51 Lake Street, Nashua, NH 03060-4513, U.S.A. • 603-880-8500 • Toll Free 800-880-8500 • Fax 603-882-6522
Internet: www.skyskan.com • E-mail: office@skyskan.com

Projectors and Dome Effective Contrast Whitepaper

Claude Ganter

Sky-Skan Inc., 51 Lake Street, Nashua NH 03060, USA

ABSTRACT:
We examine here the interaction between video projectors native contrast and dome gain. A "fill factor" is introduced in order to characterize the type of scenery. The mathematical theory behind the computation of the integrated projectors and dome contrast is explained. Finally, simulations of dome original images will be shown in order to serve as a visual guide for selecting the best projection parameters with new planetariums installations.

1. Projector Contrast

Typically for most constructors, the native projector contrast $\mathbf{C_p}$ is expressed as the ratio of illuminance between a fully saturated white image (RGB level 255 in 8 bits) to the residual background emission of a black image (level 0). It is also to be assumed that the projector is not using any dynamic control of its lamp brightness when these two separate measures are made.

In other words, the procedure is quite straightforward. Using a flat screen, one sends a white image and measures the illumination. Then a black image is generated, while the projector keeps working the exact same way, and a second measure is made at the same location on the screen. For example, if one measures with a light meter 1000 lx for white and 0.4 lx for black, the contrast is 2500:1.

The reason for mentioning a flat screen requisite is that manufacturers are using an "open field" concept which signifies that no reflection from the room should ever come back to the screen. The idea is to measure the projector contrast as some ideal value totally separated from the world, hence the term native projector contrast.

Practically it is only required to avoid unwanted illumination from spurious or constant light sources. Since reflections related to the projector lamp are proportional to its own light intensity, room effects are automatically canceled out when dividing the measure of white by the measure of black. So in this case one could very well use a cubic screen (or whatever shape) and still obtain a correct value for native contrast!

It is worth mentioning that other methods are possible.

The "ANSI contrast" measures the contrast of a 50% checkerboard on a flat screen. However this method (which generally gives not as high contrast numbers) is more difficult to implement due to the possible interactions of the pattern with the projector parts (imaging panel, lens, etc...). Also the ANSI contrast seems less relevant to the planetarium experience where dark adaptation may occur and allow a direct perception of the black level on a fully black signal.

So in this document, we are using the expression "native contrast" exclusively to characterize projector contrast.

Native contrast is also called "On/Off contrast" (though "Off" measurement is still technically "On" for the projector) or even more confusingly called "dynamic contrast" though as stated before dynamic control is not allowed here. The term dynamic just signifies that measures of white and black are made one after the other, separated in time.

Here are a few manufacturer best values / estimates for luminosity and native contrast $\mathbf{C_p}$, which I hope can be accepted since our main goal is to show how those numbers are interacting with the planetarium domes rather that establishing exact performance values.

We have limited to 3 classes for clarity of the discussion.

Our attempt at projector contrast classification:

Projection Class	Luminosity (lumen)	Contrast
Sony SRX-T110	11000	2500:1
JVC DLA-SH7	5000	10000:1
High-Contrast (Zorro, Velvet)	~1000	Up to 2500000:1

In fact, in many case real measures are not that far off from those numbers; it is just that practically they can also vary depending on parameters such as lens aperture (iris) and even batch assembly variations.

What is important to remember is that we have selected 3 classes of projectors for this document and we are going to try to see, in the next sections, how they fare on domes as far as contrast is concerned.

2. Dome Contrast

The theory of dome contrast can be related to the well established integrating spheres theory used in the industry for measuring the intensity of light sources.

This theory basically assumes that a light source which has a complex directional pattern can be in fact integrated by summation of the multiple reflections of light occurring in the cavity. The sphere also acts as a blurring device allowing though a single measure at one location the evaluation of the total energy emitted.

One condition is to assume that the surface of the sphere acts like a Lambertian (or diffuse) reflector.

What a Lambertian material is about is very common experience. Imagine a matte paint wall. If you move around it is easy to convince oneself that that light amount is pretty much constant at any angle. Now if this is a white square of matte paint on a black wall, the total energy will go down when you measure by the side since the perceived angle gets smaller. However if the measuring angle is small enough to make a spot measure inside the white square, our measured brightness won't change!

So what happens in our sphere is that each Lambertian element of the sphere reflecting light transfers the same lighting amount on any other element of the sphere. This 'magic' property results of laws of geometry which control the solid angles and the inverse square law of distance which controls the luminous energy. Indeed there is really nothing to do, besides having a Lambertian material; it just works because of laws of nature.

Ironically, industrial integrating spheres are created with the idea to amplify the source through those multiple cross reflections by using highly reflective internal walls. In the planetarium community we just try to do the opposite and increase the contrast which requires some serious optimizations as we will see. However, as opposed as are our goals, the mathematical foundation is identical.

The amplification factor A of a partial sphere is the extra amount of light energy generated by comparison to a normalized value of 1 for the intensity of the first reflected image. The following formula accounts for the summation of the multiple and decreasing reflections of light as an infinite power series:

$$\mathbf{A = 1/\rho + 1/\rho^2 + 1/\rho^3 + 1/\rho^4 + \ldots}$$

This can be expressed in this form:

$$\mathbf{A = (1 / (1 - \rho)) - 1}$$

With:

$$\boldsymbol{\rho = r \times c}$$

Where:

r is the coefficient of reflection of the dome (or gain)
c is the amount of the sphere area used (partial sphere)

While we are speaking about the dome reflection coefficient **r** (or gain), it is worth mentioning that the gain is the paint reflectivity corrected for the loss effect of the tiny holes that are generally present on the surface. For example, if the paint is reflecting 60% of light and the holes are representing 20% of the dome area, the dome published gain is 48%, that is 0.6 multiplied by 0.8, then expressed in percents. What is important to remember is that the effect of holes is already accounted for in the dome gain information provided by dome manufacturers.

For planetarium domes it is possible to compute the amount of sphere area **c** knowing the dome aperture angle **Θ** in degrees. This requires integrating the solid angle elements on the sphere (which is left to the reader as an exercise). Here is the expression:

$$\mathbf{c = 0.5 \times (1 - \cos(\Theta/2))}$$

Table of sphere area for different dome apertures:

Aperture (°)	135	150	165	180	195	210	225
Sphere area	30.9%	37.1%	43.5%	50.0%	56.5%	62.9%	69.1%

Let's now create a second table showing how the dome amplification varies as a function of the dome gain (paint and holes combined) versus the effect of the dome aperture (opening angle of the sphere). Note that the amplification can be higher than 100%.

Table of Dome Amplification:

Gain (%) \ Aperture (°)	135	150	165	180	195	210	225
20%	7%	8%	10%	11%	13%	14%	16%
30%	10%	13%	15%	18%	20%	23%	26%
40%	14%	17%	21%	25%	29%	34%	38%
50%	18%	23%	28%	33%	39%	46%	53%
60%	23%	29%	35%	43%	51%	61%	71%
70%	28%	35%	44%	54%	65%	79%	94%
80%	33%	42%	53%	67%	83%	101%	124%

From the table, one can see that a dome with a gain of 50% and an aperture of 180° has a one third (33%) increase of brightness. This 33% is the amount of light which is to be added to the intensity of the first reflected light (which is normalized to 100%), due to the multiple subsequent reflections on the dome.

