Characterizing Fulldome Planetarium Projection Systems II
— Interpretation and implications for digital non-hybrid planetarium display selections

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Abstract

In the period from May 2013 to May 2016, 20 different planetarium facilities, mostly in Europe and centred on the Munich area, were visited by staff and visitors from the European Southern Observatory (ESO) to gather subjective and quantitative information about planetarium fulldome displays. This information served to inform the choice of planetarium system for the ESO Supernova Planetarium & Visitor Centre\(^1\). This information is here summarised to inform the planetarium community about our findings.

This paper (Paper II) concludes 3 years of non-contiguous research into what the different planetarium systems can offer, and of learning about the state of the field of planetariums. Paper I (Rößner et al., 2016) summarises the results of a measurement campaign in seven of the planetariums, delivering quantitative information to support some of the conclusions in this paper. Despite considerable uncertainties for some of the parameters, we include a template spreadsheet that can help inform some of the decisions.

For non-hybrid digital fulldome systems, and with the current (2016) technical possibilities and equipment price points, our findings are as follows:

1. To ensure a proper representation of the colours of astronomical content, we recommend selecting a system bright enough to deliver a white dome luminance of at least 5 cd/m\(^2\).
2. To lower cross-reflection, a dome reflectivity of at most 50% is recommended.
3. We recommend calculating the planetarium resolution as: The average number of pixels along all half great-circles, after edge blending.
4. We recommend using an eye-resolution of 1 arc-minute as a canonical aim for a “good” planetarium display.
5. An 8k-10k display today can be considered a “good” display with regard to resolution. Arguably the resolution problem will only really disappear for all spectators in a dome when it becomes possible to achieve displays (and content) with much higher resolution, like 15k or even more, especially when vector content like stars, lines and text are displayed.
6. Based on our calculations we recommend not focusing on projector native contrast, but on the resulting dome checkerboard contrast. We recommend selecting an on-dome checkerboard contrast of at least 6:1.

\(^1\) supernova.eso.org
Fig 1: Immersed in a fulldome environment spectators are transported to places they have never been.  
Credit: Evans & Sutherland

Preface
When we researched planetarium fulldome systems for the ESO Supernova, we recognised a need in the community to provide an unbiased view of the topic supported by measurements. With just a few thousand fulldome installations this is clearly a niche field. Combined with planetariums’ often being cash-strapped, ESO as an intergovernmental organisation has with the advent of the ESO Supernova — “the world’s first open source planetarium” — taken on the role to deliver various free services to the community. This also involves giving advice on issues such as fulldome systems.

All the visited installations were treated equally, and neutrally. The conclusions are presented without bias, and solely represent the subjective opinion of the author and not of ESO.

Introduction
Needless to say, the choice of the planetarium display is one of the biggest decisions for a planetarium, as it can break or make the operational model. The system can either be a source of daily aggravation and loss of time, or a flexible, carefully tuned and maintained machine, the limitations of which are understood and taken into account in the operational model.

It is estimated that in 2015, up to 123 million people visited the 4105 planetariums around the world (Loch Ness Productions, 2015). The environment planetariums offer immersive experiences unmatched by any other type of museum environment.

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2 Estimated numbers are only based on visitors’ attendance at 10% of the world’s domes (independent of dome size), so the extrapolation to a global attendance estimate should be made with caution.
In the use case we’re particularly interested in, a fulldome (non-hybrid) system would deliver an intense, immersive fulldome experience to leave the visitor in awe of our Universe. Choosing a planetarium display system that can deliver this special experience is a complex process involving many different considerations of an artistic, technical and managerial nature. Further complexity in the choice arises from planetariums being very different (in size, inclination, dome construction, etc), and, unlike cinemas which are required to be DCI compliant (SMPTE, 2011), standards for dome displays do not exist.

