Passport white balance

3- Calibration data placement

HDRI Reconstruction

The reconstruction of an HDRI includes the following steps:

- Extracting bracketed exposures from the camera in RAW format.
- Converting it to a workable TIFF format.
- Applying chromatic aberration and vignetting correction.
- Stitching bracketed exposures into an HDR panorama.
- White balance and luminance calibration, plus range validation.

RAW to linear RGB 16 bit TIFF

RAW format is the proprietary file format of the camera. For Canon 6D it is CR2.

A RAW file contains camera sensor data, i.e., native RGB values in a Bayer mosaic pattern. To be manipulated, the RAW file must be converted to a linear RGB 16 bit (or 32 bit) file. In this document we call linear RGB the color space defined with sRGB primaries and the D65 white point but without any gamma correction.

dcraw is used to convert RAW files extracted from the camera into a linear 16 bit TIFF. PTGui can load a RAW file directly (PTGui uses dcraw internally, like most HDRI tools) but our team decided to perform some extra manipulation (like chromatic aberration and vignetting corrections) before sending the shots to PTGui. dcraw has many options: we use the following command lines in our workflow:

DCRaw is used to convert RAW files extract from the camera into a linear 16 bit TIFF format.

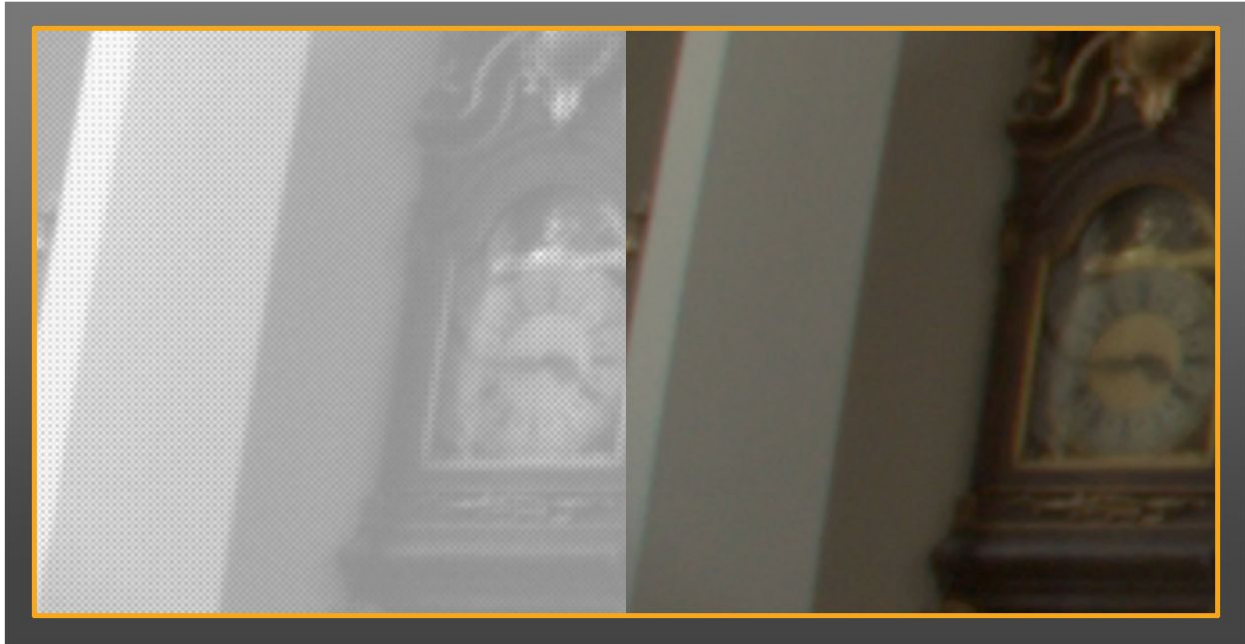
DCRaw option : `-v -4 -T [file]`.

`-v` : print verbose messages. To follow the conversion process.

`-4` : Convert to linear 16 bit format to keep a 16 bit linear workflow. No gamma applied, no automatic brightness correction.

`-T` : Write in TIFF instead of PPM. To have a compatible format for Photoshop and PTGUI.

These options generate a 16 bit TIFF in linear RGB.



Left images is the RAW as it is acquired by the sensor (luminance). The right image is the linear TIFF generated.

Having a good linear reconstruction is important to have correct HDR values, thus we prefer dcrw compared to other software such as Adobe Camera Raw due to its improved control and because it conserves linearity.

Correcting image artifacts (Optional)

More details about image artifacts correction can be find in this presentation:

http://blog.selfshadow.com/publications/s2016-shading-course/unity/s2016_pbs_unity_hdri_notes.pdf

Convert 16 bits to 32 bits TIFF

PTGui processes 16 bit TIFFs and 32 bit TIFFs differently. It automatically applies a non-linear transform on 16 bit TIFF inputs (it applies gamma correction to convert from sRGB to linear space) and does nothing for 32 bit TIFF inputs (i.e., considers it as linear space). dcrw outputs 16 bit TIFF so it needs to be converted to 32 bit TIFF before being sent to PTGui to avoid any modification of the inputs.

This is done with Adobe Photoshop after the various image corrections (if any). The image is loaded then saved as 32 bits TIFF (create an Adobe Photoshop script to execute this on a folder)..

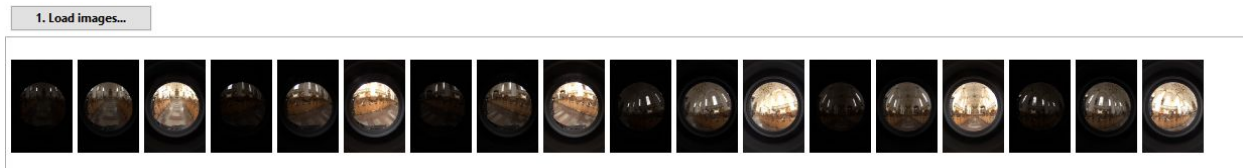
Create the HDR panorama

PTGui Pro is used to stitch bracketed exposures into an HDR panorama (the Pro version is required to reconstruct the HDRI). The goal is to stitch well exposed images together, apply the stitching template to other overexposed or underexposed images, then generate an HDRI. In case of very bright light sources taken with the process described in Section 4.4.1 it is required to have the same number of brackets for each view to load images in PTGui. If the bottom view is not taken with the ND filter, some black images should be created to generate the same number of brackets as the other views.

Stitch bracketed exposures into a HDR panorama

Step in PTGui:

1. Import the images in PTGui (linear TIFF 32 bits). It is preferable to load the bracket according to its exposure. This helps PTGui for the reconstruction



2. In case of very bright light sources it is necessary to manually edit the exposure of the shots with ND filters. PTGui uses the EXIF metadata created at shot time to recover the exposure but the camera has no information about what kind of ND filters are in use.
 - Active the Advanced Mode in Project Assistant tab.
 - Choose the Image Parameters tab and edit the exposure values of shots captured with ND filters. The goal is to replace these values with their effective one taking into account ND filters EV reduction.
 - Use "Sun" Table to retrieve the virtual shutter speed corresponding to the current shutter speed and use that as the new exposure. Note: PTGui refers to exposure instead of shutter speed, but it is equivalent as it is the only varying parameter.

