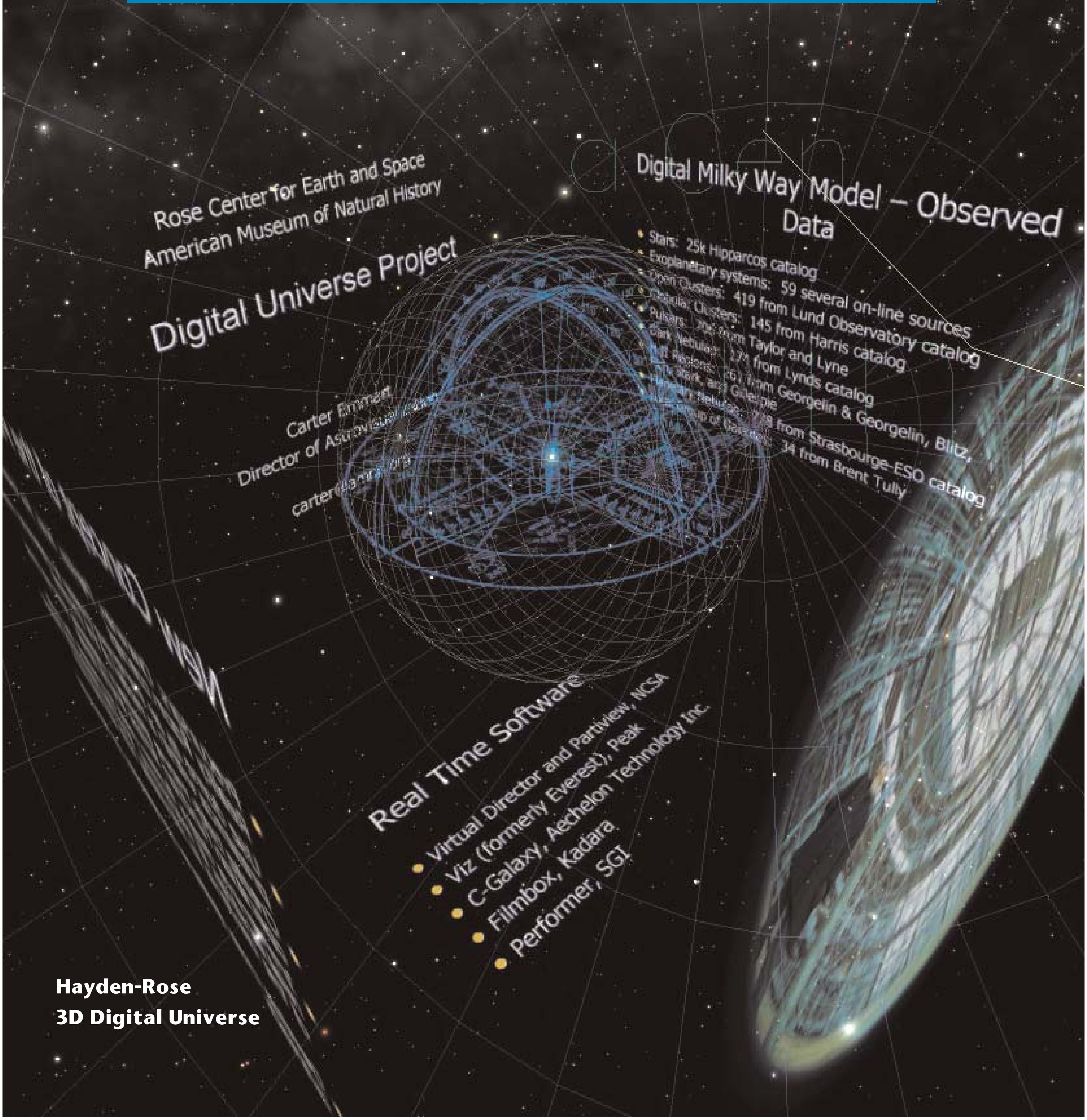
Vol. 34, No. 4 December 2005

PLANETARIAN

Journal of the International Planetarium Society



Hayden-Rose
3D Digital Universe

Spherical Mirror: A New Approach to Hemispherical Dome Projection

Paul Bourke
Swinburne University
P.O.Box 218
Hawthorn
Melbourne, Vic 3122 Australia
pdb@swin.edu.au

Abstract

Planetariums and smaller personal domes can provide an immersive environment for science education, virtual reality, and entertainment. Digital projection into domes, called "full dome projection", can be a technically challenging and expensive exercise, particularly for installations with modest budgets. An alternative full dome digital projection system is presented here that is based upon a single projector and a spherical mirror to scatter the light onto the dome surface. The approach offers many advantages over the fisheye lens alternatives, results in a similar quality, but at a fraction of the cost.

Introduction

Historically dome environments have been restricted to large planetariums and used primarily for public education in astronomy, illustrating the positions/motion of planets, stars, and constellations. These planetariums have used a variety of specialised projection hardware such as star projectors [1], laser projectors, and multiple edge-blended slide projectors. If the planetarium had the ability to present real-time digital graphics, the graphics were limited to a small portion of the dome, typically using a single CRT projector.

Even though planetariums have been limited by the available technology, the immersive possibilities have been obvious, mostly due to two characteristics of the hemispherical surface: the viewers' peripheral vision is engaged, and proceedings were conducted in the dark where there are often no frames of reference other than the projected imagery. The former is responsible for the vertigo one often experiences with rapidly rotating imagery; the later allows the apparent shape of the dome to be changed and is also credited with depth perception similar to stereoscopic 3D effects.

In more recent times planetariums have been upgraded to provide full dome digital projection, that is, a movie is seamlessly projected onto the dome surface at typically 30 frames per second. For larger planetariums this full dome projection is achieved with multiple projectors, most commonly CRT projectors. The projectors are carefully aligned and edge blended across overlapping projection regions. The system is driven by movies made up of fisheye images, these are usually diced into pieces and played back using specialised graphics hardware. Even more recently, high-end graphics systems have been able to project interactive graphics in real-time so it is no longer necessary to limit the content to movies. The content is not even limited to astronomy or even to science education, but indeed to any subject matter including, but not limited to, a wider range of educational topics, immersive spatial environments, virtual heritage, and even pure entertainment.

With the success of digital projection in large planetariums and the development of formal standards [2], interest has been growing in how to offer the same experience in smaller domes. These smaller domes are typically around 10m in diameter (found in many science centers) down to the smaller 5m diameter inflatable domes [3] that can be installed almost anywhere. The difference between these smaller domes and the large planetariums is largely in the system cost they can sustain. Not only do multiple projector systems have a high initial cost, they also have higher requirements in local expertise, and incur a significant cost of ownership. The solution to these cost problems has been to employ a fisheye lens attached generally to a single commodity data projector. The projector and lens are located in the center of the dome; fisheye frames from movies or generated by real time interactive applications are projected through the lens, and if created correctly they look undistorted on the dome. Such solutions have the benefit of being easy to manage and don't usually require specialised computer hardware. There are issues such as resolution and brightness, but they are largely a reflection of the price one is prepared to pay for the projector. However for small operations based around public education or research-based virtual environments, the cost of a good fisheye projection system may still be prohibitive. The alternative projection system introduced here significantly reduces the cost of dome projection while maintaining a similar quality and even offers some interesting advantages over fisheye projection.