Despite the ~100 million annual visitors to planetariums, the planetarium as an optical system has not been thoroughly characterized and understood yet. The findings presented here were informed by in-situ measurements (see Rößner et al., 2016, hereafter Paper I, which in turn relies heavily on Ganter, 2012). Paper I characterizes the way light propagates in the largest optical element of a planetarium: the dome itself. In an ideal world, one would aim for a projection system with high luminance and high contrast. However, in reality effects such as cross-reflection occur, compromising the projection quality. An important physical difference between the standard displays in our daily lives and the dome, is that the dome does not emit light, but reflects light back to the spectators. Since the dome is hemispheric, a significant portion of the light from one part of the dome is cross-scattered and ends on another part of the dome (see the section on Contrast below). It is important to take this into consideration and address it in the technical requirements for the system.

**Fig. 2:** A great-looking image (left) will tend to suffer significantly from cross-scattering in a dome — it “washes out” (right). To some degree one can compensate for this effect during the show production, but the main issues need to be addressed in the requirements for the dome reflectivity and projection system during construction. Note that only the electronic version of this figure represents the calculations well. Credit: ESO/S. Brunier.

Paper I outlines the theory of light propagation in a dome and is complemented by in-situ luminance and contrast measurements in seven domes: Vienna, Freiburg, Munich, Laupheim, Münster, Heidelberg and Augsburg.

**Brightness**

As a result of financial and technical limitations, very few planetarium displays so far have been what would subjectively be called bright and vivid. It is expensive to purchase bright projectors and in addition the cross-scattering washes out some of the colours. How can the optimal brightness of a display be determined? It is a known fact in the community, although rarely stated, that most planetarium displays, subjectively assessed, are faint. Very few displays are considered “too bright”. Astronomical images and renderings have
not been projected with the same richness, contrast and intensity as a DCI-compliant cinema movie, a movie displayed on an TV OLED display, or a laser show. This is illustrated in Fig. 3.

Fig.3: An illustration of the difference between vivid colours seen in print, on computer displays and in TV (right) versus a typical subdued, low-saturation fulldome display (left). Credit: ESO/M. Kornmesser.

For colourful images of astronomical objects in particular this is an important aspect, since the native dynamic range and gamut of astronomical observations are very large.

Informed by the measurements in Paper I and the subjective impression of the displays, we have the following finding:

**Finding 1:** To ensure a proper representation of the colours of astronomical content, we recommend selecting a system bright enough to deliver a white dome luminance of at least 5 cd/m².

**Dome reflectivity**

As described in detail in Paper I, the dome as an optical element presents certain limitations to the contrast that appears on it. Contrast specifications that projector manufacturers publish often, if not always, describe the luminance ratio between a “full white” and a subsequent “full black” projection (the inter-frame contrast). These numbers can be very high, typically more than 10,000:1. However, depending on the particular use, this definition of the term “contrast” can be misleading. For fulldome videos, what is more relevant is the degree to which light from bright areas of the dome “spills” onto black areas as a result of dome cross-scattering. The intra-frame (or ANSI-) contrast is a more appropriate number to describe this. It describes the ratio of black and white areas projected alongside in the same frame. This “type” of contrast is, therefore, also referred to as the checkerboard contrast.
The lower the dome reflectivity, the better the checkerboard contrast. On the other hand, the lower the dome reflectivity, the lower the (maximum) luminance of the projection. With today’s technical standards and price-points, we find a 50% dome reflectivity to be a good compromise, provided that the projectors are powerful enough to ensure a white dome luminance of 5 cd/m² at that dome reflectivity.

Finding 2: To lower cross-reflection, a dome reflectivity of at most 50% is recommended.

Resolution

For a discussion of the optimal realistic resolution of the display on the dome (the Dome Diameter resolution) please also see the excellent article by Voss (2012).

There is a lack of consistency in the industry about how the terms “4k” and “8k” are defined, but many seem to agree this should refer to the mean pixel count on all half great circles across the dome — the diameter of an equivalent dome master frame. Different half great circles can give different resolutions due to the uneven pixel density on the dome.

