# Digital Fulldome Projection Technology

Paul Bourke, May 2011

## Introduction

The following are some notes around the technologies used for immersive displays based upon portions of a sphere. The intention is to ensure discussions start with a common basis, from which further more targeted questions may arise. I will begin with an outline of the data projection options, followed by some comments on real time image generation using computer graphics, and finally summarise some of the options/issues with physical dome surface construction.

## Digital projection

There are 4 main categories for how digital fulldome projection can be achieved: single projectors with either a fisheye lenses or a spherical mirror, twin fisheye lens projection, and multiple short throw lens projectors. In this context "fulldome" applies to the interior of a hemisphere (half a sphere) with the audience also in the inside. These techniques generally relate to domes from a few meters in diameter up to large planetariums of 30 meters in diameter, although in some cases the physical dimensions of the projectors may preclude their use in small domes. The discussion here will be limited smaller domes and applications around virtual environments, gaming, and simulators.

While video projection into hemispherical environments has been experimented with for some time, a key contributor to the commercial uptake was the Visionstation range of products released by Elumens around 2000. These were driven by a single digital projector with a novel "tru-theta" fisheye lens mounted under the console table, it was this lens that was the key IP of the product.

Fisheye lens, single projector

The most natural (and simplest) image format for representing images destined for a hemispherical surface is fisheye. As such the obvious means of digital projection is a data projector with a fisheye lens. An early supplier and current leader in this area is *The Elumenati* (*www.elumenati.com*), they have a range of fisheye lens solutions, generally integrated into the projector (all the projector optics are replaced) but sometime they are external units, as in the following.

The main deterrent to the commercial fisheye offerings is price, the good optical solutions start around US$20K. There are low cost fisheye solutions based upon fisheye lenses from the camera industry and an intermediate lens. This is described as the Lhoumeau Sky System (www.lss-planetariums.info).

The term “tru-theta” relates to the radius on the fisheye image plane being directly proportional to the latitude angle on the projected dome. Other relationships are possible and indeed these have been used to circumvent the patent on tru-theta lenses, the nonlinear variation being ignored or compensated for in software.

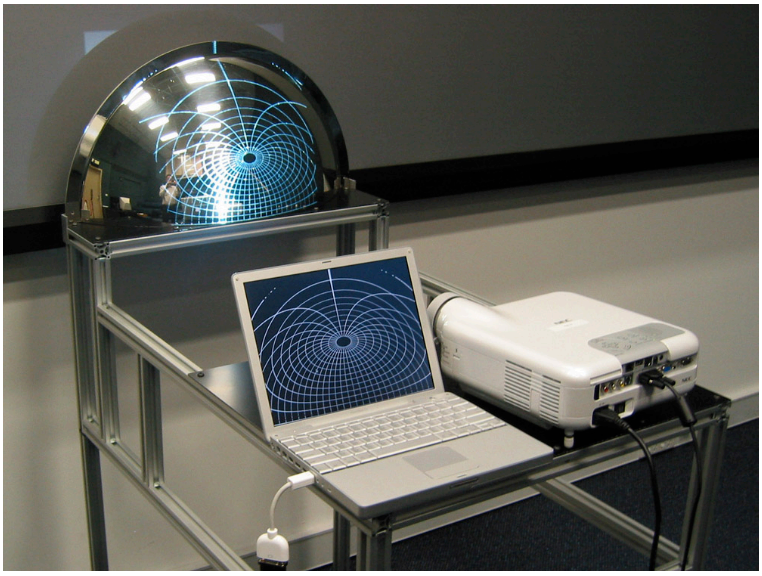
An important thing to appreciate with fisheye systems is that for true hemispherical coverage the pixel efficiency is very low, that is, the circular fisheye image is inscribed in the rectangular frame of the projector and as such there are a lot of unused pixels. This is a problem with 4/3 aspect projectors (the most square aspect) and is worse with current 16/9 or 16/10 projectors. The usual solution to this is to limit the surface of the dome used, truncating the fisheye. See appendix 1 for some of the main configurations in usage today. Please note that most of the truncated products in appendix 1 are based upon data projectors with vertical lens shift. This means that if a truncated fisheye is 180x155 degrees then it can be used in a truncated dome which may be physically truncated at the top or the bottom, or both as long as the total vertical field of view is at most 155 degrees.