Spherical mirror projection

The projection system proposed here uses a spherical mirror instead of a fisheye lens to distribute light in a wide solid angle. It can be readily appreciated that a spherical mirror can reflect light from a rectilinear frustum (produced by a commodity data projector) over almost the whole surface of a dome (see figure 1). There are a number of options for the projector/mirror placement in relation to the dome, but the geometry discussed here will consider a single projector within a small dome. In this case the spherical mirror is placed as close as possible to the rim of the dome (see figure 2). A number of alternative geometries and environments have been proposed in the past, for example "Ensphered Vision" that uses a convex mirror to project into cylindrical environments [4] as well as polyhedral spaces. The author has additionally explored dual mirrors/projectors located in the middle of the dome [5] with a single edge blend across the middle. Another

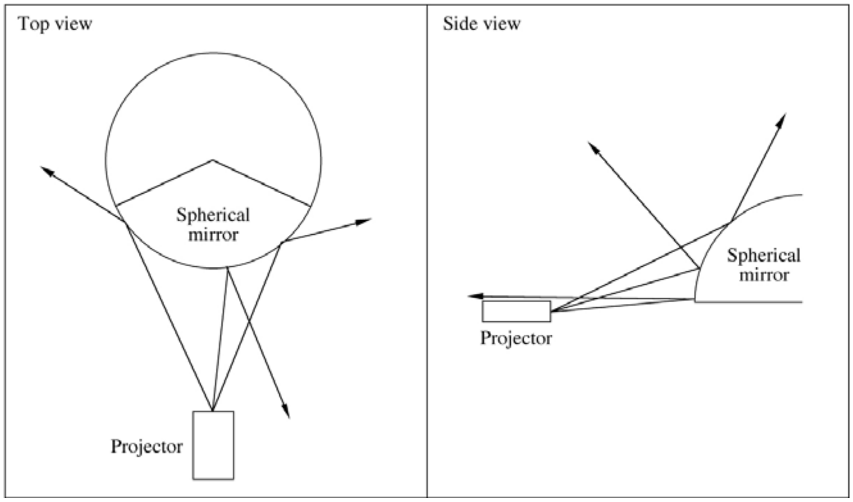


Figure 1. Representative rays off a projection source and reflected from a spherical surface. All illustrations are by the author.

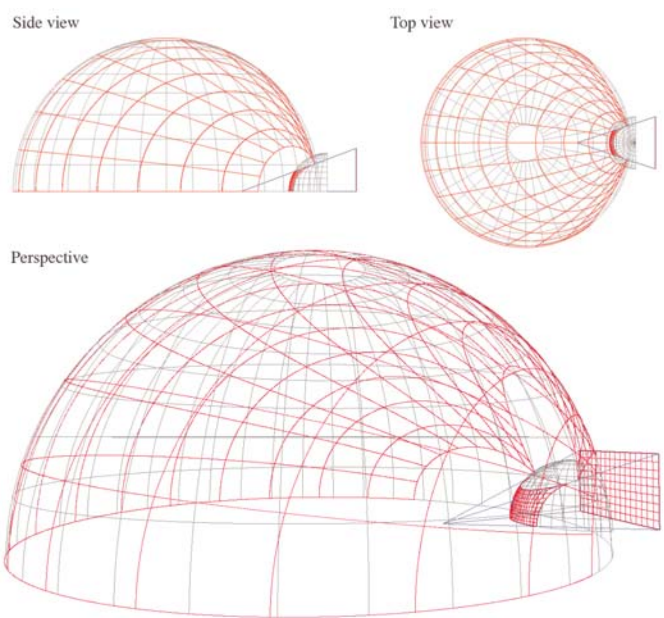


Figure 2. Typical position of the projector (16:9), mirror, and dome in a planetarium environment. Red lines illustrate the projected distribution of a regular grid.

installation by the author located a mirror at the base of a vertically mounted truncated dome [6].

There are a number of comparisons one can make between a spherical mirror reflection arrangement and a fisheye lens system:

1. It can be advantageous to locate the projection hardware away from the center of the dome since the center is generally the best location for undistorted viewing. This is the classic problem for single-person domes with fisheye lens projection; the viewer and fisheye lens cannot occupy the same space.
2. The projector and optics have been separated, making it possible to choose projectors based upon the characteristics important for the application at hand, for example: price, brightness, resolution, or contrast ratio. Fisheye lens can typically only fitted to a very narrow range of projectors.
3. The coverage on the dome can be controlled by varying the distance between the mirror and the projector or by varying the projector zoom. While it is true that the whole dome surface cannot be totally covered, it is equally not common for fisheye projection to cover the whole dome for pixel efficiency reasons [4].
4. The system is scalable to multiple projectors and mirrors in order to achieve higher resolution and complete dome projection. For example, a dual mirror and projector arrangement would give a single edge blend across the middle of the dome [5].
5. Unlike a fisheye projector located in the center of the dome, the path length from the projector to the dome is not constant, resulting in an intensity variation. Fortunately this is straightforward to compute and correct for.
6. Unlike fisheye projection, where not all the available pixels in the typically rectangular aspect ratio of the projector are used, all the pixels can be used in spherical mirror projection if the image is entirely contained on the mirror. Note, however, that not all pixels are used equally efficiently.
7. Unlike the fisheye lens solution, the images projected need to be warped before projection. Strictly speaking this is no different to fisheye projection; it too is a warped image, but one we are more familiar with.
8. Angular fisheye lens with good optical design is in focus at all positions on the dome surface. When using a spherical mirror there is a variation in path length from the projector to different parts of the dome. The effect of this focusing problem can be minimised by choosing projectors with a good depth of focus.

Warping

For the image on the dome surface to look correct and undistorted, a precisely warped image needs to be projected. The form of the distortion can be seen in figure 4. Figure 4a is

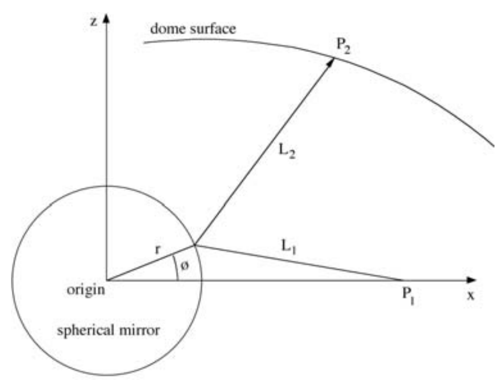


Figure 3. Geometry after the coordinate system has been transformed to place the spherical mirror at the origin and the intersection of the projected ray on the mirror/dome in the x-z plane.