Finding 3: We recommend calculating the planetarium resolution as: The average number of pixels along all half great-circles, after edge blending.

According to Ackerman (1962) the typical eye resolution limit is about 1.7 arcminutes (5 • 10⁻⁴ radians) for most people. In an extreme case for those with most acute vision in optimal circumstances it can be as low as 0.8 arc-minutes (Wikilectures, 2014). Taking 1 arc-minute as a canonical best estimate for the eye resolution limit during a mixed planetarium show (stars and pre-rendered content), a 10,800 pixels display is needed if a visitor in a seat in the centre of the dome (180 degrees x 60 arc-minutes) should not experience pixelated images.

Comparing with print resolutions, we note that designers apply a golden rule of 300 DPI (dots per inch) for print graphics (Spoon Graphics, 2016). An A4 page (21 cm wide, or 8.27 inches) would need 2480 pixels to print at this nominal print resolution of 300 DPI, giving a width of one pixel of 8.46 x 10⁻³ cm. With a typical reading distance of 40 cm; this corresponds to an angular resolution of 43°, just a bit better than the suggested 1 arc-minute/pixel eye resolution limit confirming this as a “good” resolution to aim for.

Finding 4: We recommend using an eye-resolution of 1 arc-minute as a canonical aim for a “good” planetarium display.

A designer will argue that printing at significantly below the canonical 300 DPI for the print resolution causes visibly pixelated prints at normal reading distances. It is generally accepted that one should not print below 150 DPI for high-quality results. A planetarium display of, for instance, 4k corresponds to a print-out at 81 DPI at normal reading distance⁴. A planetarium display for a viewer in the centre with the same quality as a 300 DPI print product would need to have a resolution of 15k⁵.

Furthermore, a print designer might also argue that the golden rule of 300 DPI is only really valid for bitmaps, i.e. pixel-based images. For vector graphics, like typefaces or line art, a significantly higher resolution than 300 DPI, like 800 or even 1200 DPI, is often recommended (see e.g. CreativePro, 2014). A line can be visibly

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³ \[ \text{arcsin}(8.46 \times 10^{-3} \text{ cm} / 40 \text{ cm}) = 12.12 \times 10^{-3} \text{ deg} = 43'' \]

⁴ 180 deg / 4000 px = 0.045 deg/px. Equivalent pixel size on a printed paper at 40 cm distance: 40 cm * sin(0.045 deg) = 0.031 cm. This corresponds to 1/0.031 px/cm = 31.8 px/cm = 80.85 px/inch, or DPI.

⁵ 180 deg / 0.012 deg = 15k
jagged if rasterized and printed even at 300 DPI\(^6\). In live planetarium displays stars, grids and texts displayed on the dome are inherently vector objects, rendered as bitmaps, and one could argue they would benefit from being rasterized at an even higher resolution than that which corresponds to 300 DPI (~15k in a dome) to display without artifacts.

![Fig.4: Simulations comparing a 4k “darker” system (left) with an 8k “brighter” right. Stars can be smaller and less pixelated in the high-res “bright” system.](image)

These theoretical considerations are supported by our own subjective experience during the visits to the planetariums. A 4k system produces fairly large “fluffy” stars which are not as representative of a natural night sky as an 8k system.

Two additional factors need to be considered. Firstly, as anyone who has grown up watching TV in PAL or NTSC resolution (which actually looked kind of OK), there is a considerable difference in the perceived resolution of moving images and that of stills/prints. This is an argument for reducing the need for very high res displays somewhat. Another indication pointing in the same direction is the very nice article from NSC Creative that provides the results of side-by-side screening of 4k and 8k CGI images side by side in an 8k planetarium. The conclusion is that it is hard to see the difference, also as the 4k material benefits from the 8k display (NSC Creative, 2014)\(^7\).

Secondly, the discussion above is only valid for the centre of the dome. The average spectator sits closer to the edge, and a resolution up to a factor 2 higher than the estimates above would be needed.