This is indeed a very noticeable effect compared to the measures obtained on a flat screen (assuming the same distance of course). In this example, if we measure a flat screen using a luminance meter at 10.0cd/m² then we would find 13.3cd/m² in the case of the dome.

It is important to understand that the subsequent reflections of light do not retain information about the initial image structure (created by the first light reflection). The amplification amount spreads as a uniform glow adding itself on top the first reflected image. Again this is because of the "magic" way light is reflected inside a sphere.

Now let's imagine we generate a dome image with a tiny black circle (mice hole) somewhere in the image. Since the circle is extremely small, it won't change our measure of 13.3cd/m² in the white areas. But inside the mice hole we will only perceive the amplified amount which is 3.3cd/m2. Dividing those 2 numbers give the measure of the fulldome contrast, which is 4:1 in our example, and here is the general expression:

$$\mathbf{C_{fd} = (1 + A) / (0 + A) = (1 + A) / A}$$

Table of Fulldome Contrast:

Gain (%) \ Aperture (°)	135	150	165	180	195	210	225
20%	16.2	13.5	11.5	10.0	8.8	7.9	7.2
30%	10.8	9.0	7.7	6.7	5.9	5.3	4.8
40%	8.1	6.7	5.8	5.0	4.4	4.0	3.6
50%	6.5	5.4	4.6	4.0	3.5	3.2	2.9
60%	5.4	4.5	3.8	3.3	2.9	2.6	2.4
70%	4.6	3.9	3.3	2.9	2.5	2.3	2.1
80%	4.0	3.4	2.9	2.5	2.2	2.0	1.8

Moving forward, let's assume that we make our mice hole much bigger. In fact, what would happen to the dome contrast if we generate a checkerboard made from an equal number of pure white (100%) squares and pure black (0%) squares?

In this case, the first image reflection is blurred ('integrated') and then distributed with the same amount back on all the squares. Hence we can distinguish 2 parts.

1) The white squares have a luminance of: $1 + 0.5 \times A$
2) The black squares have a luminance of: $0 + 0.5 \times A$

The 0.5 value comes from the fact that our checkerboard covers 50% of the fulldome image. Finally, the checkerboard dome contrast C_{cd} is then equal to the ratio of (1) divided by (2):

$$\mathbf{C_{cd} = (1 + 0.5 \times A) / (0.5 \times A)}$$

Table of Checkerboard Contrast:

Gain (%) \ Aperture (°)	135	150	165	180	195	210	225
20%	31.4	26.0	22.0	19.0	16.7	14.9	13.5
30%	20.6	17.0	14.3	12.3	10.8	9.6	8.6
40%	15.2	12.5	10.5	9.0	7.8	6.9	6.2
50%	12.0	9.8	8.2	7.0	6.1	5.4	4.8
60%	9.8	8.0	6.7	5.7	4.9	4.3	3.8
70%	8.3	6.7	5.6	4.7	4.1	3.5	3.1
80%	7.1	5.7	4.8	4.0	3.4	3.0	2.6

From the table, one can see that a checkerboard image projected on a dome with a gain of 50% and an aperture of 180° has a 7:1 contrast. To continue our previous example, one would measure 11.67cd/m² in the white squares and 1.67cd/m² inside the black squares.

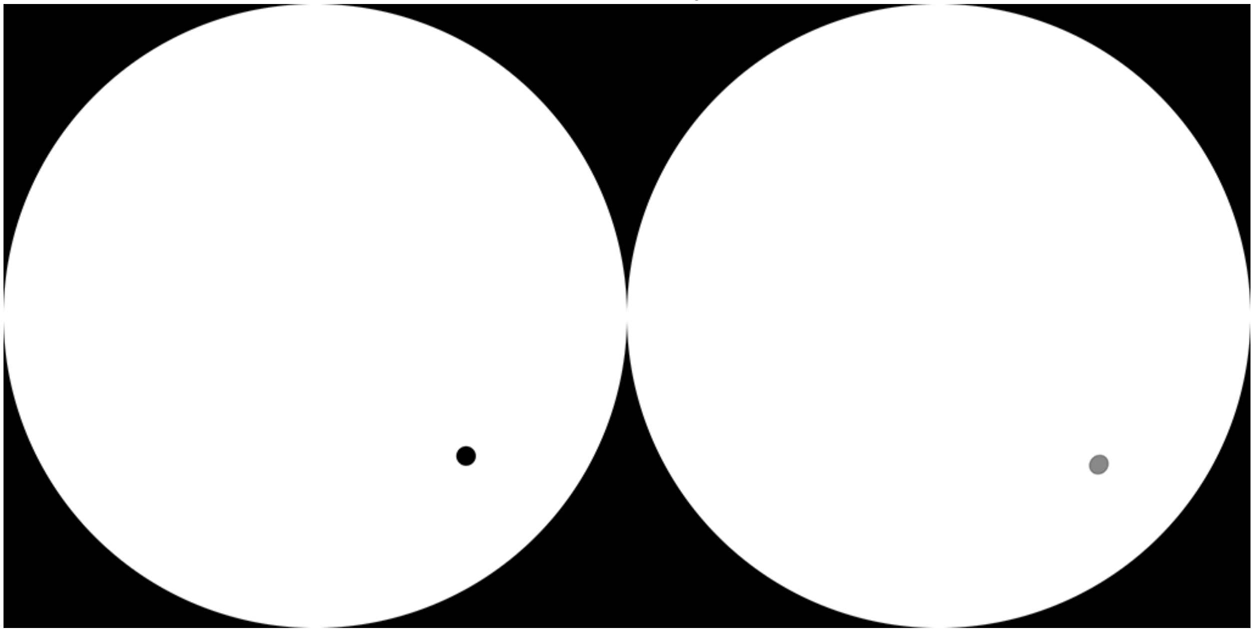
In a sense, this measure of the dome contrast is analog to the ANSI method for projectors but applied for domes. The measures can happen in a simultaneous way so it can be also described as a "static contrast". However one needs to keep in mind that we do not account for the effect of the projection system in this section.

In general, the obvious ways to improve the fulldome and checkerboard image contrast are:

- Reduce the reflection coefficient using for example a darker paint.
- Use a smaller dome aperture (less than 180°) if possible.
- Sell the dome and start again with a flat screen theater.

(Fig.1) Mice hole: (left) dome original, (right) equisolid fisheye view for r=50% Θ=180°