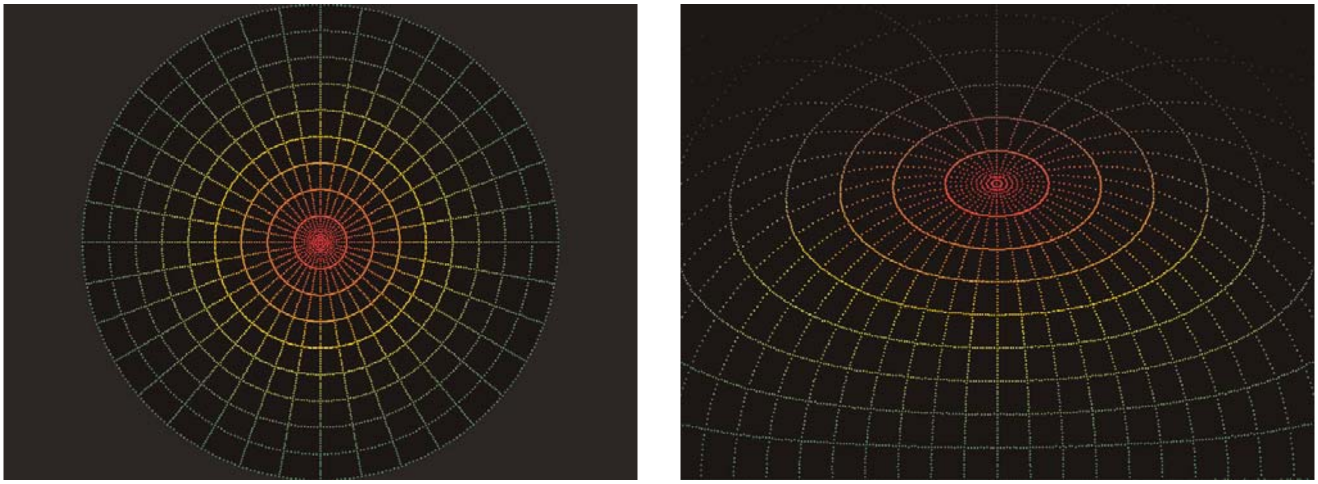


Figure 4. Warping of lines of longitude and latitude. The fisheye image in 4a consists of equally separated lines of longitude and latitude and is a convenient test pattern for dome projection. If 4b is correctly projected and viewed from the center of the dome, the central pole should be at the highest point in the dome, the lines of longitude and latitude should all appear vertical and horizontal respectively, and the line of 0 latitude should encircle the horizon of the dome. Note the intensity is varied so it fades gradually to back at the rear of the dome.

a regular polar grid appropriate for fisheye projection and figure 4b is the warped version that will look correct on the surface of the dome. Figure 5 shows the projector and mirror arrangement with a warped polar mesh on the computer display and the resulting image on the mirror.

The alternative projection system introduced here significantly reduces the cost of dome projection while maintaining a similar quality and even offers some interesting advantages over fisheye projection.

Creating correctly warped images given a particular projector, mirror, and dome arrangement requires finding the point on the projector frustum for any point on the dome. The problem is three-dimensional but can be turned into a simpler two-dimensional problem by firstly translating the geometry so the spherical mirror is at the origin and then rotating the geometry so that the point on the mirror, dome, and projector lies in a single plane. In figure 3, the projector is located at P_1, the mirror is of radius r, and the position on the dome is P_2. The path length from the projector to the mirror is L_1, the path length from the dome to the mirror is L_2, these are given as a function of ø below

$$L_1^2 = (P_1x - r\cos(ø))^2 + (r\sin(ø))^2$$
$$L_2^2 = (P_2x - r\cos(ø))^2 + (P_2z - r\sin(ø))^2$$

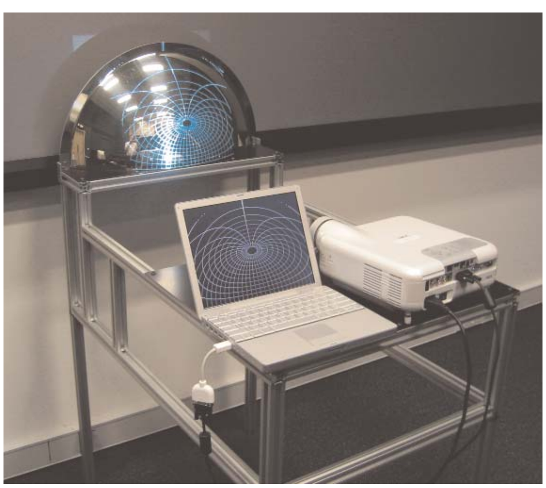


Figure 5. Projector and mirror in development configuration, the projected image on the laptop screen and mirror surface is a warped polar grid.

Fermat's principle states that light travels by the shortest route, so ø can be found by minimising the total light path length from the projector to the position on the dome, namely minimising $(L_1^2 + L_2^2)^{1/2}$.

Once a relationship can be made between positions in the projection plane and the dome, a regular mesh can be created where each node is represented by normalised frustum coordinates (x, y), fisheye image texture coordinates (u, v), and an intensity value. The intensity value can be used for compensating for the brightness variation due to the range of light path lengths, to softly fade the image towards the back of the dome, and to implement edge-blending for multiple projector configurations. Figure 6 shows a fisheye image applied as a texture onto a regular mesh using OpenGL. Similarly, a standard approach to creating fisheye images in interactive OpenGL applications is to render four faces of a cube and form the fisheye image by applying those as textures on a mesh with precisely specified texture coordinates. Figure 7a shows the mesh onto which four cubic map textures are applied to form the correctly warped fisheye; figure 7b shows a resulting screen dump from a real time driving simulator.

It should be noted that while the discussion here has concentrated on hemispherical domes, it can also be employed in any situation where extremely wide angle projection is required. In particular, it could be used to wrap the output from a single projector into a rectangular room, achieving an undistorted result similarly requires the calculation of the correct warping function.

Conclusion

An alternative dome projection system has been designed and demonstrated to be suitable for small planetarium domes. The mathematics required and practical issues involved in warping fisheye images as a preprocessing stage and in real-time have been developed and tested. By comparison to the more conventional fisheye solutions, the spherical mirror solution suffers from no serious disadvantages and offers some advantages at a significantly lower cost. Future work includes creating an optimal mirror surface rather than using a spherical surface. Such an optimal surface will use all pixels in the rectangular image plane and attempt to

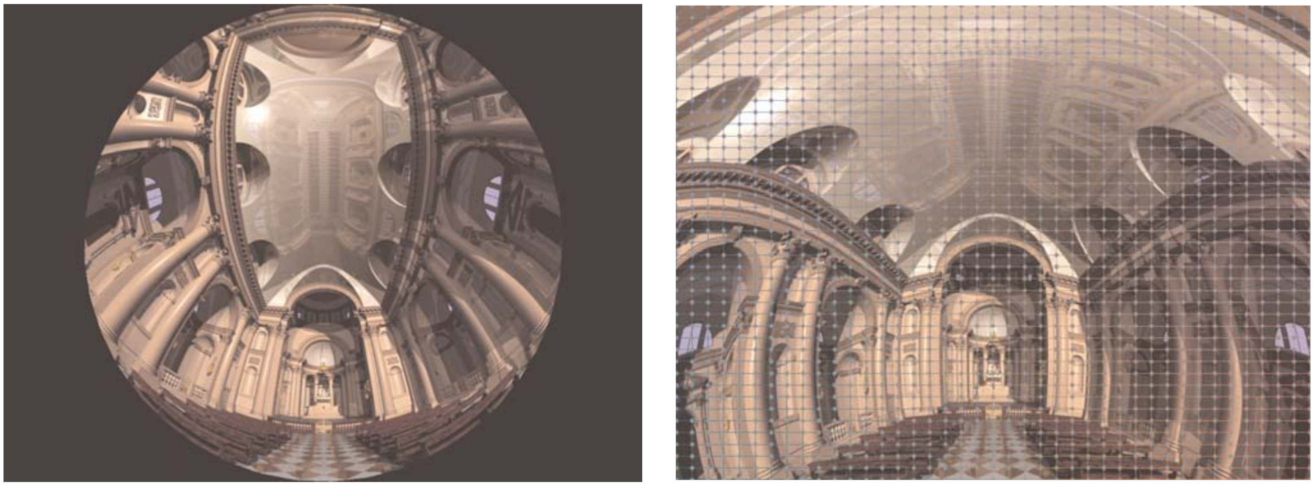


Figure 6. Fisheye image shown in 6a is applied as an OpenGL textured mesh in 6b. Each mesh node in 6b is represented by (x,y) coordinate in normalized projection plane coordinates, a (u,v) texture coordinate that relates to the fisheye image, and an intensity value that can compensate for the variable light path length.