**Finding 5:** An 8k–10k display today can be considered a “good” display with regard to resolution. Arguably the resolution problem will only really disappear for all spectators in a dome when it becomes possible to achieve displays (and content) with much higher resolution, like 15k or even more, especially when vector content like stars, lines and text are displayed.

\(^6\) The Fourier transform of e.g. a line on a background contains very high (spatial) frequency components. To avoid aliasing (the Nyquist–Shannon sampling theorem applied in the spatial domain), one has to sample the vector line at a very high spatial frequency when rendering a bitmap. This requires a high resolution.

\(^7\) Is true that most fulldome content today (2016) is still 4k as the difference in production time for 4k and 8k CGI (computer generated imagery) frames is very high (far higher than a factor of 2). However, as argued in Voss (2012), the “sky” planetarium displays are not limited in the same way. Systems today can easily output planetarium real-time content in 8k (or even more). Also several (partially) 8k shows are already available on the market and the number can be expected to increase in the next years. Also note than an 8k system will show 4k content better than a 4k system.
Contrast and black dome luminance

When developing a planetarium system, one should not select the projection system by looking at the projectors alone. One has to have a look at the entire system: projectors, dome, and also the human perception of visual stimuli. Cross-reflection causes bright content on the dome to create stray light that increases the brightness of content that is actually meant to be black.

Therefore, it is wise to decrease the reflectivity of the dome and to increase the projector’s brightness accordingly. At first glance this might seem to be a waste of projector output brightness. But in fact it means that the second reflection of light on the dome is significantly reduced, and a fortiori the third and every following stray light reflection is reduced as well. In this way a better contrast can be achieved.

This also means that projectors that offer an extremely high native contrast, or dark background, may perform poorly in terms of contrast when they are operated in a dome of high reflectivity. For example, when a planet is shown against the dark background of space, the light scattered by a high reflectivity dome will increase the light level of the black areas of the dome — and the advantage of the superb native contrast that a high contrast projector offers can vanish. The measurements in Paper I (see Fig. 5 below) suggest that above a certain fill factor (i.e. when a certain fraction of the dome is filled with content), the native contrast of the projector no longer plays a significant role, and resources may better be invested in other aspects of the projections system, such as brightness or resolution.
Fig.5: Effective intra-frame contrast in the dome. Projectors that offer an extremely high native contrast, or dark background, may perform poorly in terms of contrast when they are operated in a dome of high reflectivity. The underlying physics is published in the seminal paper by Ganter (2012). The measurements are from Paper I. Note that unknown circumstances in the planetariums measured make it hard to compare the different installations: e.g. the age of the projection lamps, dust accumulation on the dome, dome size and funding available for initial procurement. Note also that the fit between theory and measurements deteriorates at low fill factors due to these unknowns. Hence we do not recommend using these measurements to conclusively compare between different vendors.

**Finding 6:** Based on our calculations we recommend not focusing on projector native contrast, but on the resulting dome checkerboard contrast. We recommend selecting an on-dome checkerboard contrast of at least 6:1.

Fig.6: A physical simulation showing the contrast and the brightness of two display types. Left: low contrast, high brightness, low dome reflectivity system, displaying a slightly lower contrast than the input image. Right: High contrast, low brightness, high reflectivity system with low effective contrast as a result of cross-scattering. The low-contrast, high brightness, low dome reflectivity system performs better, as it is much brighter and has a better contrast. The simulations were calculated based on the formulas in Ganter (2012), assuming a dome that is perfectly Lambertian (which, as argued, may be an oversimplification). Image credit: ESO/S.Brunier

The caveats of the theory

One of the aims of Paper I and II was to arrive at a situation where we could provide a numerical way to calculate planetarium display output parameters from known equipment specifications. However the measurements in Paper I showed that important assumptions in Ganter (2012) and Paper I itself did not hold. None of the seven domes turned out to be true Lambertian surfaces with an ideal “matte” or diffusely reflecting surface (with the same apparent brightness to an observer regardless of the observer’s angle of view — i.e. isotropic luminance). Other important factors which vary between different planetarium installations are the different ages and output of the lamps at the time of the measurement (up to a factor of two), dust accumulation on the dome, different optical configurations (lenses, mirrors etc.) and possible backscatter of light from the seating area, carpet, railing etc. onto the dome. An important weakness of the approach in Paper I is the limited sample size of just seven planetariums. Despite considerable uncertainties due to these unknowns, a template spreadsheet is included below¹ to illustrates the underlying theoretical principles.