The leading manufacturer of fisheye lenses for projectors is Navitar, presentation.navitar.com.

Spherical mirror, single projector

The spherical mirror approach was developed by the author in an attempt to create a lower cost alternative to fisheye lenses. This arose from the realization that there are other ways of spreading the light from a data projector about a large angle. The additional work performed in software is pre-distort the fisheye imagery such that when the image is reflected off the mirror and strikes the dome it looks correct and undistorted, just as if a fisheye lens were used with the same fisheye image. With current graphics cards and the method of warping the imagery, this is an almost zero performance hit on modern machines.

In contrast to fisheye systems, the wide 16/9 aspect of current projectors improves the pixel efficiency of the spherical mirror approach. However pixels are now no longer all of equal size so direct comparisons are difficult. In practice and with careful design a spherical mirror projection system can compete favourably with all single projector fisheye solutions except the latest WQXGA based system, generally using the relatively new Projection Design F35. The spherical mirror in contrast with the fisheye lens costs in the order of US$1K.



The non-equal size of pixels on the dome is important when designing where the projector and mirror should be placed for any particular application and dome orientation. For the traditional iDome of the author the highest resolution pixels are towards the lower and center of the iDome, the largest pixels towards the top of the iDome. This is an appropriate match to most content, ie: one does need high resolution to represent the sky.

For small domes the main benefit of the spherical mirror approach is that the projection hardware is located well away from the centre of the dome.

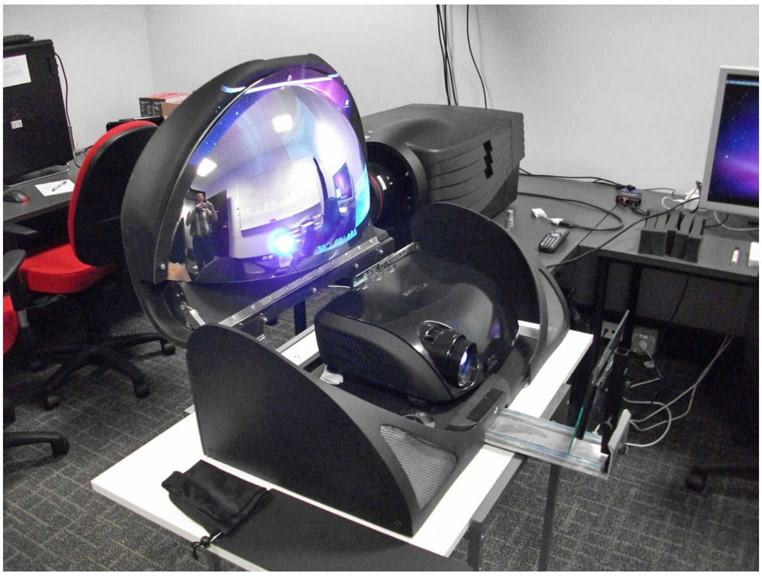
A benefit of the spherical mirror is that the optics is decoupled from the projector, in general a fisheye lens system is designed for a particular projector make and perhaps even model. There is however a limitation with the spherical mirror approach and that is not all projectors are suitable. The projector being used needs to be able to focus on a relatively small image, typically for a 60cm spherical mirror the projector needs to be able to focus on an image around 50cm wide on a flat wall. Many projectors are suitable but many are not and it is generally not something manufacturers quote so suitability of any particular projector needs to be tested. In addition to being able to focus projectors with a greater depth of focus will give more focused results with improved focus on the periphery of the dome.

It is this limit to how small an image projectors can create that has determined the size of the spherical mirror. As one tries to use smaller and smaller mirrors (for compactness) the harder it will be to find suitable projectors. Note also that the size of the mirror is not related to the size of the dome, the author has used the standard 60cm spherical mirror in domes from 1.5 to 30m in diameter.