Figure 7. 7a shows the warped appearance of the four texture regions and mesh outline as used by real-time OpenGL applications. The textures are derived from 4 virtual cameras each with the face of a cube as the projection plane. 7b is a single frame from a real-time driving simulator using the warped texture meshes in 7a.

distribute them equally on the hemisphere.

References

1. The History of the Planetarium, Chartrand, M.R., *Planetarian*, Vol 2, #3, September 1973.
2. Proceedings of the IPS 2004 Special Session Fulldome Standard Summit. Valencia, Spain, July 7/8, 2004.
3. Inflatable planetarium domes, Starlab Inc. [http://www.starlab.com]
4. Ensphered Vision, Hashimoto, W., Iwata, H., Ensphered Vision: Spherical immersive display using convex mirror. *Transactions of the Virtual Reality Society of Japan*, 4 (3) 497-486.
5. Bourke, December 2004. [http://astronomy.swin.edu.au/~pbourke/projection/dualdome]
6. Spherical mirror projection for an uprig-dome. Paul Bourke, May 2005. [http://astronomy.swin.edu.au/~pbourke/projection/uprightdome] ☆

Astronomy Visualisation in Reflection

C. J. Fluke & P. D. Bourke
Centre for Astrophysics & Supercomputing
Swinburne University of Technology
PO Box 218
Hawthorn VIC 3122 Australia

Digital Planetariums for Everyone:

The earliest telescopes were refractors made with combinations of glass lenses. They suffered from chromatic aberration and other optical defects, were difficult to scale to larger size (due to weight and cost limitations), and while providing better image quality and higher contrast (as there is less loss from a light path based on transmission that does not have to pass barriers such as secondary mirrors), they have mostly been supplanted by reflecting telescopes. This is because reflectors are generally cheaper, easier to construct and have fewer optical limitations – e.g. although a highly polished surface is required to maximise reflectivity, there is no chromatic aberration.

With the aim of not pushing an analogy too far, jump forward nearly 400 years from the time of Lipperhey and Galileo to the new era of single projector digital planetariums. The current generation of lens-based fisheye solutions suffers some of the same problems of the early telescopes: chromatic aberration near the edge of the field, high-cost, and possibly scalability. Like Newton's revolution in telescope design, we have recently used light reflected from a spherical mirror to illuminate the dome, providing an alternative that may further change the way audiences experience planetariums in the future. Working together, both fisheye and mirror based systems have a common advantage – as single projector solutions they are providing greater opportunities for smaller fixed and portable planetariums to share in the amazing visual and educational experience that has mainly been the domain of larger facilities: Fulldome.

In this invited review on the future of the digital planetarium, we reflect on our experiences in astronomy visualisation from the fourfold position of astrophysics researchers, public educators, content creators and technology developers. While this paper may demonstrate a certain personal bias, we would hope that some of our ideas will be of interest to planetariums of all sizes, as more facilities are challenged by the question: when to go digital?

Making the Leap from Stereoscopic Projection to Digital Domes

In 1999, the Centre for Astrophysics & Supercomputing at Swinburne University of Technology, Melbourne, Australia, was approached by Museum Victoria to produce a short computer animated sequence showing the relative sizes of, and distances between, the Earth, Moon and Sun [1]. This was to feature in the Science Hall of the new Melbourne Museum. Little did we realise that this would be a first step into a wider world of astronomy visualisation for public education that would stretch from stereoscopic theatres and 3D movies, to innovations in dome projection.

The Centre formed from the much smaller astronomy research group that Professor Matthew Bailes had brought with him to Swinburne from the University of Melbourne in late 1997. Both authors were among the first new staff to join the Centre in 1999: Paul Bourke (with a diverse background ranging from architectural visualisation to brain imaging) was hired as Swinburne's visualisation research fellow, and Chris Fluke (fresh from completing a PhD in astrophysics studying cosmological gravitational lensing) was to spearhead commercial activities with an aim of generating income that would help grow the Centre. With support from the University, several strategic hires, numerous successful grant applications, the development of a world-leading on-line graduate astronomy program [2], and income from a growing range of astronomy public education content and technologies, the Centre has rapidly become one of the largest astronomy research groups in Australia.

Our main educational interaction with the public has been through the Swinburne Virtual Reality Theatre (VRT). In its first incarnation, this stereoscopic projection environment used a single CRT projector operating at 120 Hz that displayed frame-sequential 3D images viewed with electronic shutter glasses. Originally designed to help astronomers and other Swinburne researchers to visualise their work, the VRT soon become a popular destination for the Vice-Chancellor and visiting dignitaries. Following a letter from a schoolboy to Matthew Bailes, the first school session was run in late 1999. With the students reacting very positively to the stereoscopic 3D effects on display, Matthew wrote to the Victorian State government requesting funding for a set of 30 pairs of shutter glasses, and the AstroTour school program was born.

A major visualisation project conducted in 2000, initially as a two-dimensional animation for television and web delivery, was the *Flight Through the Universe*. Working with astronomers from the 2dF Galaxy Redshift Survey team [3], the Centre created a sequence showing what it would be like to fly through this 2dF dataset – with galaxies in their correct locations in space. This segment, commemorating the milestone of 120,000 galaxy redshifts, received a great deal of attention both within Australia and internationally, even featuring in the BBC's award-winning television series *SPACE* (2001). By now, a strong working relationship had developed between the Melbourne Planetarium and the Centre, so there was a natural progression into planetarium content production. With the encouragement and support of Jack White and Sky-Skan Inc., we produced an initial fulldome version of 2dF (Figure 1).

In November 2000, Chris Fluke traveled to the United States on a study mission (funded by a Victorian State Government Victorian Fellowship) to promote some of the Centre's activities. This included a brief presentation at the Fulldome Festival at the Houston Museum of Natural Science, and a crash course in fulldome production techniques from Kevin Ballieu in Nashua. Encouraged by the level of interest in our work, a decision was made to convert the Swinburne VRT from an active stereoscopic system to a passive projection system that used low-cost polarising glasses. At the same time, we assisted with the installation of a passive stereoscopic system at the Parkes Observatory Visitors Discovery Centre in New South Wales, which would also be the location for the debut screening of our first "full-length" (20 minute) stereoscopic movie *Our Sun:*

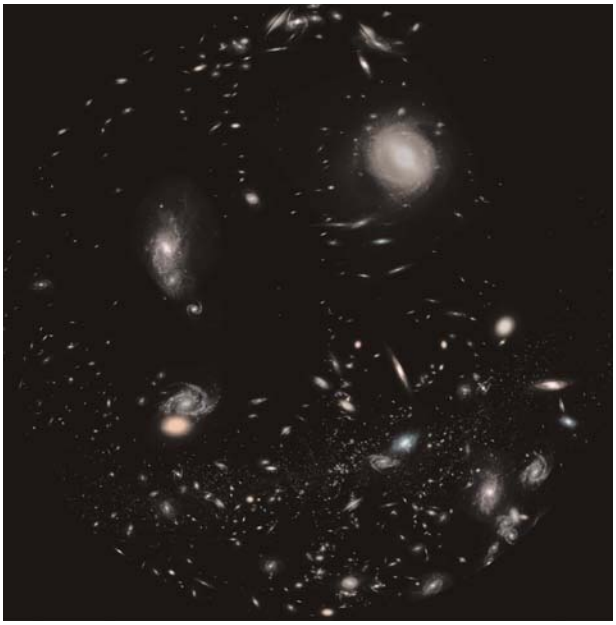


Figure 1: A Flight Through the Universe: a dome master from the 2dF Galaxy Redshift Survey sequence. Galaxies are in their correct spatial locations, but sizes have been scaled up by a factor of 100.