Project Assistant Source Images Lens Settings Panorama Settings Crop Mask Image Parameters Control Points Optimizer Exposure / HDR Project Settings Pr																		
Enter the parameters of your images, or use the Panorama Editor (in the Tools menu) to set the values by dragging your images in your panorama.																		
	Image	Warped	Link	Yaw	Pitch	Roll	Lens type	FoV	a	b	c	HShift	VShift	HShear	VShear	Exposure	Exposure	
Shots with ND Filters	6			<input checked="" type="checkbox"/>	-152.928	18.4351	-0.5478	Circular	176.4179	-0.1816	0.2467	-0.238	-5.2416	23.1366	0	0	1/2048	1/65536
	7			<input checked="" type="checkbox"/>	-152.928	18.4351	-0.5478	Circular	176.4179	-0.1816	0.2467	-0.238	-5.2416	23.1366	0	0	1/1024	1/32768
	8			<input checked="" type="checkbox"/>	-152.928	18.4351	-0.5478	Circular	176.4179	-0.1816	0.2467	-0.238	-5.2416	23.1366	0	0	1/512	1/16384
	9			<input checked="" type="checkbox"/>	-152.928	18.4351	-0.5478	Circular	176.4179	-0.1816	0.2467	-0.238	-5.2416	23.1366	0	0	1/256	1/8192
	10			<input checked="" type="checkbox"/>	-152.928	18.4351	-0.5478	Circular	176.4179	-0.1816	0.2467	-0.238	-5.2416	23.1366	0	0	1/4096	
	11			<input checked="" type="checkbox"/>	-152.928	18.4351	-0.5478	Circular	176.4179	-0.1816	0.2467	-0.238	-5.2416	23.1366	0	0	1/2048	
Shots without ND Filters	12			<input checked="" type="checkbox"/>	-152.928	18.4351	-0.5478	Circular	176.4179	-0.1816	0.2467	-0.238	-5.2416	23.1366	0	0	1/1024	

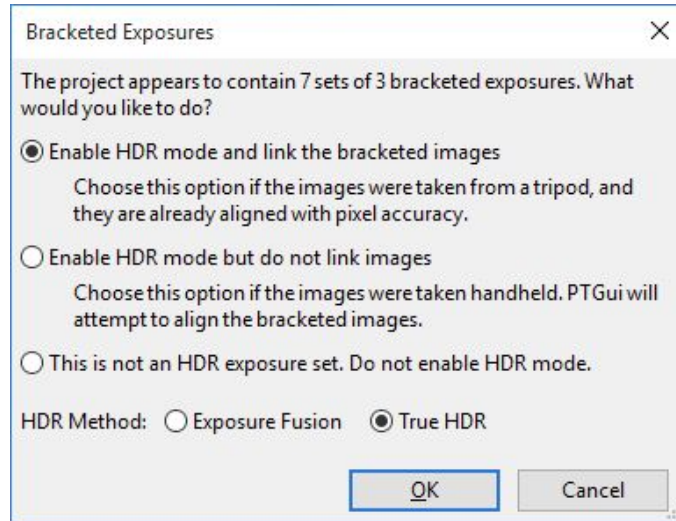
ND32	Virtual
1/125	1/4096
1/250	1/8192
1/500	1/16384
1/1000	1/32768
1/2000	1/65536
1/4000	1/131072

Example of exposure correction with an ND32 filter in PTGui. All the shots with ND filters are edited. A value of 1/2048 need to be replace by its equivalent virtual shutter speed of 1/65536, 1/1024 by 1/32768 etc.

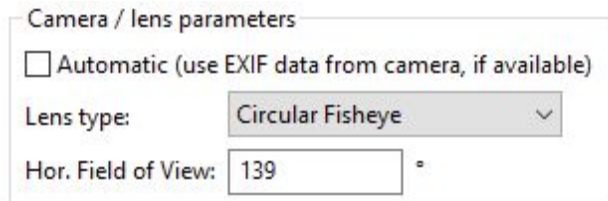
3. Crop the area of the fish eye.



- In the Bracketed Exposures option window, choose Enable HDR mode and link the bracketed images to align the image with True HDR method. It is best to link first before applying masking. When exposures are linked, the mask that is applied on a view is copied to all exposures.



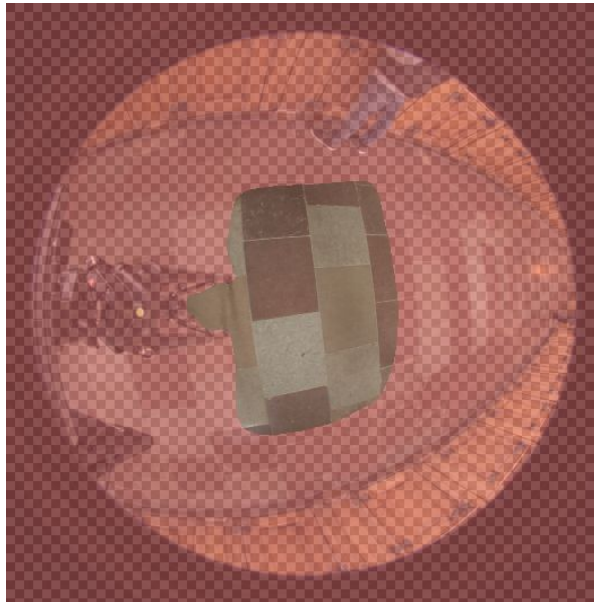
- If the lens parameters are not recognized properly, they can be entered manually.
 - Set Lens Type to Circular Fisheye
 - Enter the FOV depending if filter support or ND filters are used:
 - No filter = 180
 - Filter support = 139
 - One ND filter = 124
 - Two ND filters = 124



- Mask the tripod and the nodal head (with a fisheye and a nodal head the tripod is present in the shot, this will be removed during the stitching step).



7. Mask areas unwanted in the bottom view and keep only the center to override the tripod in other shots.



8. The horizon can be adjusted with one view taken as reference. Modify the pitch and roll to set the real values (Pitch +/- 30, Roll 0) and use the optimizer with the modified image set as the anchor image.
9. The result is an HDR panorama (all views have been stitched) but is not calibrated. At Unity, we export HDRIs as 8192x4096 latitude/longitude EXRs.



With very bright light sources, verify in Adobe Photoshop that no artifacts are visible at any exposure.



Correct equipment misalignment (Optional)

In case the equipment was not perfectly aligned (it often happens when the user doesn't have enough experience) or the bottom view was not perfectly centred, the reconstructed HDR panorama exhibits deformation at horizon. It can also exhibit seams where the bottom view is stitched with other views.

To correct this:

- In PTGui, re-adjust the horizon with the Panorama Editor to fix the deformation. It is important to have the horizon at the nodal pivot as the absolute HDR process relies on it.