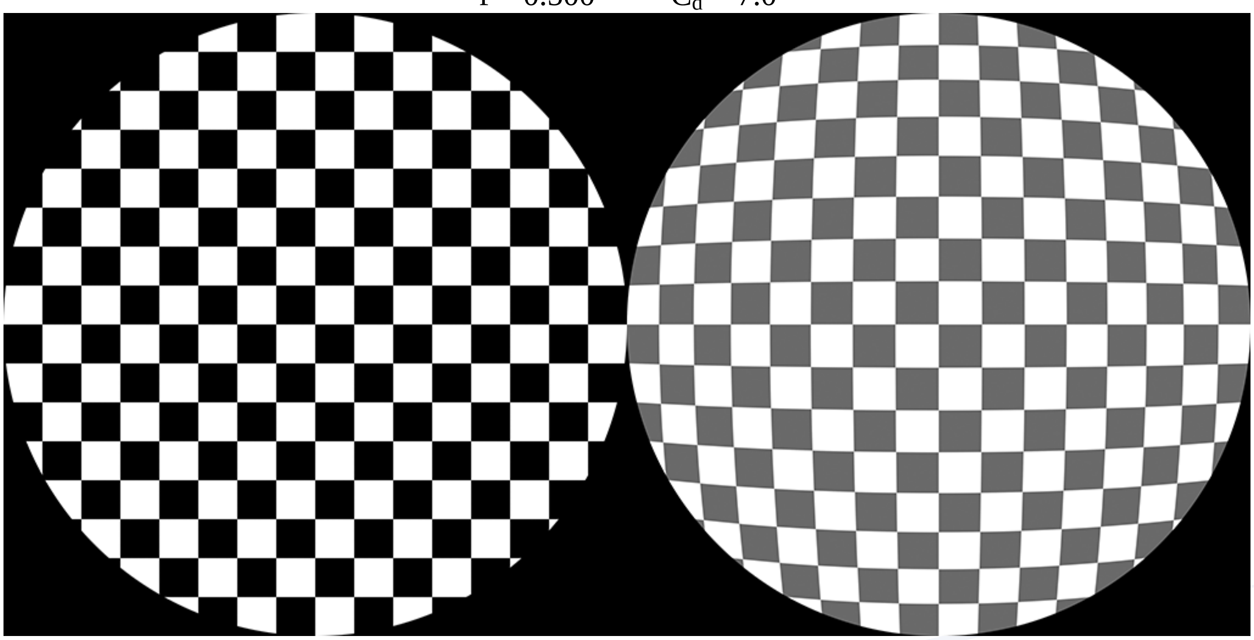
f = 0.999 C_d = 4.0



(It's not black anymore inside the mouse hole)

(Fig.2) Checkerboard: (left) dome original, (right) equisolid fisheye view for r=50% Θ=180°

f = 0.500 C_d = 7.0



(Gray in checkerboard is actually darker than in mice hole)

Of course, people are generally not showing checkerboards in their domes but real images. To the exception of scenes like explosions (supernovae?) it can be said that most images contain much less light.

One important concept here is that we are not talking here about the scene reflectivity as it is in nature. In fact what we have here is more like a photographic scene which has its dynamic range compressed and clipped to fit the available range of values (RGB 0 to 255 in 8 bits). Furthermore the relation between the data value (JPEG file for example) and projection brightness is supposed to follow a standard like sRGB.

Table of sRGB projection brightness with some useful values

sRGB Brightness	0.0%	0.5%	5.0%	20.0%	50.0%	100.0%
RGB value (8 bits)	0	16	63	124	188	255

If one takes a picture with a digital camera from a uniform area, the resulting JPEG file will generally show all values peaking around level 124 or in other words an intended projection brightness of about 20% (one fifth of maximum projector brightness). This result varies with camera exposure calibration and manufacturer JPEG engine, however since this is widely observable though many brands so let’s assume we have found a convenient standard for an average scene projection brightness.

Let’s call this scene projection brightness, the fill factor. The fill factor for a photographic scene will vary dramatically from one image to another; however on average we can say a camera expects a scene to have a fill factor on the projection device of about 20% (or 0.2). That is like saying we expect 80% of the pixels to be black and only 20% of the pixels to be white. Quite a different (and better) situation from the checkerboard indeed!

If **f** is the fill factor as defined above, then the general expression for dome contrast $\mathbf{C_d}$ is:

$$\mathbf{C_d = (1 + f \times A) / (f \times A)}$$

In other words, the fill factor modulates the total amount of light energy input, between a minimum of 0 (black image) and 1 (full white image), and consequently limits the amount of amplification we get. So as the fill factor gets smaller, the contrast of dome images will get higher.

Table of Standard Contrast (fill factor = 0.2):

Gain (%) \ Aperture (°)	135	150	165	180	195	210	225
20%	77.0	63.5	53.5	46.0	40.2	35.7	32.2
30%	50.0	41.0	34.3	29.3	25.5	22.5	20.1
40%	36.5	29.7	24.8	21.0	18.1	15.9	14.1
50%	28.4	23.0	19.0	16.0	13.7	11.9	10.5
60%	23.0	18.5	15.2	12.7	10.7	9.2	8.1
70%	19.1	15.3	12.4	10.3	8.6	7.3	6.3
80%	16.2	12.9	10.4	8.5	7.1	5.9	5.0

The above table is important since it gives a notion of dome contrast with real life scenes. A dome with r=50% and Θ=180° has a standard contrast of 16:1, which is not terribly good by the way.
For example, it is general practice that images distributed for fulldome shows are graded (contrast is augmented) by artists so they still look good when projected.

(Fig. 3) Mauna Kea: (left) dome original, (right) equisolid fisheye view for r=50% Θ=180°

$f = 0.167 \qquad C_d = 18.9$

(See here the dramatic loss in image contrast due to the dome cross reflections)

An important case is Astronomy.

For example let's assume we have 10 million pixels rendered on the dome. The typically inflated size planetarium Moon and planets occupies about 1000 pixels (2 square degrees). If we add 8000 stars represented each by one fully lit pixel we add 8000 pixels. And accounting for the Milky-Way at 0.2% brightness on 5% of the dome we add the equivalent of 1000 white pixels. These give the equivalent of 10000 fully lit pixels compared to 10 million pixels available. The ratio is then 0.001 (or 0.1%).

So it is realistic to assume a fill factor of 0.1% for a classic planetarium scene rendered with a digital planetarium.

Adding to this starry scene a spacecraft or a panorama will easily bring us to a 2% fill factor, much more adequate indeed for most "Space Art" scenes shown in planetariums.

Our silly attempt at scene classification:

Scene	Fill Factor
Fulldome white	1
Checkerboard	0.5
Photography / Movies	0.2
Space Art	0.02
Planetarium	0.001

At this point, our reader should note that it is not wise to built tables for the 2 last entries ("Space Art" and "Planetarium"). This is because contrast will be affected by the projector native contrast that we have not accounted for yet. However for fill factors of 0.2 or above, the previously computed tables are certainly valid starting points.

However let's fix this to be sure we got it right.

In the next section we are going to compute the effective contrast and account for projectors and dome altogether.

3. Projectors and Dome effective contrast.

In this section, things are just getting worse. Accounting for projectors is not going to improve our dome contrast numbers but make them worse obviously. With laws of classic projection, light is just going to be additive and never subtractive.

Finding the effective contrast for the dome experience is important for the reason that it allows us to see the differences between different projection technologies. Or if we take another perspective, it should allow someone to get better end result by selecting different optimization parameters.

Let's define $\mathbf{C_{eff}}$ as the effective contrast, which is the contrast from the combined effect of projectors and the dome.

We introduce now the black level $\mathbf{B_L}$ as the ratio between the black intensity and the white intensity (normalized to 1). It is quite obviously the inverse of the projection system native contrast:

$$\mathbf{B_L = 1 / C_p}$$

(This number is of course typically very small. For a native contrast of 2500:1 we have $\mathbf{B_L} = 0.0004$.)