¹ Can be downloaded from https://docs.google.com/spreadsheets/d/1PXOrBcF-FBVA_eppaj7MqmJ6SOVy2QJGnh6ptyk8ZKo/edit#gid=6
unknowns and the limited sample size makes it unwise to use this spreadsheet as an engineering tool and caution is urged in interpreting the output values.

The parameters listed are (bold parameters are deemed more important):

1. **Planetarium content - Fixed Value**
   Three types of content in the dome were considered:
   1.1. **Stars:** The classic content to project in an planetarium is a starry sky. One wants to have bright stars of small diameter on a background that is deeply black. Cross-scattering of light is nearly irrelevant as most of the projected content is black.
   1.2. **Space Art:** One often also has rectangular, “slide-like” projections (image insets). These images are required to be bright, of high resolution and with vivid colours. Cross-scattering begins to become relevant, as the background black of the sky washes out.
   1.3. **Movies:** In fulldome projections, which fill the entire dome with content, one has to find a compromise between brightness and checkerboard contrast. The dome reflectivity can be used to adjust this compromise in favour of brightness or contrast.

2. **Native contrast - Input Value**
   The contrast that a projector offers at its output lens (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), without any dynamic control of its lamp brightness. The planetarium setting is not taken into consideration. Note that there is a considerable simplification implied here, as no distinction is made between sequential (inter-frame) contrast and ANSI (intra-frame contrast), a concept that also applies to the projectors themselves.

3. **Native brightness (lumens) - Input Value**
   The light output brightness of a projector. The dome is not taken into consideration. Note that this value might be significantly lower than the one published in the projector data sheet owing to lamp deterioration, special projection lenses, dust accumulation on the dome or the like.

4. **Corrected brightness (lumens) - Calculated Value**
   Because the amount of lamp degradation in the measured systems was not known, the native brightness was corrected to fit with the quite reliable luminance measurements.

5. **Native resolution per projector (Megapixels) - Input Value**
   The number of pixels of a single projector.

6. **Number of projectors - Input Value**
   The number of projectors in the planetarium.

7. **Blending efficiency (%) - Input Value**
   The number of pixels that actually appear on the dome is lower than the sum of all pixels of all projectors due to the overlap of the projection fields, reducing the number of actually usable pixels. This is reflected in the blending efficiency, which is 100% for no overlap.

8. **Dome diameter (m) - Input Value**
   The diameter of the dome.

9. **Dome aperture (degrees) - Input Value**
   Usually 180° (a half sphere). This would have a lower or higher value if the dome occupied less or more than a hemisphere.

10. **Dome reflectivity (%) - Input Value**
    The reflectivity of the dome surface (typically 30-70%). In general, the lower, the better the checkerboard contrast (resulting from less cross-scattering).

11. **Fill factor - Fixed Value**
    The fraction of the dome that is filled with content, depending on the type of content in 1. above. It is a very low value for starry sky, up to 0.2 for movie content. The maximum possible value for the fill factor would be 1, but this is not a realistic value under normal circumstances, as it would mean a completely lit dome. For fill factors 0.2 and above, the native contrast of the projector plays a vanishing role.
12. **Dome area (m²) - Calculated Value**
The area of the dome as a function of diameter and aperture.

13. **Dome resolution (Megapixels) - Output Value**
The number of usable pixels on the dome.

14. **Dome diameter resolution (pixels) - Output Value**
The average number of pixels along all half great-circles, after edge blending. Calculated by \( \pi \times \sqrt{N/2\pi} \), where \( N \) is the total pixel count on the dome (assuming a homogenous pixel density).