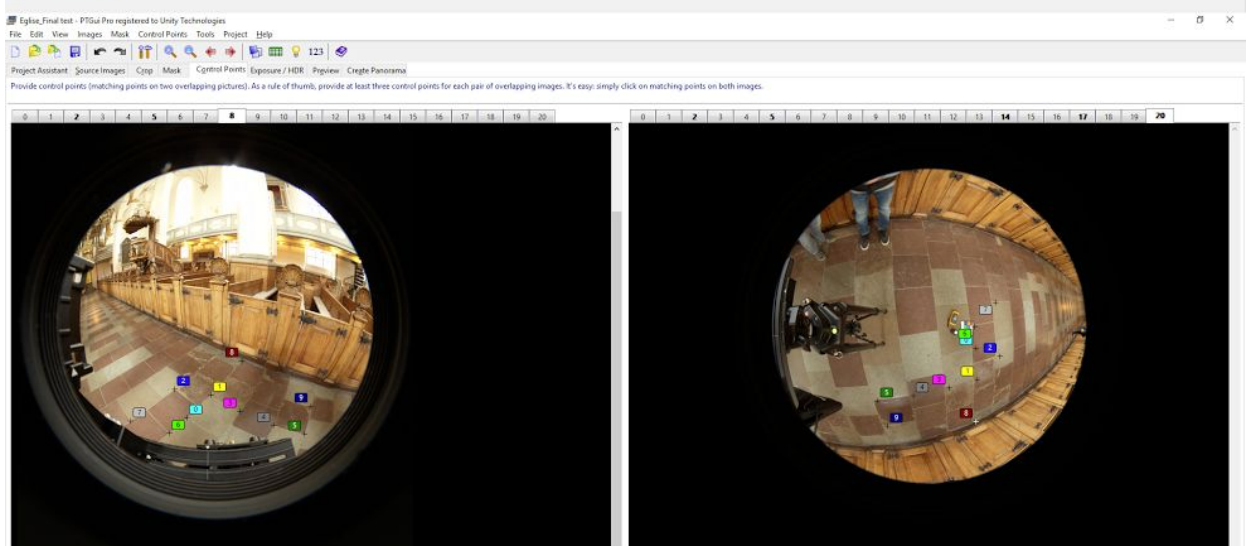
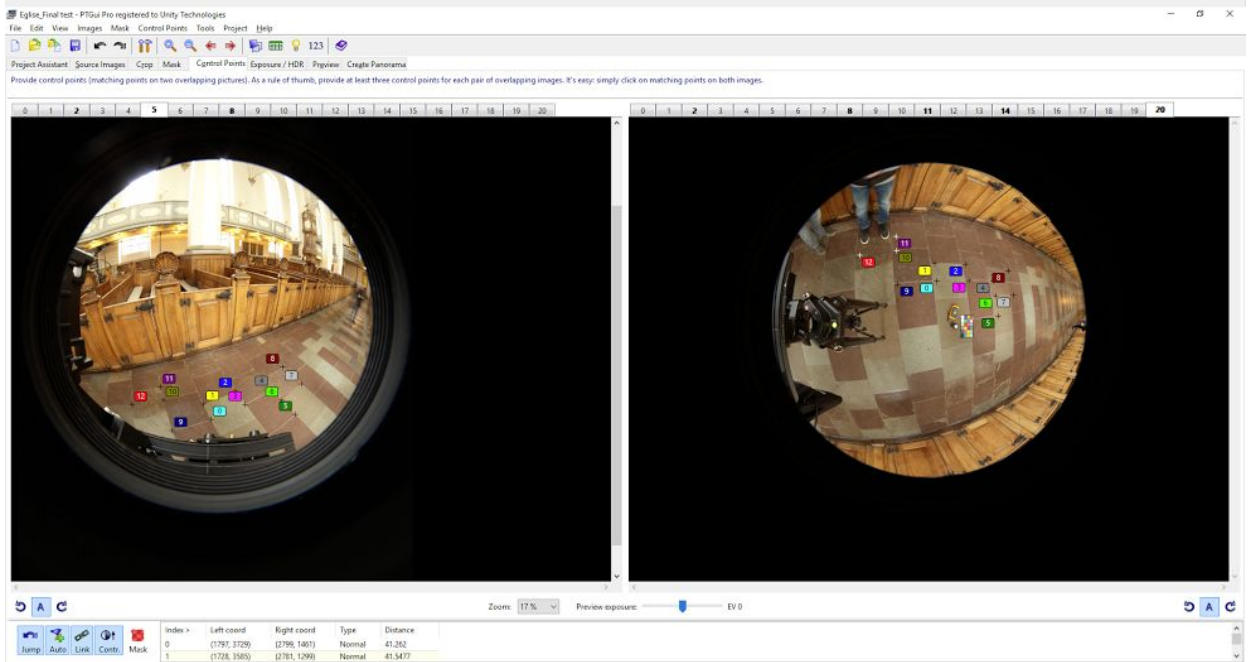
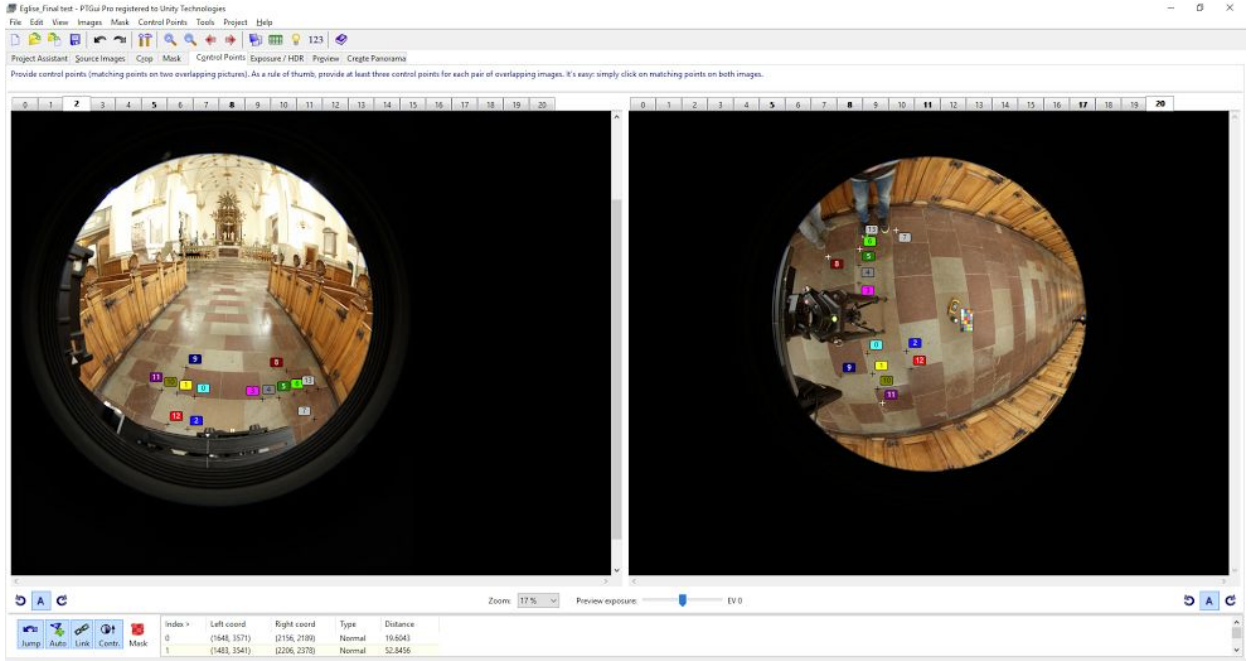
- If necessary, add some control points for the bottom view and the others towards ground views (0, 120, 240) and realign the images in True HDR.
- If necessary, apply an offset with Adobe Photoshop on all bracketed exposures of the bottom view to compensate for the move of the lens capture point. This will minimize the seams:
 - In PTGui, save the project.
 - The offset is determined only on one bracket. Choose a good exposure to work with and keep this same exposure for all views. Delete others. (Do not save! The project will be reloaded later.)
 - With Adobe Photoshop, apply an offset to the bottom view (1: red arrows) and check the modification with the PTGui preview (2).