What a Star!

Without doubt, the Centre's most important planetarium activity was our involvement in the production of Sky-Skan's *Infinity Express* (2002), to which we contributed two sequences: a flight over the surface of Mars (Figure 2), using data from the MOLA experiment of Mars Global Surveyor [4], and a revised version of the 2dF sequence. With *Infinity Express* behind us, the Centre returned its focus to the VRT, with installations at venues throughout Australia (National Museum of Australian, Sydney Observatory) and worldwide (Jodrell Bank Observatory, CosmoDream in South Korea, and the 200-seat theatre at Mahidol Wittayanusorn School in Thailand). The Centre increased its number of completed stereoscopic productions to four and with the support of Spitz Inc, these shows were translated into Spanish for display at the Papalote children's museum in Mexico City [5]. Then in mid 2004, Paul Bourke had an idea about dome projection ...

Panodome and MirrorDome

We had been aware of the elumenati fisheye lens and its use in products such as the Elumens VisionDome and VisionStation for some time, but were there any alternatives for even lower-cost digital dome projection? Our motivation was to find a solution that was:

- Affordable: so that it could be available to planetariums of all sizes and budgets, from the smallest portable domes capable of visiting remote schools to modest-sized (around 12 m) fixed domes in museums and science centres.
- Low maintenance: so that more time and money could be invested in show content, rather than keeping equipment running.
- Quick setup and display: so that additional time did not have to be spent calibrating images, correcting and aligning seams or waiting for split dome master segments to render.
- Flexible: so that a range of content, both pre-rendered movie and real-time interactive was available in all domes.

A solution seemed to be using a single projector (no seams) with a curved mirror. The idea was that by pre-distorting or "warping" content (either pre-rendered movies from fisheye dome masters, or real-time interactive content created with OpenGL graphics libraries), after reflection in the mirror, images would appear undistorted on the dome (Figure 3).

Mirrors have played a part in both stereoscopic and curved screen projection in the past. They are an ideal way to reduce the amount of physical space required, as the light path can be modified by reflecting from a plane mirror on its way from the projector to the screen. Hiroo Iwata (University of Tsukuba) created spherical surround environments (Ensphered Vision and the Wearable Immersive Display) using a plane mirror, a convex mirror and a single projector to fill a space 270 degrees horizontally by 100 degrees vertically. Images were filmed by reflection in a spheroidal mirror so they could be projected without distortion [6]. OmniGlobe from ARC Science Simulations, Colorado, USA, uses a patented convex mirror to rear-project onto the surface of a dome – imagine a planetarium dome viewed from the outside surface looking in [7]. Although other people had tried similar ideas in the

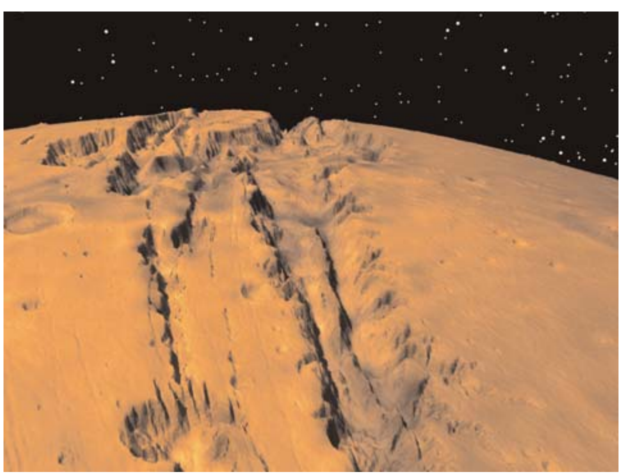


Figure 2: A view down Mariner Valley from the Swinburne stereoscopic production Elysium 7, using the Mars Orbital Laser Altimeter dataset of Mars Global Surveyor. This was the forerunner of our Mars sequence for Infinity Express.

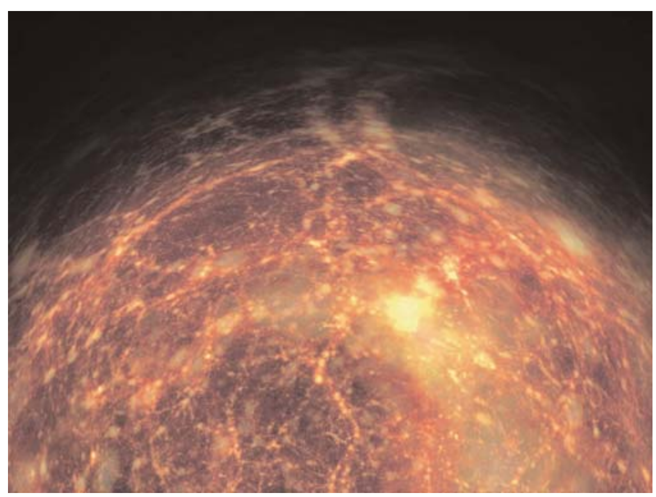


Figure 3: A warped image showing the large-scale filamentary structure of the universe ready for projection with a spherical mirror. Simulation by Dr Chris Power, visualisation by Evan Hallein & Paul Bourke.

past for domes, there did not seem to be any readily available documentation on the success or otherwise. There was even a suggestion that spherical mirrors would not be able to produce a useful image, and would only have application for ambient lighting effects.

In November 2004, we were able to test the idea for the first time, thanks to Glen Moore from the Wollongong Science Centre and Planetarium in New South Wales, using the interactive panoramic viewer (*panodome*) that Paul had developed a few months earlier [8]. The newly christened MirrorDome system uses a low-cost spherical mirror and, unlike a fisheye lens system, the optical element is separate from the projector giving more flexibility in the choice of projector. With the mirror solution, we need to apply a non-linear geometric and intensity distortion to the fisheye dome master images so they appear correct on the dome. The mirror system places the projector and mirror close to the edge of the dome, instead of the central location taken up by the fisheye lens. The effective resolution of MirrorDome can be increased with multiple mirrors, but with the complication of edge blending to achieve a "seamless" image.

As a single projector solution, both fisheye and mirror solutions are ideally suited to small domes. So, just what do we consider to be a small dome, and how many of them are out there that might be looking for a way to go digital?

Why Small Domes and Single Projectors are So Important

Although the definition is somewhat circular, we can identify small domes as those for which a single projector system is a viable alternative in terms of cost, image quality, brightness, maintainability, etc. As time goes by, the largest small dome size should increase due to improvements in digital projector brightness, pixel resolution and falling cost.