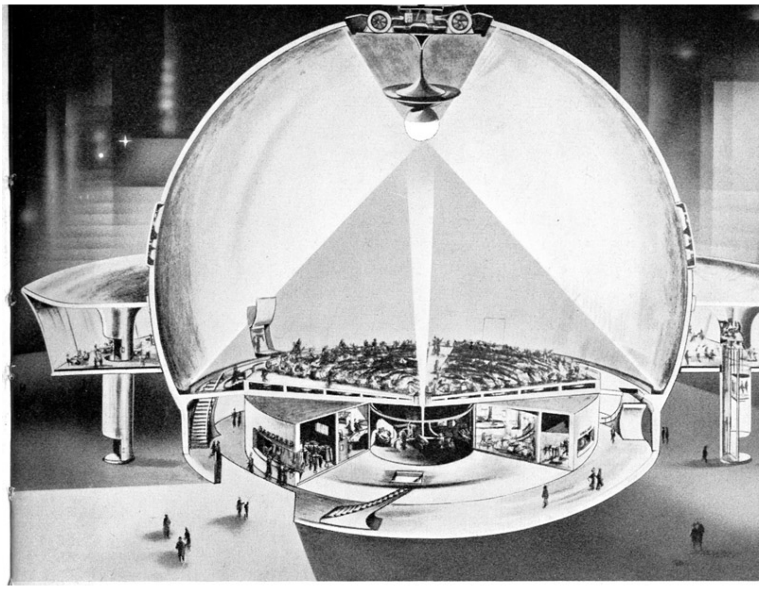
It is critical for best results to use first surface mirrors, non-first surface mirrors give a less focuses result due to refraction in the front layers before the mirror surface. At the moment there are two suppliers the author has used, the most recent also applies a protective coating. Never-the-less first surface mirrors are very delicate.

There are no IP or patents related to projection into domes using the spherical mirror.

A number of installers use a secondary planar mirror to create a more compact projector/mirror combination. Generally the distance between the projector and mirror is around 1m, the secondary mirror at least halves that.



As a historical note the first known record the author is aware of where a spherical mirror used for dome projection dates back to 1957. In this case, before computer graphics, the film was created using a geometrically identical arrangement for filming as for projection (film camera pointing at a spherical mirror). Such techniques where footage is captured by filming with a video camera and a spherical mirror don't apply to computer generated content.



## Multiple projectors

The main limitation with single projector solutions is the image resolution, the available pixels from a single projector are spread out over a wide surface area. There are only two solutions, choose higher resolution projectors or use more than one projector. Choosing higher resolution projectors isn't scalable (there are only a limited number of options) and the price of projectors above HD increases rapidly.

For planetariums one approach is to use two 16x9 projectors with a truncated fisheye lens arrangement. This gives full hemispherical coverage and a generous overlap for edge blending.

The next option is to use projectors with fairly standard short throw lenses (eg: 1:1). This translates to between 5 and 7 projectors. For simulators and gaming in small domes this is relatively uncommon and generally only for application areas that can afford the cost and system complexity. Such systems add considerable complexity to the software model (geometry correction and edge blending) and additionally often require a cluster of computers for performance reasons.

Twin projectors using a pair of spherical mirrors, as far as the author is aware, has not been attempted. The edge blending between the two images is likely to be very challenging.

## Real time content creation

The technique the author employs for creating real time graphics, in this case with the Unity game engine for the iDome, is outlined here: http://paulbourke.net/papers/cgat09b/. From a computer science and computer graphics perspective it is not difficult, summarised as:

1. The scene is rendered with a number of perspective cameras each with 90 degree field of view vertically and horizontally, the camera frustums passing through the vertices of the faces of a cube centered on the camera. The exact number of render passes required depends on the portion of the dome used, 4 are required for a hemisphere. Computer graphics people will recognize this as “cube maps”.
2. These camera views are not drawn but rendered to textures.
3. The textures are each applied to a mesh that have vertex and texture coordinates designed such that when the mesh with image is viewed with an orthographic camera the result is a fisheye image.
4. In the case of a spherical mirror projection system this fisheye image is itself applied to another mesh to achieve the warping, at least that is shown in figure 5 in the above paper. In reality the warped fisheye can be generated directly from the cube map images.