- Load all others bracketed exposures of the bottom view in Adobe Photoshop. Replicate the same offset on all images.

- Reload the project (Note: PTGui panorama preview have a hot reloading feature allowing to see any change perform in Adobe Photoshop).

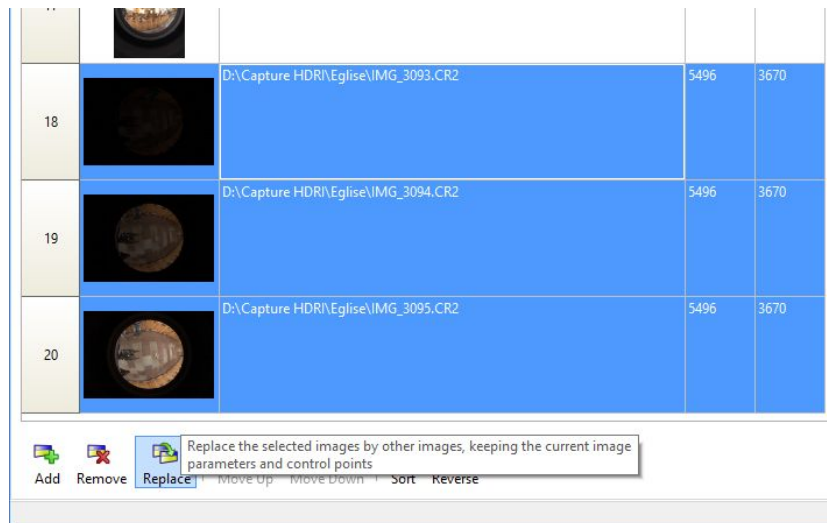
Also for the stitching, if necessary, add some control points for the bottom view (Right on the image below) and the other lower views (0°, 120°, 240° - Left on the image below) and realign the images in True HDR.



Create the HDR panorama with the ColorChecker target

To white balance, it is necessary to reconstruct a second HDR panorama with the same process previously described. But this time replacing the bottom view images with the bottom view images including the ColorChecker.

- Start from the previous reconstructed HDR panorama.
- If an offset has been applied previously, the same offset for the bottom view images must be applied to the bottom view images with ColorChecker.
- Replace bottom images one by one (we found that the multi-replace option of PTGui was not reliable).



- If the exposures have been edited (for very bright light sources), this needs to be done again as replacing the image discards the settings.
- Adjust the mask on the ColorChecker. The ColorChecker must be covered by a green area so PTGui will not blend it with the other views during the stitching (this means the final image will contain an unmodified ColorChecker).

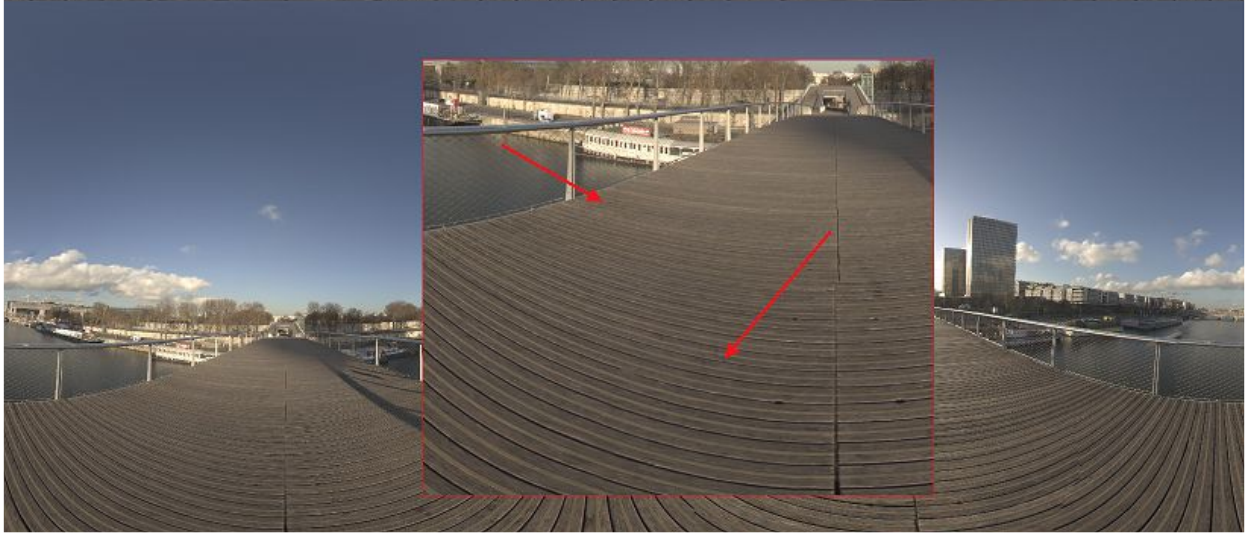
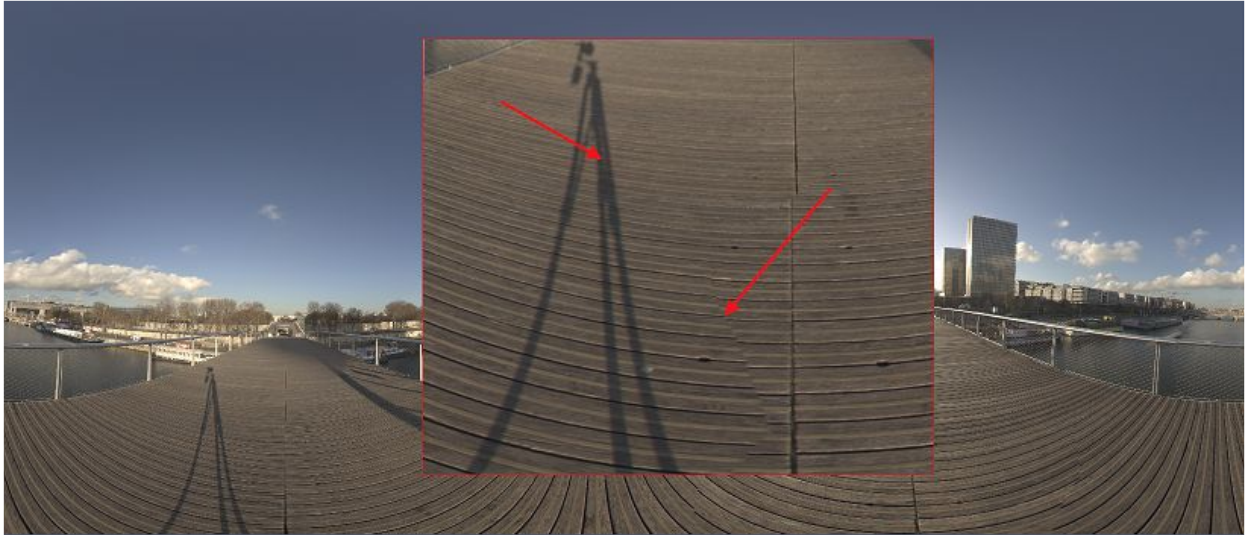