How common are small domes throughout the world? As a starting point, we use the statistics accumulated by Mark Petersen of Loch Ness Productions [9]. As of 5 September 2005, there were 1357 domes of known diameter [10] (ranging from 1 m to over 21 m) operating in the United States, and 1308 throughout the rest of the world. Choosing 12 m and above as a "large" dome and sizes below this as "small" (with no offence intended to operators of domes at the higher end of "small" who do not consider their domes to be small), we find that:

Location	Number of large domes	Number of small domes
USA	159	1198
Rest of world	363	945
Total	522	2143

Globally, small domes outnumber large domes by a factor of 4. How does this relate to visitor numbers? If we apply Mark's visitor number projection technique:

Visitors	Large domes	Small domes
USA	12.9 million	16.7 million
Rest of world	47.5 million	24.4 million
Total	60.4 million	41.1 million

Due to the large statistical uncertainties, and the non-uniform sampling rates (for example, only 35/578 potential responses for US domes below 6 m), we should treat these figures with caution. We introduce our own (completely arbitrary!) weighting to get order of magnitude estimates. Using the response rates for US planetariums, we see that there is about a 50% response rate (88/159) for domes larger than 12 m. Let us then assume that the rate for small domes is 25%, and apply these same factors to the rest of the world.

Millions of Visitors	Large domes		Small domes	
	Responses	Projected	Responses	Projected
USA	7.8	15.6	2.8	11.1
Rest of world	8.5	16.9	1.4	5.5
Total	16.3	**32.5**	4.2	**16.6**

Thus, we would expect to find 30-40% of the world's planetarium visitors attending small domes. What we should take away from this is that *small domes play a substantial role in astronomy education*, and so are definitely worthy of an investment in technology and content that will enhance the educational experience they currently offer.

What advantages do single projector solutions afford? Perhaps the two biggest factors are cost (much lower than a multiple projector system) and the rapidity with which they can be set up and aligned. The latter is particularly important for portable systems, where time with students or the public is much more valuable than time spent trying to reduce the visibility of image seams.

Another key factor is simpler software when only a single computer is required to output content for the digital dome. This is true for both movie playback, where a standard fisheye dome master can be used without slicing and splicing, or real-time interactive material. With most modern graphics cards, a single computer can actually mean up to two displays: either one for the audience and one for the presenter (e.g. with show control software), or two projectors. We discuss the single computer versus single projector paradigm in more detail below. Another advantage of a simpler software model is that it becomes feasible to operate the system from a laptop rather than requiring the generally higher performance and graphics card power of tower machines – an ideal solution for portable installations.

The biggest limitation of single projector systems, at least for the present, is resolution. The commodity digital projector market is still based around XGA (1024x768). The good news is that SXGA+ (1400x1050), which provides a 40% linear increase in resolution or an 87% increase in the number of pixels, is coming down in price and may become the standard in 2-3 years. The next echelon contains UXGA (1600x1200), although there are currently not many alternatives and there is a significant price penalty, and QXGA (2048x1536), with a seemingly exponential price increase. The new digital cinema projectors with 4K x 2K resolution may be affordable for the larger planetariums, but are unlikely to be suitable for small domes in the foreseeable future. We feel that in the 4:3 aspect ratio game, SXGA+ is the only real contender for the next 5 years, unless there are significant changes in the home theatre market – one of the main drivers for brighter and cheaper digital projectors.

Projector brightness does not appear to be a limiting factor. In our early experiments, a 2500 ANSI lumen commodity projector struggled a little on domes larger than about 10m. However, this could also be due to the grey level of the dome surface, and amount of cross reflection – as projector brightness increases, so does the cross reflection. The solution is to get a darker dome, but then a brighter projector is required ... it is a vicious cycle.

Black levels are problematic for another reason besides the poor representation of the black of outer space. "Non-black" black adds an overall ambient light level that bounces around the dome generally lighting up the space and reducing the apparent contrast. There is also a relationship to brightness: as a general rule, commodity projectors that are pushed (for marketing reasons) to have higher brightness tend to have poorer contrast levels [11].

As we noted in the introduction, fisheye lens systems can suffer from chromatic aberration at the edge of field, but this is not a problem for mirror-based solutions that use reflection rather than refraction to form an image. The bigger issue for mirrors is projector focus. Most commodity digital projectors have a fixed focus across their frustum, while variable focus is restricted to CRT projectors. Due to differences in path length from the projector to mirror to dome, the whole dome surface is not in perfect focus. We do not believe this should be seen as a significant limitation, given the other advantages of the approach.

The Future of Single Projector Digital Domes

What might be the role of single projector system in digital planetariums? At the IPS 2004 Fulldome Standards Summit, in Valencia, Spain, Philip Groce strongly advocated that single projectors were the way of the future [12]. Groce proposed that in domes smaller than 18 m: "multiple projector systems with more than two projectors will be extinct or obsolete in 5 years or less." In our opinion, low-cost single projector systems will not be ideal for domes larger than about 12 m in the near future, due to lack of pixels and brightness. However, our own testing of a mirror in 10 m and 11 m domes was very encouraging. A dual projector system with two SXGA+ would be an improvement, better yet if the UXGA (2K x 1.5K pixels) projectors fall in price over the next 5 years (this option is already available for those institutions that can afford the price tag). We feel that Groce is being slightly optimistic on the 5-year prediction of obsolescence, but bold statements can prompt the industry to respond!

Groce examined seven technical issues that both single projector (SP) and multiple projector (MP) solutions faced. However, his comparison between MP and SP systems only considered fisheye solutions. It is worth looking at how mirror solutions affect the score sheet, and whether an even stronger case for single projector solutions can now be made.

This is Groce's score sheet:

1. Fulldome standard (portability of content between theatres). There is a clear advantage to single projector solutions here, because they use a single computer, which makes implementation of a unifying fulldome standard much easier. There is no additional advantage offered by either fisheye or mirror systems.
2. Resolution and image quality/brightness. Multiple projectors provide more pixels than a single projector can. MP will always win in this category – no matter what resolution projector you use, adding a second projector will increase the resolution. The question is whether having more resolution is actually an advantage, or if the audience can discern the difference. Although content providers are extremely critical (and rightly so) about the quality of the work they produce, having to watch it endless times during production and then repeated screenings, the average public viewer is only like to see any piece of content once. Do they ever see the same faults that we see?
3. Image consistency, stability, seam visibility. With no seam by definition for SP, and no need to match image brightness or colour across projectors, they have an advantage over MP. Groce notes that the main limitation of fisheye systems is the chromatic aberration – perhaps we can note a slight win for mirror solutions here, as reflected light does not suffer from this refractive effect. However, we should not forget that they are slightly affected by the lack of variable focus projectors.
4. Effect of theatre geometry. Groce puts SP ahead of MP in this category; as it is easier to deal with different theatre set-ups, dome orientations, etc. when there is only one projector to place. There is no significant difference between mirror and fisheye here. In both cases, if the aim is to create an ideal undistorted view, then some image warping is required and the result will only be correct for one person. In reality, fisheye lenses are not placed perfectly nor is the entire audience in the centre of the dome. Similarly the warping when using mirrors will rarely perfectly match the projection/dome geometry. In both cases it could be made perfect for a single viewer, making it equally troublesome in both cases since the image for the fisheye projection would need to be warped as well.
5. Space within the theatre. While MP appeared to have an early victory here, taking the projection off the dome floor to the rim of the theatre, we propose that using mirrors can swing the balance back to SP in this category. While most fisheye solutions are placed in the centre of the dome for maximal coverage, the mirror is best placed at the dome rim.
6. Capital costs, cost & ease of maintenance. Another win to SP, with mirrors perhaps slightly ahead of fisheye. In order to upgrade to a higher resolution, brighter projector, the only change that is required is to swap a single projector, which would provide a less expensive upgrade path than for MP (remembering that the general trend is for projectors to increase in resolution and brightness, but fall in price over time), allowing more small domes to go digital sooner rather than later.
7. Patent issues. There are a growing number of MP vendors, each offering their own solution to the fulldome projection problem. This healthy competition is a good thing, as the planetariums are (hopefully) the winners in the long run with more choice and a range of price points. One of the limitations Groce identified in the potential take-up of fisheye solutions was the issue of patents, which affects the cost and availability of lens-based alternatives. However, with an alternative SP solution based on mirrors, where there are no patent issues, the patent issue may not prove to be such a limitation after all [13].