15. **Pixel resolution (arcminutes per pixel) - Output Value**
The angular size of a pixel, as seen by a visitor located at the centre of the dome. Recommended to be 1 arc-minute or lower.

16. **Illuminance (lm/m²) - Calculated Value**
The brightness that the dome is illuminated with. Not to be confused with the reflected luminance.

17. **Dome amplification (%) - Calculated Value**
The fraction of the incident light that is to be added to the incident light to account for the increase in brightness due to cross-scattering.

18. **White dome luminance (cd/m²) - Output Value**
Luminance when a completely white frame is projected. This value accounts for the entire optical system: projectors and dome.

19. **Checkerboard contrast - Output Value**
A checkerboard-like pattern is projected (black and white rectangles, so 50% of the dome area is black and 50% of the dome area is white), and the brightness of the black and white areas is measured. The ratio of these values is the checkerboard contrast. This is an important quantity, as it takes cross-reflection within the dome into consideration.

20. **Dome contrast - Output Value**
One does usually not show checkerboard patterns on a dome, but rather real-world footage, such as the starry sky or an all-sky image. In such footage, the dome is not 50% white and 50% black, as with the checkerboard pattern, but rather a ratio described by the fill factor. Therefore, the contrast is described as a function of the fill factor. Note: the dome contrast does not take the projector’s limited contrast into account.

21. **Black level - Calculated Value**
The inverse of the projector native contrast. It describes the ratio between the black luminance and the white luminance.

22. **Corrected fill factor - Calculated Value**
The fill factor, as described above, has to be corrected. This is because the imperfect black levels of the projectors make a contribution of light on top of the actual content. The corrected fill factor, therefore, will never be 0, but can still be 1 when the dome is completely lit. In a projection of a completely black frame, the corrected fill factor is just equal to the black level described above.

23. **Effective contrast - Output Value**
The dome contrast did not take into consideration that the projector has imperfect black levels. The effective contrast does take this into account. It describes the contrast of the entire optical system: projectors and dome.

24. **Black dome luminance (cd/m²) - Output Value**
Luminance when a completely black frame is projected. This value accounts for the entire optical system: projectors and dome.
Table 1: Template spreadsheet for a representative planetarium, Vienna Planetarium, used to calculate important planetarium display parameters. The two red cells contain the measurement values. The checkerboard contrast is 20% overestimated in the calculations whereas the black dome luminance is quite far off (140% underestimated). In the three other best-characterised domes the measurements of checkerboard contrast deviate from the calculations by between +17 and +34%, and black dome luminance by between -9% and a whopping -4485%.

Conclusions

Anyone building a planetarium display is encouraged not to look only at projector specifications but at the entire optical system: the projectors, the dome and the eye.

In an ideal world a planetarium display would have just one projector, located in the centre of the dome. The dome would be relatively grey (relatively low reflectivity, for example: 30-50%). The white dome luminance would be at least 5 cd/m² and preferably something a bit closer to a DCI compliant cinema (48 cd/m², SMTPE, 2011).
The resolution calculated as the average number of pixels along all half great-circles, after edge blending, would be at least 8k and possibly 15k. The resulting on-dome checkerboard contrast should be at least 6:1.

A backlit OLED display with less cross-scattering problems would in some distant future provide a much better experience.

During this work we ascertained that planetarium display systems have a number of unknowns that have not yet been properly modelled or measured. They include factors like:

1. Deviation from true Lambertian surfaces
2. Different ages and output of the lamps at the time of the measurement (gives up to a factor of two different light output in the same installation)
3. Varying dust accumulation on the dome
4. Different optical configurations (lenses, mirrors etc.)
5. Possible backscatter of light from the seating area, carpet, railing etc. onto the dome.

With the limited sample size of just seven planetariums in Paper I, more measurements are needed to improve our physical understanding of these, and possibly other parameters.

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