In what follows I will make some random comments/requirements.

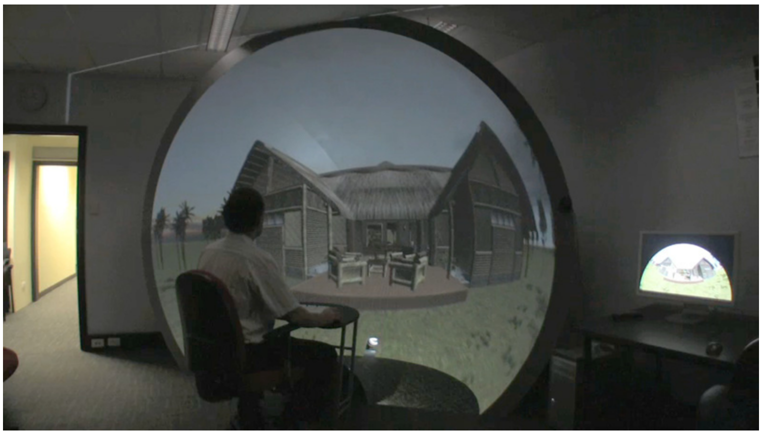
Realtime graphics APIs such as OpenGL only support two camera types, orthographic and perspective. Neither of these by themselves are suitable for creating imagery for immersive displays, by immersive I mean displays that occupy a significant portion of the human visual system. The reason being that a perspective projection becomes increasing inefficient as the field of view increases. While multiple flat panels can be supported by simply rendering multiple perspective views, a hemispherical dome is best supported (irrespective of the image projection hardware) by the creation of fisheye images. In the same way as spherical displays require spherical panoramas (equirectangular projections) and cylindrical displays greater than 100 degrees require portions or whole cylindrical panoramas.

If a fisheye lens and projector are used then the fisheye image is sent unmodified to the data projector. If a spherical mirror is used then the fisheye image is warped before being send to the projector. If two fisheye lens projectors are used then the fisheye image is split in half and edge blending applied before each half is sent to the respective projector. If multiple projectors are used then the fisheye image is sliced up, geometry corrected, and edge blending applied before each piece is sent to its respective projector.

For the spherical mirror the precise warping depends on the exact geometry of the projection system, this includes the optics of the projector (throw, aspect, lens offset), the size of the mirror and dome, the relative positions of all the components. As such there is a calibration process required in order to warp the fisheye to get the correct result on the dome, in concept this is identical to how image warping is achieved for cylindrical shaped displays, and any other non-planar geometry.

The exact warping required is derived by a simulation of the optical elements, rays are traced from the virtual projector through the mesh nodes (x,y coordinates of the mesh), they are bounced of the virtual mirror, and finally strike the dome (this determines the u,v coordinates of the node). The author uses a separate utility to perform this calibration, it generates a simple text file describing the mesh, all software uses this mesh file for warping the fisheye image.

It should be pointed out that the image will only appear strictly correct for a single viewer position. The further one moves away from that position the more distorted the image will appear.  For example straight lines will no longer look straight. In the following image the architectural aspects look curved, this is because the camera taking this image is set back from the dome, the lines look straight from the user at the center of the dome. The center of the dome need not be the sweet spot, the position from which the geometry looks correct can be positioned anywhere, but can only be in one place!