We have to correct the fill factor from the effect of the black level contribution. The corrected fill factor $\mathbf{f_c}$ can only vary between the minimum value $\mathbf{B_L}$ and the maximum which is 1:

$$\mathbf{f_c = (1- B_L) \times f + B_L}$$

Then we have to also modify the main contrast expression in order to account for the direct contribution of the black background after the first image reflection; you can see the value $\mathbf{B_L}$ that appears at the denominator:

$$\mathbf{C_{eff} = (1 + f_c \times A) / (B_L + f_c \times A)}$$

Let's see how the standard contrast table defined previously (fill factor = 0.2) is affected by a projection system with a native contrast of 2500:1 for example:

Table of Standard Contrast (fill factor = 0.2) with 2500:1 projection system:

Gain (%) \ Aperture (°)	135	150	165	180	195	210	225
20%	74.6	61.8	52.3	45.1	39.5	35.2	31.7
30%	49.0	40.3	33.8	29.0	25.2	22.3	19.9
40%	35.9	29.3	24.5	20.8	18.0	15.7	14.0
50%	28.0	22.7	18.8	15.9	13.6	11.8	10.4
60%	22.8	18.3	15.1	12.6	10.7	9.2	8.0
70%	19.0	15.2	12.4	10.2	8.6	7.3	6.3
80%	16.1	12.8	10.3	8.5	7.0	5.9	5.0

As expected there are very little differences that can be seen with the previous table. For 'standard contrast' applications as "Photography / Movies" which have typically a fill factor around 0.2 this is just a confirmation that there is no practical advantage in selecting higher contrast projectors.

What about "Space Art"?

Here the fill factor is around 2% (0.02) and chances are that we see a larger difference. First let's check with the same 2500:1 system and then with the 2500000:1 system!

Contrast Table for "Space Art" (fill factor = 0.02) with 2500:1 projection system:

Gain (%) \ Aperture (°)	135	150	165	180	195	210	225
20%	575	493	428	376	334	301	273
30%	404	340	290	251	220	195	175
40%	307	254	214	183	158	139	123
50%	244	199	166	140	120	103	91
60%	200	161	133	110	93	79	68
70%	167	134	108	89	74	62	52
80%	142	112	90	72	59	48	40

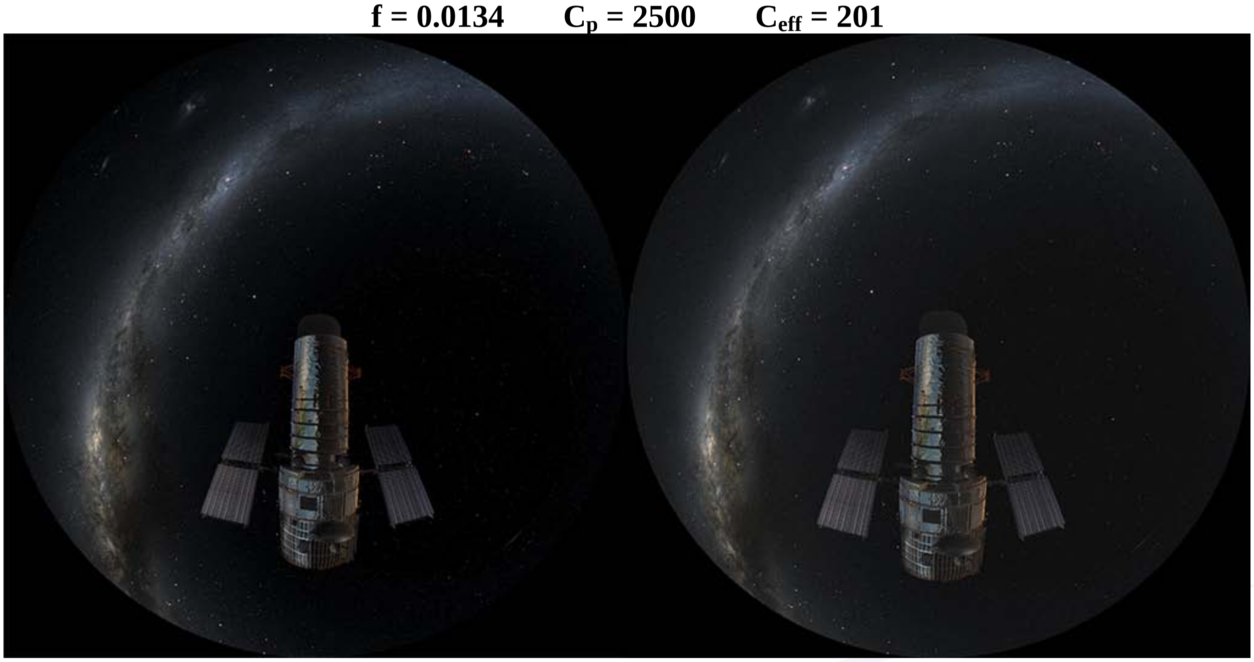
Contrast Table for "Space Art" (fill factor = 0.02) with 2500000:1 projection system:

Gain (%) \ Aperture (°)	135	150	165	180	195	210	225
20%	761	625	526	451	393	348	313
30%	491	401	334	284	246	216	192
40%	356	288	239	201	172	150	132
50%	275	221	181	151	128	110	96
60%	221	176	143	118	98	83	72
70%	182	144	115	94	77	65	54
80%	154	120	95	76	62	50	41

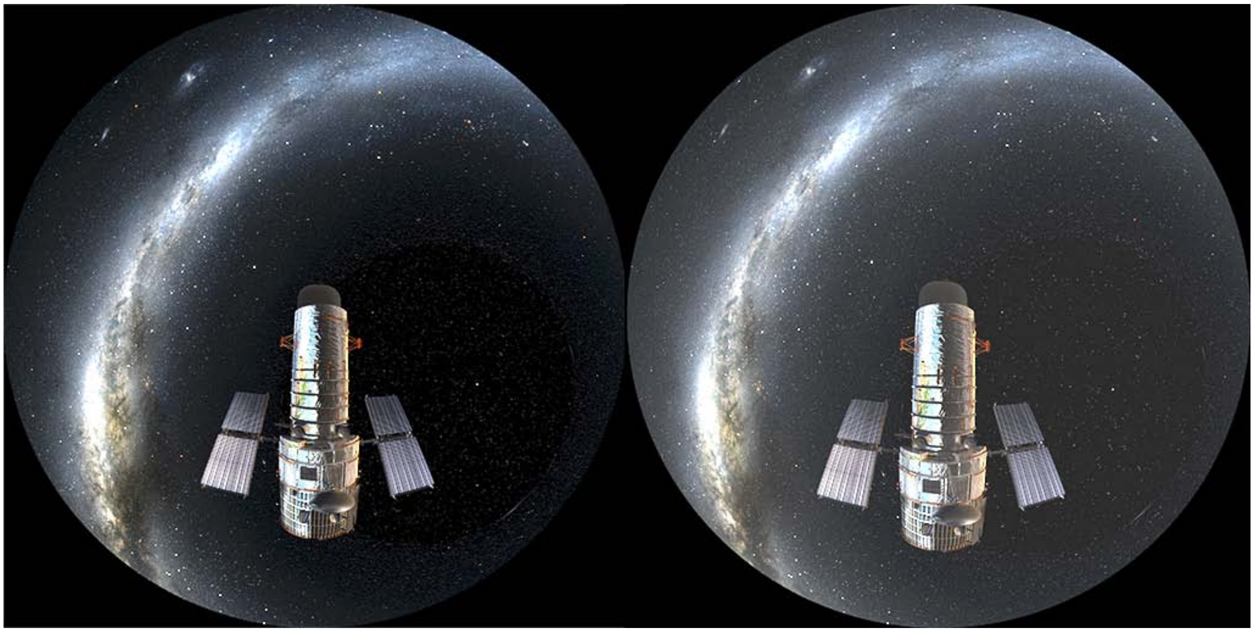
While the effective contrast does improve 8% (for a 50% gain / 180° aperture dome) with the 2500000:1 projection system compared to the 2500:1 system, it is clear this time again that there are no serious differences between the lowest and highest contrast systems in this case as well.