- Create a new HDR panorama including the ColorChecker.



Correcting common problems

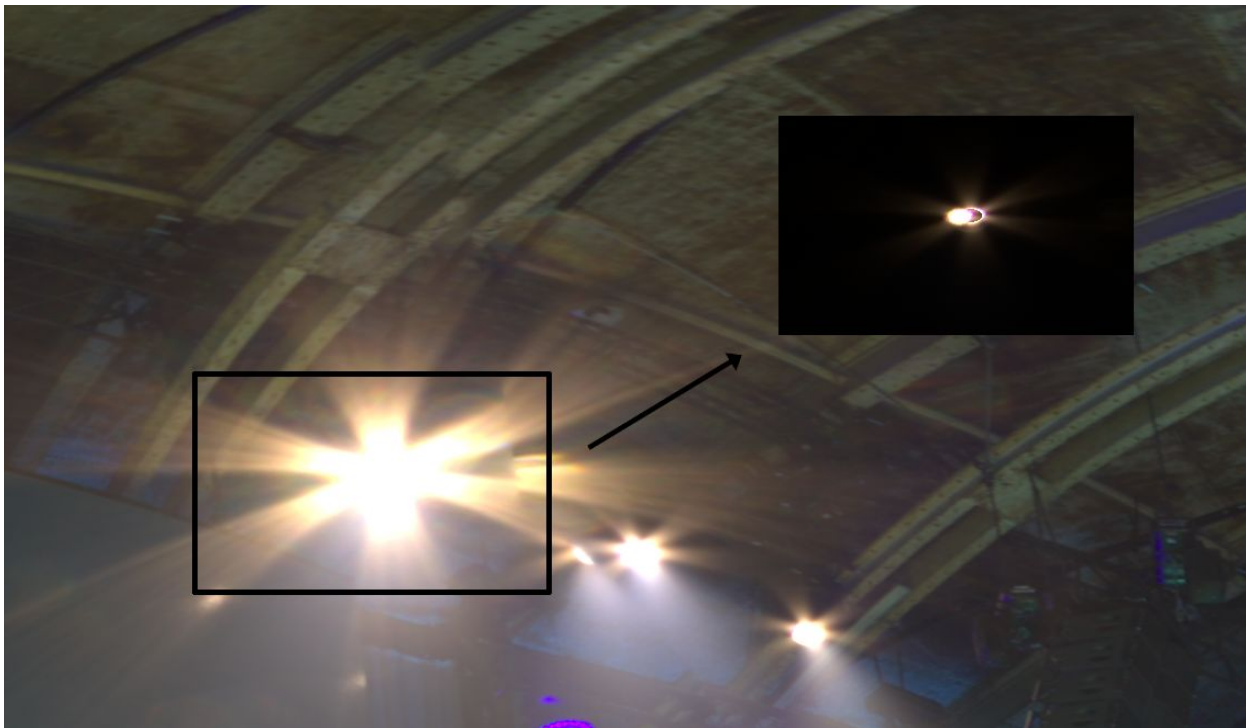
In some conditions, it is not possible to avoid difficulties such as tripod shadow or incorrect view alignments. The Adobe Photoshop tools can be used to correct them directly in the reconstructed HDR panorama. In the case below, the HDRI was corrected via stamp and select/warp tools.



The sun capture is really sensitive if clouds are moving a lot. Due to the very high intensity of the sun, cloud movements create artifacts during the HDR process. In the HDRI below, some clouds that are moving in front of the sun during the capture create an artifact (border in red).



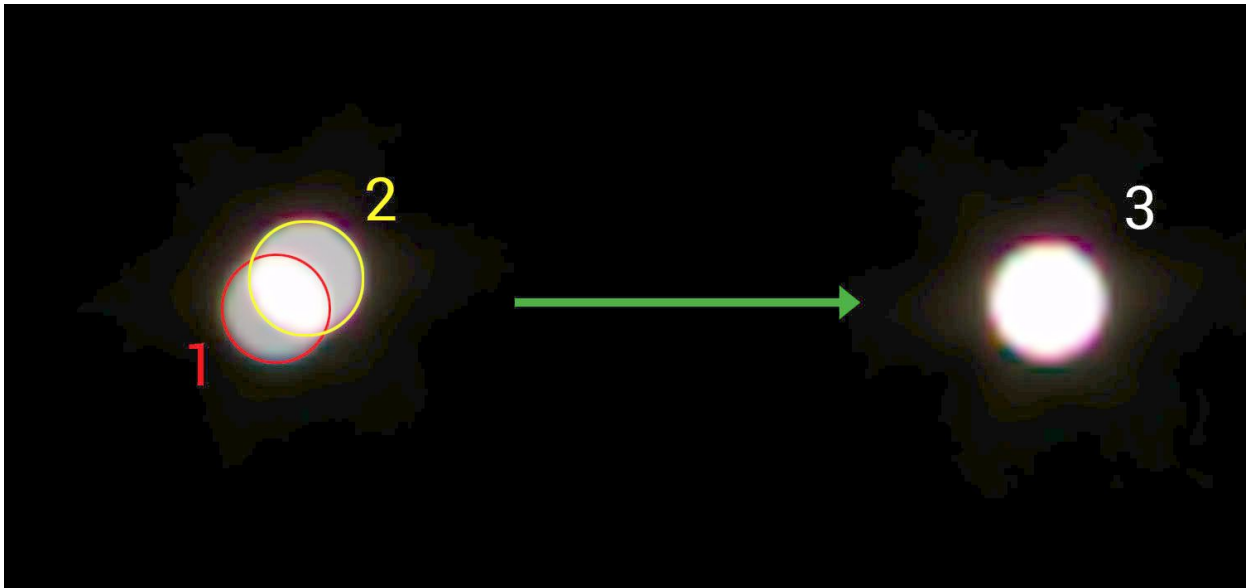
If the highlights are not stitched correctly, this can produce similar artifacts (black areas in the light). This can be resolved by masking the highlight in green in the most appropriate view.