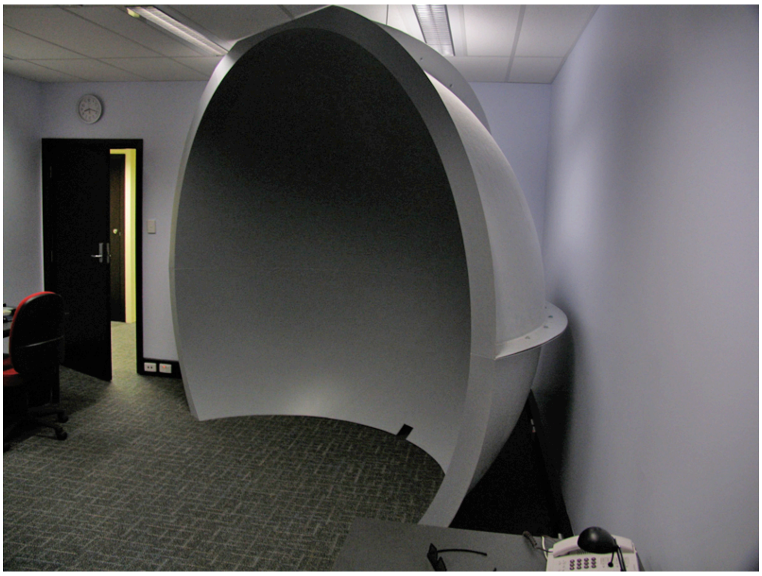
## Dome types and construction

### Fiberglass

For small domes, from 1.5m (Visionstation) upwards this is the preferred method for getting a smooth high quality surface. Fibreglass domes have been used in small planetariums, 8m diameter is not uncommon. In general the domes are created external to the final installation and due to access limits they are created in smaller sections and assembled onsite. This does raise a challenge of how to introduce adverse visual affects arising from the seams.

There are acoustics issues since almost all sound is reflected and focused, this can result in “interesting” acoustic effects at various locations.

Hemispherical domes also possess light inter-reflection issues, a bright source in one part of the dome reflecting and washing out the imagery in another part of the dome. General surface finishes therefore have low reflectivity, typically no more than 50% reflectivity. The brighter the projector available the darker the surface can be made and the better contrast and colour reproduction possible.



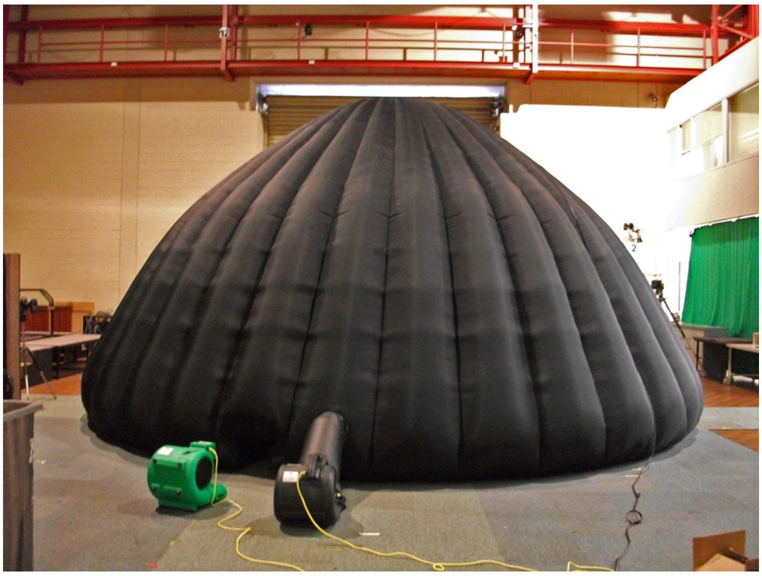
### Steel mesh

Almost all larger domes, for example planetariums, are constructed with a steel mesh. The ratio of holes to solid can be used to vary the overall reflectivity of the dome. The holes in the mesh also greatly assist with acoustic performance, strongly sound absorbing material is placed behind the dome.

### Inflated (skin)

In these only the surface "skin" is inflated, the main consequence is that there can be an open door solving the main issue with internal pressure inflated domes.

The main product of this type is the so called GeoDome from *The Elumenati*, shown below.



## Inflated (internal)

This is the most common solution for portable domes. The interior is maintained at a positive pressure by using a blower/fan. The inflatable dome surface does not have a floor, rather the seal with the floor is made by the pressure on curved sections around the rim. The main drawback of this approach is the airlock required for the entrance, an open door would result in deflation of the dome. Such inflated domes can range in size from 5m diameter (generally the smallest practical) to over 30m in diameter. They have reasonable sound transmission characteristics but interesting acoustic nodes can still exist.