(Fig.4a) Hubble: (left) dome original, (right) equisolid fisheye view for r=50% Θ=180°

f = 0.0134 C_p = 2500 C_{eff} = 201

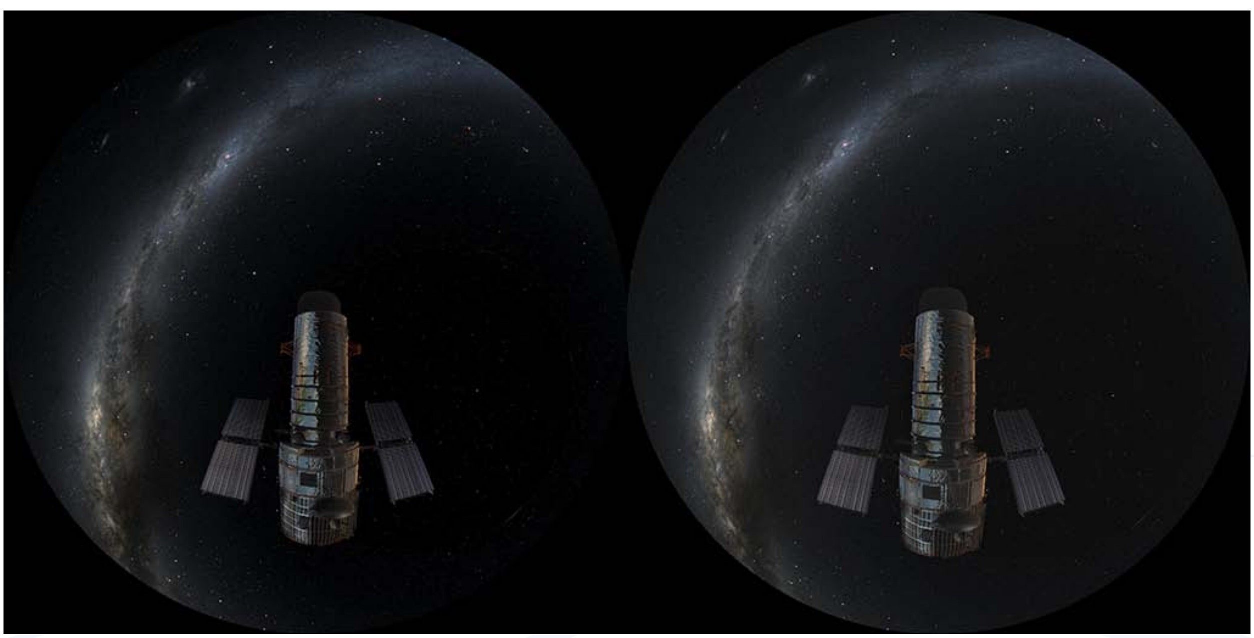


(Fig. 4b) Same as above but brightness has been multiplied 10 times to help visualize black levels:

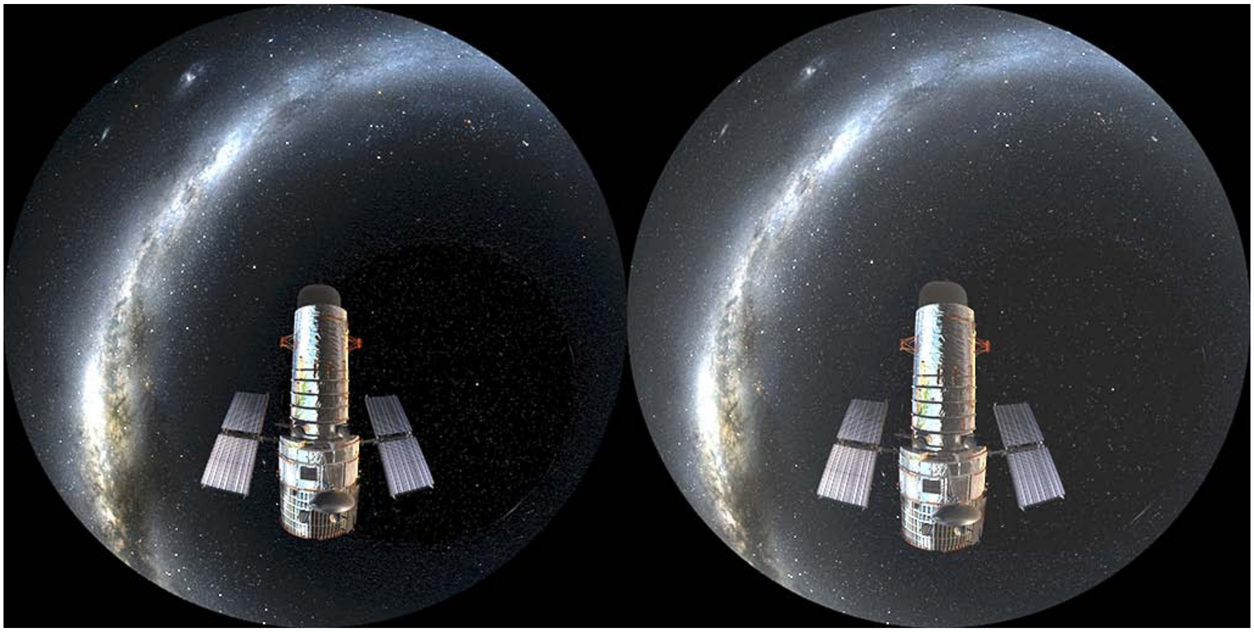


(Fig. 5a) Hubble: (left) dome original, (right) equisolid fisheye view for r=50% Θ=180°

f = 0.0134 **C_p = 2500000** **C_{eff} = 225**



(Fig. 5b) Same as above but brightness has been multiplied 10 times to help visualize black levels:



Finally, we have to compute the case of a planetarium scene where the fill factor can be as low as 0.1% (0.001). This is a very important discussion since we are here dealing with the core of the planetarium users who need a good contrast to perceive stars. In fact, it is not a secret that a 2500:1 projection system is not ideal for classic planetarium usage. So how the 10000:1 and 2500000:1 systems compare is critical in our discussion.