When we look at the combined advantages of mirror and lens-based SP systems, the only category where MP still is the preferred alternative is image resolution – but as we noted, just how important is resolution really? We think there is a very compelling case for more theatres, of all sizes, to consider the benefits of a single projector and the possibility of going digital sooner rather than later.

Single Projector or Single Computer?

Are the requirement for edge blending and some projector alignment really such a problem? The issue here is the extent to which the edge blending and alignment negate the other advantages of SP. We see a distinction between systems that use just one computer and those that require more than one computer. Moving to more than a single computer (assuming we are not talking about specialised machines) seems to be the most significant increase in system complexity, particularly on the software side of things. A single computer means either one or two projectors; the complication of edge blending is not nearly as great as for multiple computers. For example, while we have not actually tested this, we believe that a dual projector set-up could be driven with a single Apple Macintosh G5 using our existing playback tools and some of the techniques we use for stereoscopic movies (e.g. making side-by-side movies, where we have a double-width frame consisting of the left eye and right eye images – see Figure 4). We currently use a brightness mask in creating warped images for our mirror solution, to account for differences in path length from

Figure 4: A side-by-side stereoscopic pair from the Swinburne 3D production Spinning in Space. Our approach to playing back stereoscopic movies using QuickTime can be extended to a dual projector digital dome.

the projector to dome surface, which can also be used to support gamma-corrected edge blending. The same ideas apply to real-time interactive content.

Although the software model is simplified for dual projectors compared to greater numbers of projectors, as soon as there is more than one projector, some time will have to be spent on alignment. It is hard to see it as viable for anything other than fixed installations – for portable domes, stick with SP and spend your time with the audience.

Having shared our thoughts on future prospects for single projector digital planetariums, are there any other untapped markets for digital dome projection? We believe there is one very important field where the low cost of SP could be an advantage.

The Astronomer as Visualiser

Astronomy is possibly the most visual of all the sciences, in the way the data is both collected and analysed. Optical telescopes take images of the night sky so that the position, orientation, size, shape, brightness and colour of celestial objects can be determined. Radio telescopes record intensity, polarisation and velocity data that is converted into pseudo-colour images or 3D cubes. Numerical simulations produce datasets that are often inspected visually before being compared statistically with surveys. Data reduction, a key step in the analysis of astronomy data, is best performed by eye - the human brain has incredible pattern matching abilities that are yet to be reproduced with a computer algorithm [14].

To the ancient astronomers, the night sky was an enormous sphere rotating around the Earth. Although our world-view has changed dramatically, this spherical model is still very convenient to use. With the millions of dollars spent annually on telescopes, instruments and computing resources, it is somewhat surprising that astronomers display their surveys of the night sky on small, flat, low angular-coverage monitors using mapping techniques that distort areas and spatial relationships [15]. The obvious exception is the astronomy education world, where planetarium domes provides an ideal representation of the sky. With the amazing advancements in digital projection and opportunities for immersive, interactive explorations of datasets, it is a little surprising that astronomers have not yet turned to domes to learn more from their data.

There are of course some exceptions, most notably the Hayden Planetarium in New York (which has been used to visualise astronomical surveys in the Digital Universe project and large-scale numerical simulations [16]) and the Gates Planetarium at the Denver Museum of Natural Science (with their Cosmic Atlas). But as a general rule, planetarium domes have been under-utilised as a data exploration environments. Reasons for this include:

- Availability and accessibility. Fixed installations require a great deal of physical space, leading to their placement in museums/science centres away from researchers.
- Limited dataset size. Traditional opto-electrical star projectors could not show generic datasets and the first generation of digital star projectors (appearing in the 1990s) were limited to datasets of a few thousand particles.
- Lack of software tools. Designed to integrate with other planetarium show playback components, these systems do not use formats that astronomers are more experienced with.
- Low resolution/low definition. Early single-projector solutions suffered from image distortions (e.g. non-uniform pixels so that digital stars near the horizon are stretched), and projected in monochrome.
- Cost: a fulldome projection system plus the construction of a large (>10 m) dome can cost well over $1 million. Unless the system was to be in nearly constant use for scientific visualisation, the expenditure is extremely hard to justify.

The availability of affordable single projector systems in portable, inflatable domes can now make the digital dome available to more astronomers. This is an area that we will be pursuing over the next few years, as we try to encourage more astronomers to think outside the square frame of their monitors. The first step in promoting such a change is awareness – how aware are astronomers of the visualisation alternatives available to them?

To answer this question, we conducted the Advanced Image Displays for Astronomy (AIDA) survey from March-May 2005. This on-line survey posed a range of questions about the current state of knowledge of image displays for astronomy visualisation. For the purpose of the survey, an advanced display was anything other than a traditional 2D monitor! Advanced displays we considered included digital domes, stereoscopic projection, head-mounted displays, multiple-wall environments (e.g. CAVE) and tiled displays. Advertised to members of the Astronomical Society of Australia (ASA), we received responses from 41 people, representing about 10% of the ASA membership. Our sample contained a mix of students (41%), postdoctoral researchers (25%), contract researchers (10%) and tenured academics (20%). 29% of respondents reported that they used large surveys (<50% of the sky, >1000 objects), an area that we feel would benefit from the all-sky capability of a digital dome.

A key outcome of the AIDA survey was that around 70% of respondents indicated they did not have sufficient knowledge of advanced image displays to utilise them for their own research. Other factors limiting their use were lack of software tools (46%), lack of local facilities (46%) and cost (41%). 78% had seen digital dome projection, and the level of awareness of this technique was very high (95%). Only 2 respondents reported ever having used a digital dome in their research (on an occasional basis – less than 50% of the time).

We are now ready to start using the dome as data exploration environment. We have identified an initial selection of datasets that could benefit from all-sky projection, where a clear understanding of spatial relationships and sizes is crucial. These include, but are not limited to:

- All-sky covering factor of High Velocity Clouds and Lyman-Alpha absorbers;
- All-sky/large area pulsar surveys;
- Square Kilometre Array beam-shapes and radio-frequency interference patterns;
- All-sky volume rendering; and
- Large-scale structure determined from galaxy surveys (e.g. Tully catalogue, 2dF, 6dF, Sloan Digital Sky Survey).