When capturing the sun, the time spent removing the ND filters between each round can cause a sun misalignment because the sun is moving. In practice we observe a shift of around two pixels for one minute. This shift causes error during PTGui's reconstruction of the sun.



It is important to correct this artifact as the sun is very intense. The sun usually requires ND500 + ND1000. Removing the ND500 on top of ND1000 after the first round takes us around one minute; removing the ND 1000 after the second round is insignificant. To correct the shift between first and second rounds we align the first round of shots to the second one with Adobe Photoshop with a move command.



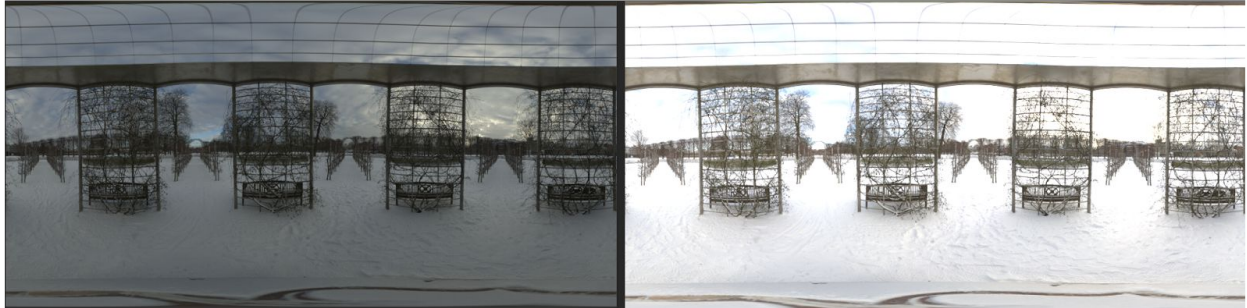
Shot with ND500 + ND1000. 2: Shot with ND1000. 3: Corrected shot with Adobe Photoshop where shot with ND500 + ND1000 is aligned with the shot with ND1000.

Calibration

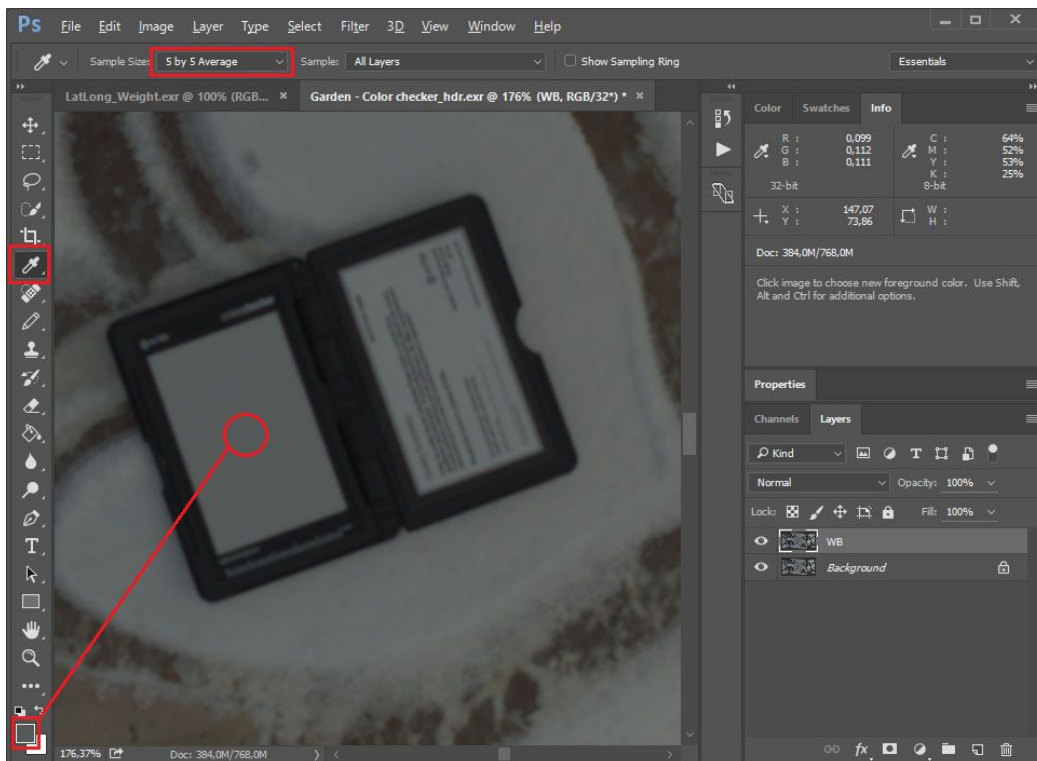
After acquisition and processing, an HDRI needs to be calibrated in both chrominance (white balance) and luminance (optional)

White balance process

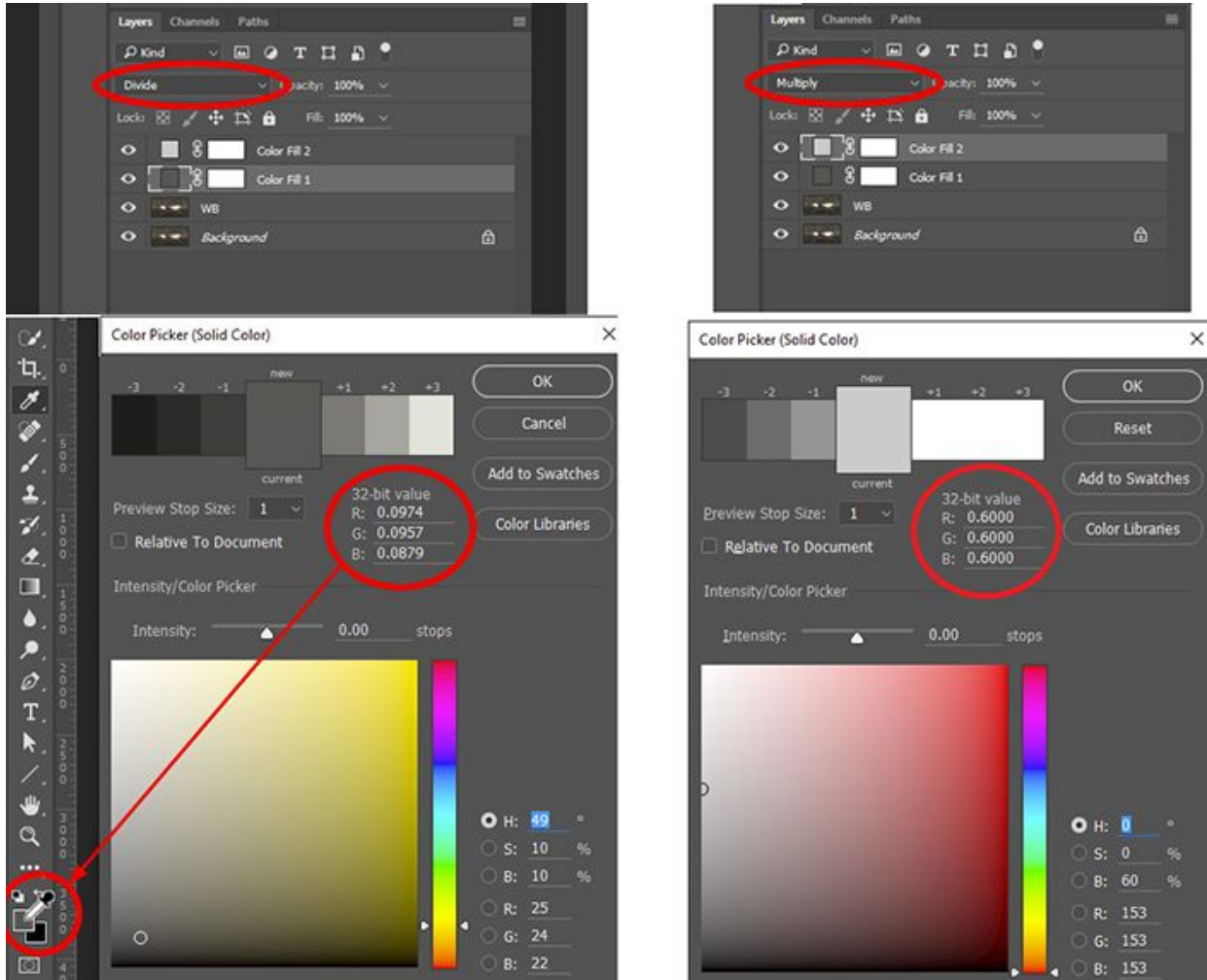
The goal of this section is to go from a white unbalanced HDRI (left image) to a white balanced HDRI (right image):