## Negative pressure

In order to achieve a smooth and seamless interior surface one approach is to evacuate the air behind a light material, the shape of the material is constructed in such a way to create a hemispherical surface. These require a structural airtight cavity from which the hemispherical dome material is hung. The GeoDome above is of this type, the fan to extract the air behind the interior surface is located at the top of the dome.

## Approximations: ribbed skins

A popular low cost construction method is to stretch the hemispherical shaped material over stiff circular ribs. The ribbed appearance on the projection surface is invariably obvious.

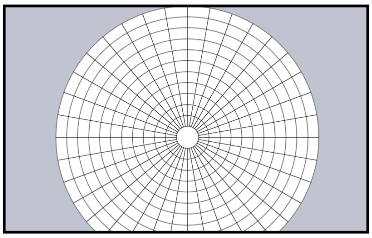
Approximations: polygonal

Planar approximations based upon geodesic domes of other polyhedral approximations are also popular for low cost construction. As with the ribbed skins the non-smooth nature of the surface is invariable clear, and distracting.

## Appendix 1

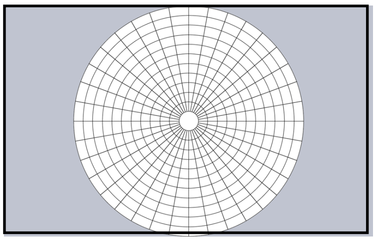
Table showing the main fisheye lens options from commercial vendors at the time of writing.

Truncated fisheye
WUXGA (1920x1200)
180x155 degrees



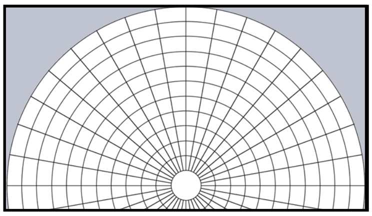
~1.4 million pixels

Full fisheye
WUXGA (1920x1200)



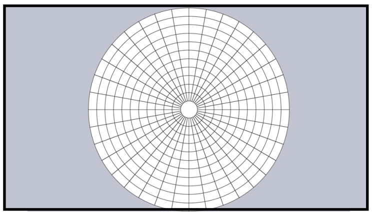
~1.1 million pixels

Truncated fisheye
HD (1920x1080)
180x101 degrees



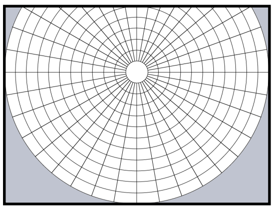
~1.65 million pixels

Full fisheye
WUXGA (1920x1080)



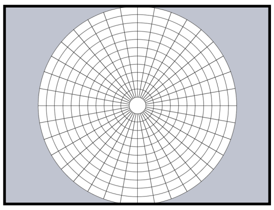
~0.9 million pixels

Truncated fisheye
SXGA+ (1400x1050)
180x135 degrees



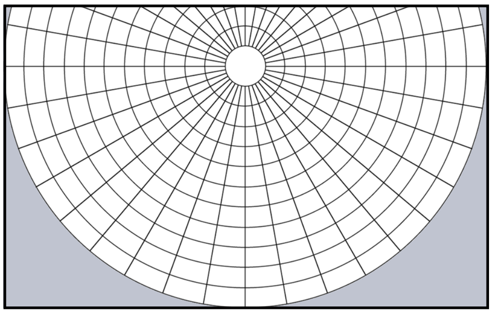
~1.2 million pixels

Full fisheye
SXGA+ (1400x1050)



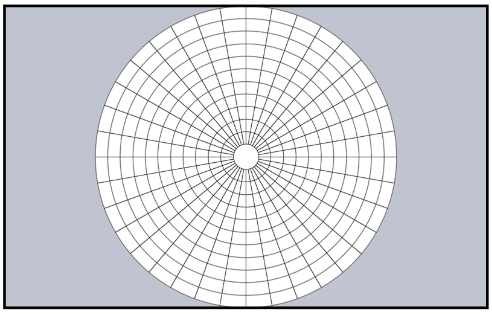
~0.87 million pixels

Truncated fisheye
WQXGA (2560x1600)
180x112 degrees



~3.3 million pixels

Full fisheye
WQXGA (2560x1600)



~2 million pixels