Sky-Skan

Let's see here the comparison for planetarium usage between the 2 higher contrast systems:

Contrast Table for "Planetarium" (fill factor = 0.001) with 10000:1 projection system:

Gain (%) \ Aperture (°)	135	150	165	180	195	210	225
20%	5800	5320	4880	4500	4160	3870	3620
30%	4710	4210	3770	3400	3080	2810	2580
40%	3920	3430	3020	2670	2370	2130	1920
50%	3330	2860	2470	2140	1880	1650	1470
60%	2860	2410	2050	1750	1510	1300	1140
70%	2480	2060	1720	1450	1220	1040	880
80%	2170	1780	1460	1200	990	820	690

Contrast Table for "Planetarium" (fill factor = 0.001) with 2500000:1 projection system:

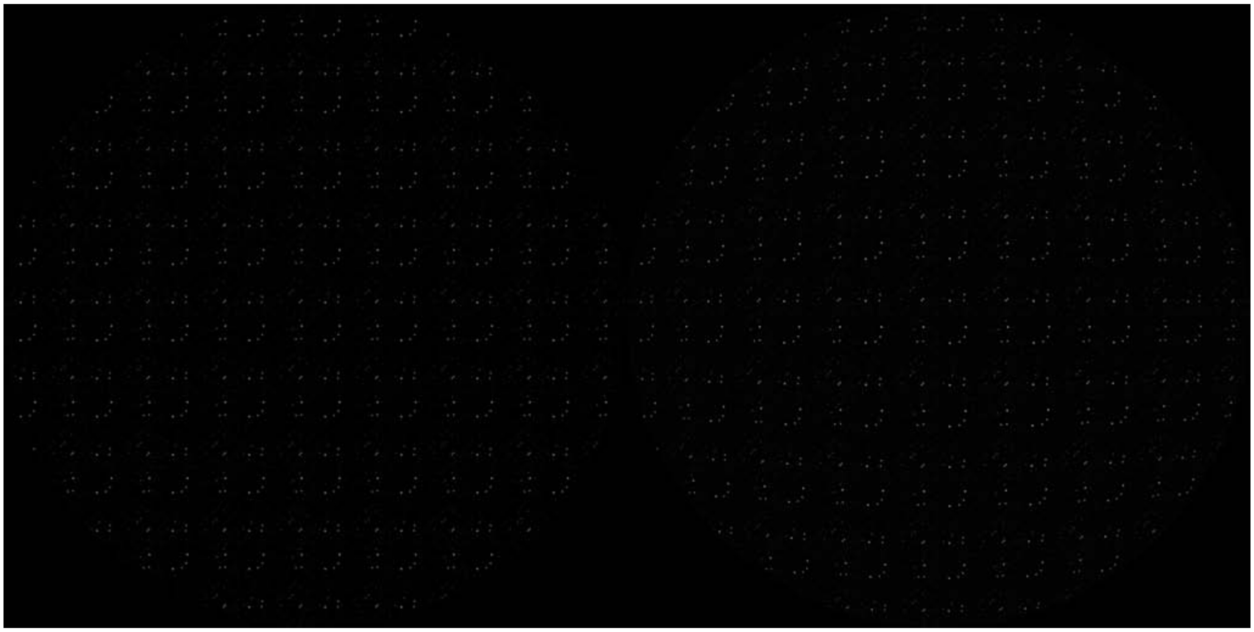
Gain (%) \ Aperture (°)	135	150	165	180	195	210	225
20%	15100	12430	10450	8970	7820	6920	6220
30%	9760	7970	6650	5650	4890	4290	3820
40%	7080	5730	4740	3990	3420	2970	2610
50%	5470	4390	3590	3000	2540	2180	1890
60%	4390	3490	2830	2330	1950	1650	1410
70%	3620	2850	2280	1860	1530	1270	1070
80%	3050	2370	1870	1500	1210	990	810

This time there are more differences. Obviously the native 2500000:1 system wins with a 3000:1 effective contrast (for a 50% gain / 180° dome) while the 10000:1 result in a more humble 2140:1 effective contrast.

However, visually the small improvement does not follow the huge difference in native contrast numbers. Here, one would have to select a very dark screen with a very small dome aperture to really benefit from the highest contrast technology (not possible in general).

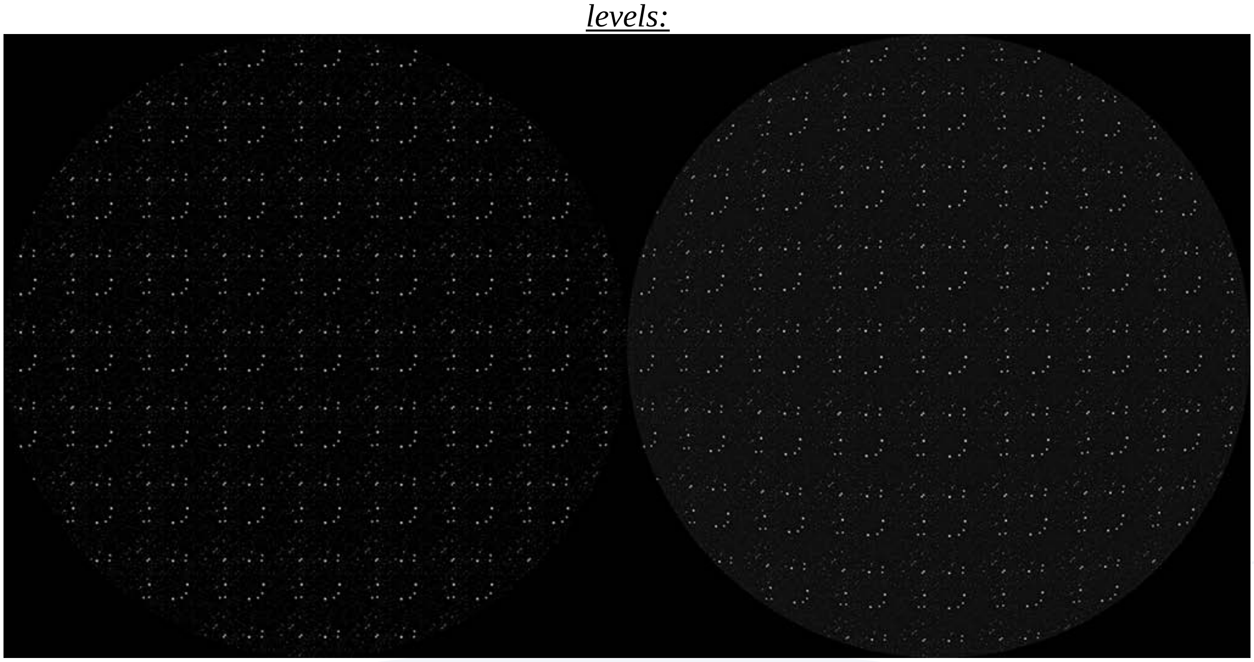
(Fig. 6a) Stars pattern: (left) dome original, (right) equisolid fisheye view for r=50% Θ=180°