- Open the HDRI white unbalanced in Adobe Photoshop.
- Create a layer on top of it and name it WB, then copy-paste the HDRI with the white balance target in it.
- If the white balanced target is not visible (this may happen in case of a dark HDRI), then adapt the exposure of the WB layer to see it correctly. Then apply the same exposure adjustment to the background layer.
- Select the eyedropper tool, set the sample size to 5 by 5 Average and pick the color value in the center of the white color target.



- Create a new solid color adjustment layer in 32-bit value, set the blend mode to divide, and pick the foreground color as solid color (use Ctrl+Backspace to fill a solid layer with foreground color; this may be used when creating a Photoshop action).
- Create a second solid color adjustment layer in 32-bit value, set the blend mode to multiply and the value to RGB 0.6, 0.6, 0.6 (Value of the white color checker).



- Verify that the white balance target is now RGB 0.6, 0.6, 0.6 then delete the WB layer.
- Flatten the layers using: Layer / Flatten
- Optional: the generated HDRI is just relative luminance. An exposure correction may be applied at this step without having any impact on the luminance calibration. An exposure correction can be used to produce more pleasant thumbnails in various software packages, such as Unity. The thumbnail usually looks like the Adobe Photoshop view. Below is an example of a white balanced HDRI (left image) and a more pleasant correction (right image):



Maximum range

In case of very bright light sources, the relative HDRI may have values greater than 65504 (max value in a EXR float 16bit file). There is a high likelihood that these values will be clipped either due to Adobe Photoshop itself (the current version of Adobe Photoshop doesn't support 32 bit values when saving in EXR, so it clips them to 16 bit values) or in the game engine. We recommend re-exposing the HDRI in Adobe Photoshop in order to remap the maximum value of the HDRI to 65504 to avoid this clipping.

Luminance calibration

Luminance calibration data

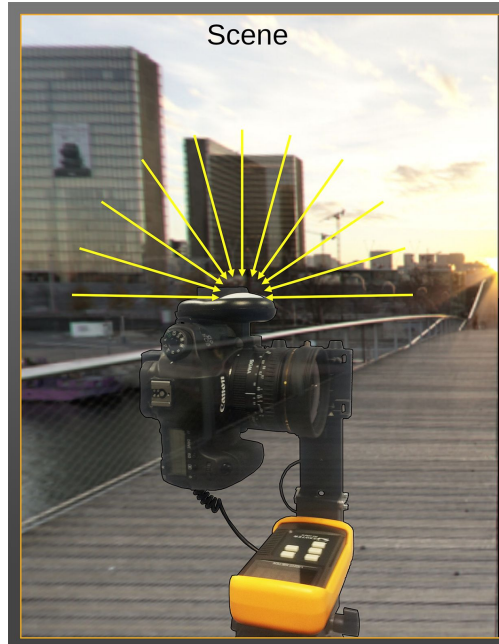
In order to reconstruct absolute luminance HDRIs (i.e., with real world luminance), it is necessary to take some light measurements at the location where the HDRI has been acquired. With the measurement in the captured scene and the one retrieved from the reconstructed HDRI, it is possible to make them match and recover an absolute HDRI. A lux meter is a cheap and accessible device to do this.

Measuring lighting for enclosed indoor environments only requires a single measurement, the lighting is usually fixed. However, for outdoor environments, lighting changes are frequent (clouds are moving, sunlight varies etc.), so outdoor light measurements are challenging. To avoid adding too much complexity to the workflow, we decided to only perform two measurements in this case and average them, one at the beginning of the shooting session and one at the end. But keep in mind that in case of changing conditions, the HDRI itself is built with different lighting conditions for each view, so it is not possible to be fully accurate.

Lux meter

The lux meter measures the illuminance of the scene (lighting coming from the upper hemisphere oriented in the sensor direction). Try to measure illuminance at the same position as the camera: the sensor should be as close as possible to the lens capture point.

Caution: The sensor environment should be free from any occlusion - whether from the tripod, human body (crouched when taking measurements) and not in shadow. This should be representative of the captured environment.



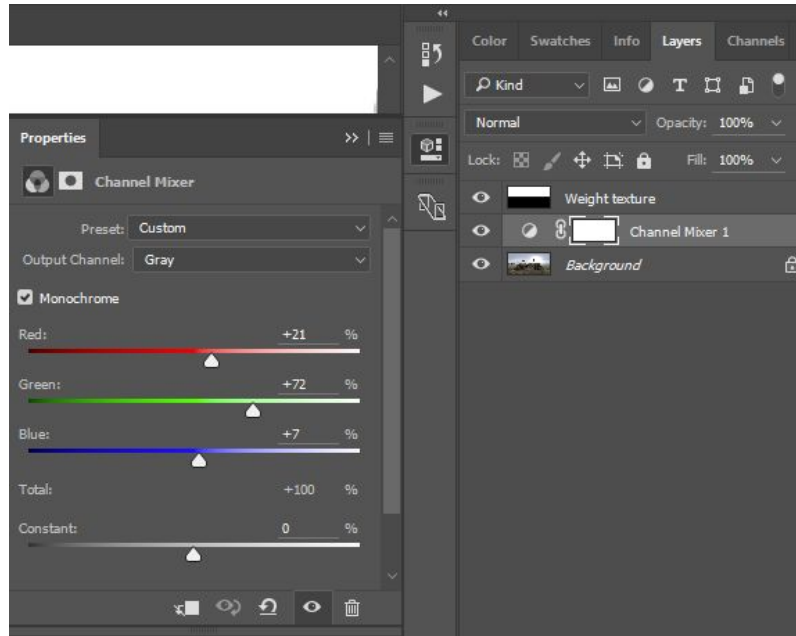
Absolute HDRIs

This step happens after having white balanced the HDRI.