f = 0.0011 C_p = 10000 C_{eff} = 1958



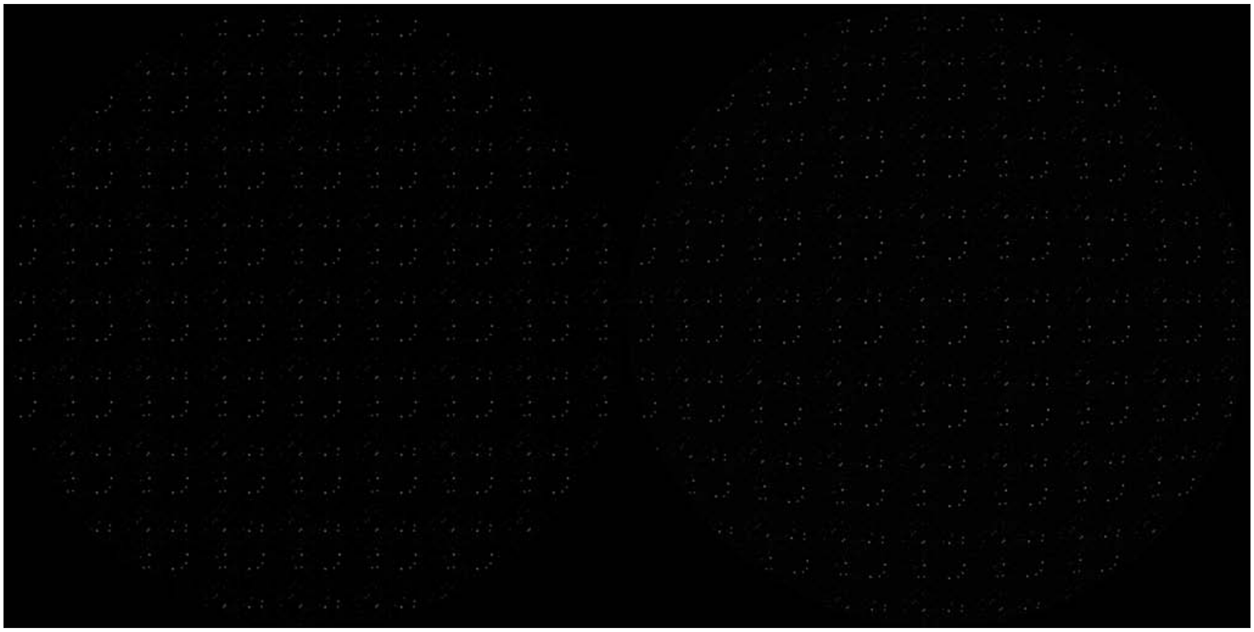
(Sorry but it's really dark here)

(Fig. 6b) Same as above but brightness has been multiplied 10 times to help visualize black levels:



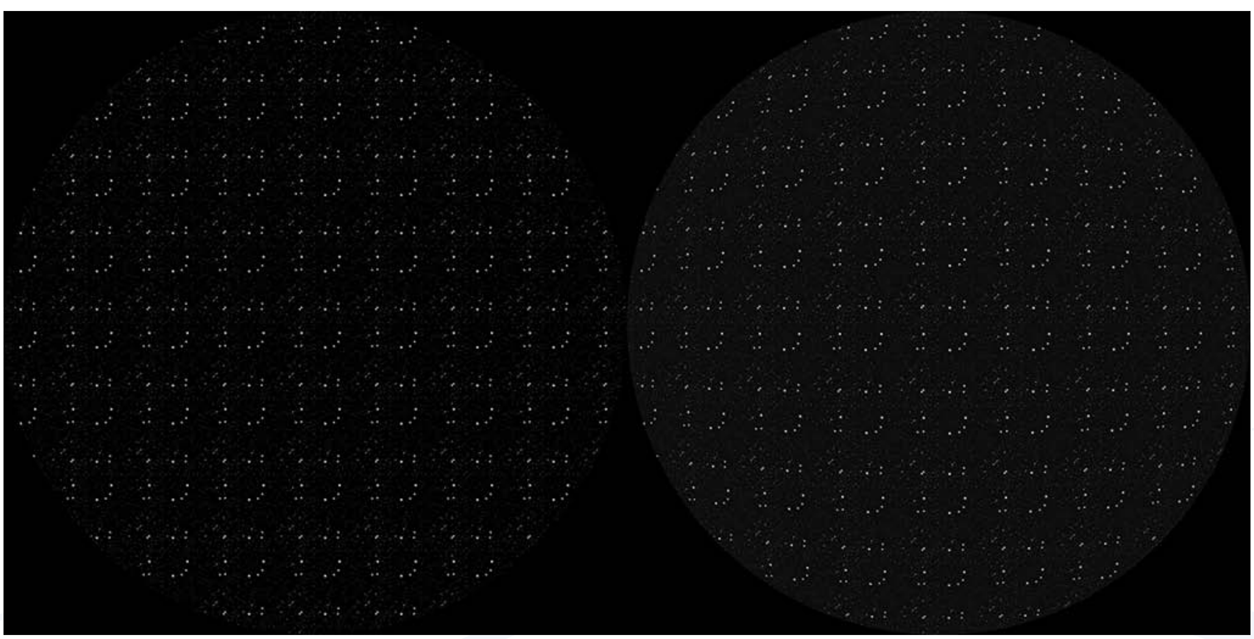
(Fig. 7a) Stars pattern: (left) dome original, (right) equisolid fisheye view for r=50% Θ=180°

f = 0.0011 C_p = 2500000 C_{eff} = 2645



(Sorry but it's really dark here)

(Fig. 7b) Same as above but brightness has been multiplied 10 times to help visualize black levels:



What about the importance of dome gain optimization?

Actually the 10000:1 system is able to produce 3400:1 effective contrast if the dome gain can be reduced from 50% to 30%. This is quite a realistic trade-off since this class of projector is typically 5 times more powerful to start with.

A possible optimization between 2 higher-contrast systems:

Projection Class	JVC-DLA-SH7	High-Contrast (Zorro, Velvet)
Native contrast	10000	2500000
Number of projectors	6	6
Masking efficiency	60%	67%
Brightness after masking (lumen)	18000	4000
Dome diameter (m)	20.00	20.00
Dome Aperture (°)	180	180
Dome area (m^2)	628	628
Illuminance (lx)	28.6	6.4
Dome gain	30%	50%
Dome amplification	18%	33%
Luminance for white (cd/m^2)	3.22	1.35
Effective Contrast for "Photography / Movies"	29.2	16.0
Effective Contrast for "Space Art"	275	151
Effective Contrast for "Planetarium"	3400	3000

As one can see the effect of diminishing the dome gain has extreme influence on the practical results.

Surprisingly, we can see that the 10000:1 system is the best compromise because the higher native brightness allows for lower dome gain with the astonishing result that the effective contrast can be better in all practical projection modes, including planetarium mode, while maintaining more than twice the luminance (better colors).

But can we find some situations where the highest contrast projectors do have advantages?

- Obviously they are better when there is nothing on the dome assuming no other spurious source of light exists (the only case one can “see” native contrast).
- Also, when using optical star projectors having very low luminance there is some advantage in being darker (however as soon as some content is projected from the digital system, lower brightness will impact color perception and effective contrast will plummet).
- Existing domes with high gain that cannot be upgraded (however this does not really improve contrast with most scenes as we have shown here, and projectors extra cost has to be compared with the cost of a new dome).

4. Conclusion

In conclusion we have established a way to evaluate precisely the effective contrast resulting from the combination of a projection system and a dome.

The main result is that for practical usage, including planetarium scenes, digital projectors with a contrast of 10000:1are the best current solution. The reason is that superior brightness can be trade-off with dome gain to achieve the best contrast possible in all practical situations.
Higher contrast projectors with 2500000:1 could play a role in the future when their brightness (and cost) will get closer to the 10000:1 projector class.

Nevertheless, one may wonder if they are really the correct solution to the problem of contrast control in a dome environment.

ADDENDUM:

Image simulation pipeline:

We start with 4K resolution image in 8bits per color channel as they are distributed in fulldome shows. However some images, like the mice hole or the stars, were prepared for this document. We used Photoshop for the steps below:

Step 1
Open image, assign a "sRGB" color space tag if required, and convert to 16 bits per color channel, save image.

Step 2
Transform the equidistant image to equisolid projection. This is necessary to ensure we have a linear relation with dome area.

Step 3
Convert sRGB color profile to a simplified RGB gamma of 1 to simulate projector brightness (linear data). Using the selection tool and the histogram, measure the fill factor as luminosity (30% red, 59% green and 11% blue, a separate processing for each color is normally recommended but was not necessary here).

Step 4
Compute the white and black effective brightness for this image as the numerator and denominator of effective contrast $\mathbf{C_{eff}}$ defined in this document. Derive correction values as exposure and offset to apply to the image. The exposure correction avoids saturation if needed, the offset value carries the effect of background cross reflections.

Step 5
Convert back to sRGB color space. Increase brightness by 3.32 stops (10 times) if needed for clarity, resize to 0.5 K resolution and convert to 8 bits using dithering for distribution.

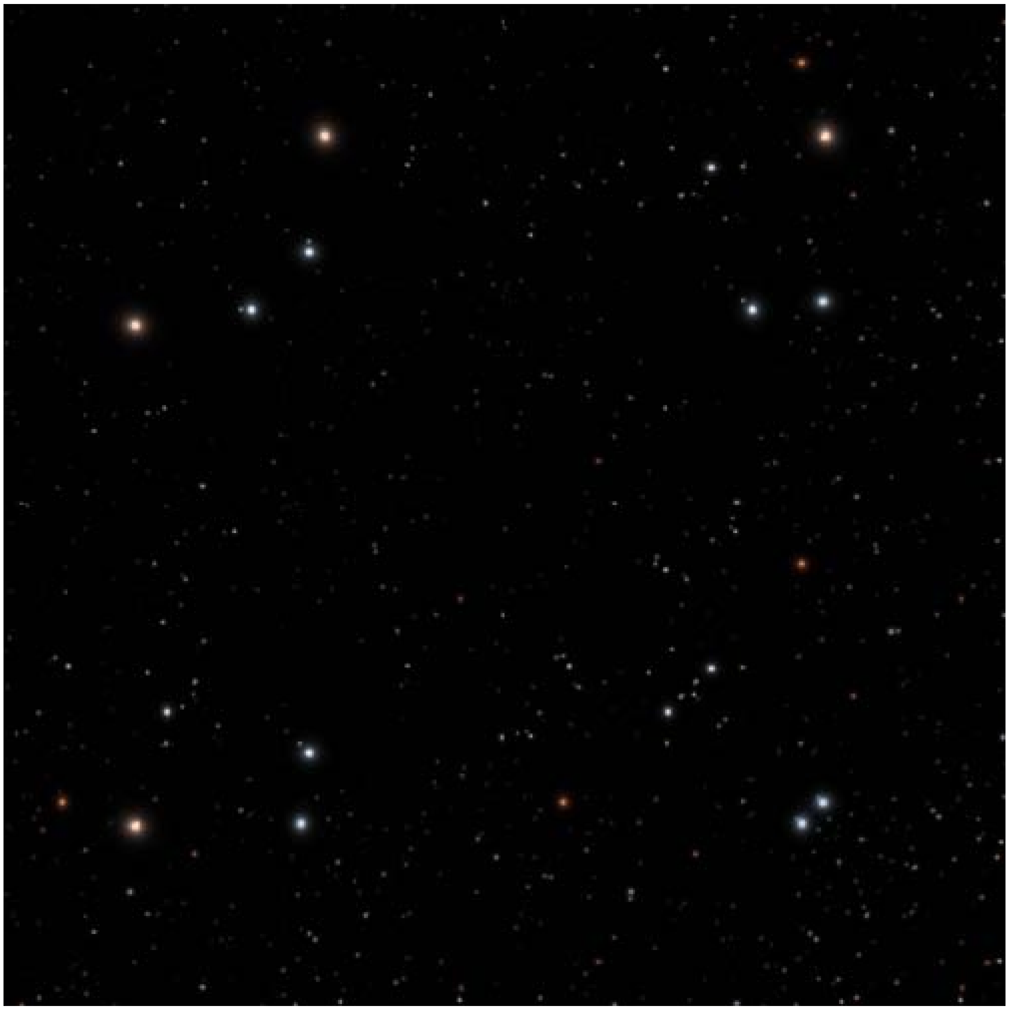
Simulation table for r = 0.5, Θ = 180°, Cp = 10000:1

	r	g	b	f	fc	White	Black	Exposure	Offset	Contrast
Checkerboard	127.5	127.5	127.5	0.5000	0.5001	1.1667	0.1668	-0.22	0.1430	7.0
Mice Hole	254.7	254.7	254.7	0.9989	0.9989	1.3330	0.3331	-0.41	0.2499	4.0
Mauna Kea	34.53	40.63	75.53	0.1672	0.1673	1.0558	0.0559	-0.08	0.0529	18.9
Hubble	3.22	3.45	3.78	0.0134	0.0135	1.0045	0.0046	-0.01	0.0046	218
Stars pattern	0.29	0.29	0.28	0.0011	0.0012	1.0004	0.0005	0.00	0.0005	1958

Stars pattern:

Here is a detail of the full resolution 4K image that was used for generating the stars pattern.

(Fig.8) Detail of the stars pattern used to simulate the planetarium scene



The image is a square with 500 pixels side which has been tiled to generate the 4K (4096 pixels side) dome original used for our planetarium scene simulation.

This square has a fill factor **f** of 0.11% when measured in a gamma 1 RGB color space.

REFERENCES:

In the industry, the practical measurement of projectors contrast in production can follow a more involved ANSI standard than discussed here. Typically a nine measuring point method is used, but in its essence the dynamic contrast (on / off method) is what is used.

As mentioned, we based our white paper on the well established theory of 'Integrating Spheres' used in the industry for measuring light sources. A good introduction to this potentially complex subject can be found here:

http://www.labsphere.com/uploads/technical-guides/a-guide-to-integrating-sphere-radiometry-and-photometry.pdf

We tried here to avoid getting into mathematical demonstrations! However, part 3.2 should satisfy our most demanding readers since it contains the full explanation of the energy transfer invariance (what we called our 'magic' property).

Interesting information about the sRGB standard which describes how the gamma transformation is working in order to transform sRGB data into a linear domain can be found here:

http://en.wikipedia.org/wiki/SRGB

We used Photoshop CS6 to illustrate our document.

While Photoshop is not a scientific tool at its core, it can be used for linear image data processing using a custom color space (simplified gamma, or linear CIE 6500K).

Geometric mapping transformations can be applied using PanoTools plugin, Hugin or ImageMagick.

http://www.photocreations.ca/panotools/

Here are the panotools coefficients that were computed for our dome original transformations:

	a	b	c	d
Equisolid to Equidistant	0.008522	-0.12146	0.002499	1.110443
Equidistant to Equisolid	0.099415	-0.0417	0.047949	0.894334

And the following reference has wonderful illustrations about projections used with fisheyes and other lenses:
http://www.pierretoscani.com/echo_fisheyes_english.html

ABOUT THE AUTHOR:

Claude Ganter, born in 1959, is Scientific Director at Sky-Skan.
In 1989, he earned a PhD in Physics from Louis Pasteur University in Strasbourg (France) on the subject of Silicon Analysis using Infrared Spectroscopy and Nuclear Methods.

Claude Ganter has been Research Engineer at the Palais de la Découverte science museum in Paris and Director of the Brittany Planetarium for a period of 12 years where he developed a digital planetarium program running on a Windows network.

Now working at Sky-Skan in Nashua NH since 2001, his current interests are related to software algorithms and more specifically with optical systems used in planetarium digital technology.