Download weight texture

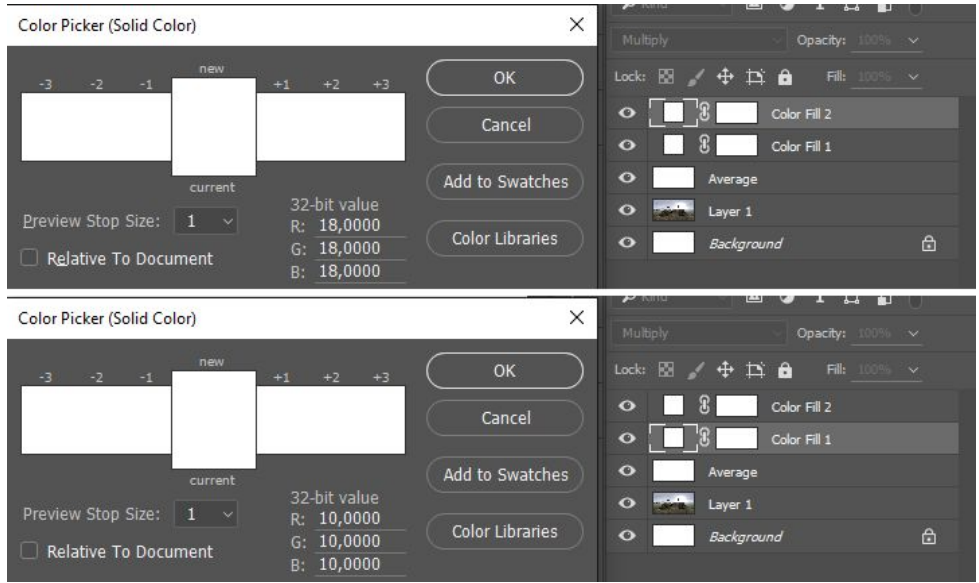
The weight texture allows to emulate math to calculate illuminance at the center of the HDRI inside Adobe Photoshop. The weight can be downloaded by clicking [here](#) (TODO: The link is currently on confluence).

- Open the HDRI and the weight texture (if the HDRI was already open, close it and open it again).
- Resize the weight texture to the same size as the HDRI.
- Add a Channel Mixer adjustment layer on top of the HDRI to generate a grayscale image. Set it up as a monochrome output with value RGB 21, 72, 7.
- Copy the weight into a layer on top of the Channel Mixer, and set its blend mode to multiply.



- Flatten the image.
- Perform an image resize to 1x1 using Bilinear as resampling algorithm. Followed by a resize to the original size of the HDRI (this will replicate the averaged value on all pixels). The pixel value is the illuminance of the image.
- Duplicate the Background layer (the current) and name it Average. Set blend mode to divide.
- Paste the original HDRI texture in between Background and Average layer (set the blend mode to normal).
- Create a new solid color adjustment layer in 32-bit value on top of the 'average' layer with multiply blend mode. Set the color value equal to lux meter measurement.
- Flatten the image, it is the absolute HDRI. The HDRI is usually completely white without exposition adjustments.

Remark: Because Adobe Photoshop does not allow editing a value greater than 20, it may be necessary to use a composition of few solid colors to get the correct value. For example, in the screenshot below the measured value is 180. In order to get this value, create a solid color RGB 18.0, 18.0, 18.0 and another one with color RGB: 10.0, 10.0, 10.0. The resulting multiply value will be 180.



The complete process to obtain an absolute HDRI with Adobe Photoshop is summarized in following diagram:



Remove Sun from HDRI

Sun or very bright sources removal in HDRIs

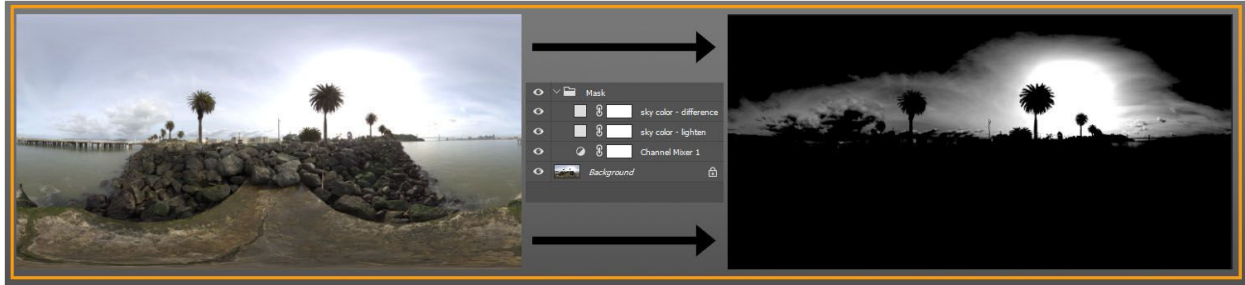


HDRI without sun can be used in the LookDev for the shadow side to remove sun reflection in the shadows.

It can be also useful to use in game a HDRI without sun with a digital sun.

Two artist friendly solutions can be used for this purpose:

- Duplicate a representative part of the sky to replace the sun area.
 - Load the white balanced HDRI in Adobe Photoshop.
 - Create a luminance mask to work only on the area of high intensity. This luminance mask is only necessary if you have no sky information overlapping the sun area (like the tree on the figure):
 - i. Add a new folder to contain everything needed to produce the mask and select it.
 - ii. Add a Channel Mixer adjustment layer to generate a grayscale image. Setup it as monochrome output with value RGB 21, 72, 7.
 - iii. Add a solid color layer with the highest sky value picked in the area representative of the sky. Set this layer to Lighten.
 - iv. Add another solid color with same value. Set this layer to Difference.



- Duplicate background.
- With the Adobe Photoshop stamp tool, find a clear zone in the sky that is big enough to cover the sun disc and is representative of the average intensity of the sky.



- Apply the mask above on the stamped layer to have the final result. If necessary, do a retake with the stamp tool to have a nice transition.



Or second alternative Clamp the high values of the sun and the surrounding area.

- Load the white balanced HDRI in Adobe Photoshop.

- Add a solid color layer on top. Pick a representative sky value at the opposite side to the sun as RGB.
- Set the solid color layer to Darken mode (this applies a min between the two images).
- If needed, build a mask to only affect the sun area (opposite sky values can have lower values than the ground part).
- Save the new HDRI. This approach is simple but can exhibit non natural reflection.