While attending DomeFest 2005, one of

the authors was struck by the different visual information that the dome provided compared to stereoscopic representations of the same dataset. Viewed in stereo, the three-dimensional spatial structure of the Tully catalogue of nearby galaxies really stands out. On the dome, the Zone of Avoidance springs clearly into view, reminding the viewer that the dataset is incomplete because of the obscuring nature of the Galactic plane, yet this feature is much less obvious in 3D. We believe that the greatest strength of the digital dome is to provide alternatives to be used in combination with other techniques for data exploration, including the traditional 2D approaches – currently these are better suited to quantitative data exploration. However, a research interest of ours is to provide quantitative tools for the dome to rectify this balance. Then astronomers will have no excuses for not using domes.

Conclusions

What the telescope did for the night sky was to provide a much richer experience that could be experienced by all audiences, whether they could afford a simple spyglass or a 10 m segmented mirror. Single projectors can now bring the same increased level of richness to planetarium domes of all sizes and budgets, whether through a fisheye lens or light reflected from a mirror.

The future looks very bright for digital domes of all sizes, and we hope that our involvement will continue to help inspire a fascination in the Universe, through research and public education.

Acknowledgements

We would like to thank Charles Treleaven (Cosmodome Australasia) and Glen Moore (Wollongong Science Centre and Planetarium) for access to their domes (inflatable and fixed) in order to develop and test MirrorDome; David Barnes for general discussions and ideas about potential datasets to study; and Ed Lantz for inviting us to share our thoughts with the planetarium community. Our MirrorDome research is funded through the Swinburne Researcher Development Grant scheme.

Notes

[1] The curator responsible for the science hall at the time was none other than Martin Bush, now president of the Australasian Planetarium Society!

[2] Swinburne Astronomy Online: www .astronomy.swin.edu.au/sao.

[3] See Colless, M., et al., 2001, MNRAS, 328, 1039.

[4] http://ltpwww.gsfc.nasa.gov/tharsis/ mola.html

[5] At the time of writing the fifth show, *Spinning in Space*, was nearing completion, and pre-production had commenced on show six.

[6 See http://intron.kz.tsukuba.ac.jp/ vrlab_web/enspheredvision/enspheredvision_e.html and Iwata, H., 2004, *International Journal of Computer Vision*, 58, 227-235.

[7] See http://www.arcscience.com/omni .htm.

[8] As a side note, *panodome* made its first public appearance in a digital dome installation at the “Burning Man” art festival in Nevada (Aug-Sep 2004) in collaboration with elumenati. This tool provides interactive navigation of a 360˚ panoramic environment, similar to QuickTime VR, however instead of creating a perspective projection for a traditional rectangular monitor/projector, it creates a fisheye image for dome projection. *Panodome* makes full use of a graphics-processing unit in order to handle high-resolution images. See http://astronomy.swin.edu.au/~pbourke /projection/panodome/.

[9] See “Tallying The World’s Planetarium Attendance” by Mark C. Petersen, Loch Ness Productions, available from http:// www.lochness.com/pltref/attend.txt.

[10] We have excluded the 367 domes of unknown size.

[11] For example, in the Swinburne VRT, we operate the projectors in economy mode rather than full brightness, as the contrast appears better.

[12] See “The Past, Present and, Future of Full Dome, Full Colour, Single Projector Digital Planetariums.” Available from http://www.fulldome.org/images/stories/IPS2004.

[13] We would actively encourage manufacturers to make better mirrors that are more durable and have greater reflectivity; digital projectors with higher brightness, more pixels and variable focus for lower cost; etc.

[14] See Norris, R.P., 1994, in *Astronomical Data Analysis Software and Systems III*, eds. D.R.Crabtree, R.J.Hanisch & J.Barnes, 51.

[15] Consider the Mercator projection common for maps of the Earth. This mapping of the spherical Earth to a 2D surface does not preserve area, so that polar countries like Greenland appear highly distorted.

[16] See Abbott, B.P., Emmart, C.B., Levy, S., Liu, C.T., 2004, in *Toward an International Virtual Observatory*, eds. P.J. Quinn & K.M.Gorski, 57; Abbott, B.P., Gawiser, E., Emmart, C.E., Wyatt, R.J., 2003, AAS, 203, 118.07 and Tueben, P.J., Hut, P., Levy, S., Makino, J., McMillan, S., Portegies Zwarts, S., Shara, M., Emmart, C., 2001, in ASP Conference Series, Vol 238, Astronomical Data Analysis Software and Systems X, eds. F.R. Harnden Jr, F.A. Primini & H.E. Payne, 499. ☆

Digital Domes and the Future of Planetariums

Mark Matthews
Visual Acuity Limited
Castle House
Sea View Way
Brighton BN2 6NT UK
mark@visual-acuity.com

There is a small English pub near where we live, situated next to a small river that ambles slowly past it. The location is not shown on any maps. Leading to it there is a one-and-a-half mile single-lane track, with few passing places, with large bushes and trees that grow over the track in an arch. Only locals know of this pub and it is always busy. You can sit at tables by the river, or take a picnic into the fields opposite and sit on the riverbank in the sun. The pub also has a small jetty where six-seat canoes can be rented by the hour. My family and I often will rent a canoe and paddle up the river. The river has many gentle curves and bends and there is constantly new scenery appearing. Watching the banks pass with the occasional fish jumping, dragonflies hovering and weaving around, the odd creature scurrying into a hole in the riverbank, there are a multitude of events that cause constant conversation delight. Passing drinking cows that back off as we approach or sheep with their lambs on the riverbank we come to a tree jutting over the river where there is a large rope dangling invitingly over the water. Of course we have to paddle to the shore so that the kids can get to the rope and swing out over the river. As they lose momentum and realize they cannot get back to the bank, we paddle frantically over to get to them into the canoe, asking why they hadn't removed some of their clothes and footwear before getting onto the rope. Just as we get close to a rescue, the child, who has now managed to get one leg over their hands to keep them out of the water, loses their grip and plunges head first into the less than clean water below, splashing and soaking those in the canoe in the process. After much laughter we continue up the river for more adventure. When we plan a visit to this place, my children are always very excited and eager for the time to come when we head off for their favorite day. It is a great day for the whole family.

... we really have to put technologies into the category of tools that have various inherent capabilities and functions. First and foremost you need to understand the job to be done before you can begin to understand the appropriate criteria for the selection of the right tools. ... The tool that does the job is the best one!

Conversely, we have also visited many theme parks, ride parks and water parks where the children thrust their jacket, backpack and water bottle at me and rush off to something they've seen that appeals. They join a long line and get bored waiting. I start looking in hope that there may be a bench where I can put all of their belongings, usually in vain, and I become aggrieved that I had to pay the equivalent of $30 to stand and hold the coats and watch everyone else wait for a good time. At one park I had to stand in line for 90 minutes so that my youngest could go on a merry-go-round. They had simply let too many people into the park and we ended up having to leave early for our own sanity. Not surprisingly, the kids didn't grumble about this at all. In peak season we managed to get on four of the major rides in a day. These rides last around 90 seconds each so we paid around $200 for six minutes of fun!

These are very contrasting experiences, and the one that features whole family interaction, participation, exploration, learning, adventure, fun, and requires the most effort, gets my family's vote every time.

The Visitor Experience

In thinking about these family experiences, I have to come back to the basic question regarding all planetariums and digital domes: "What is the purpose of these theaters?" In nearly all cases the purpose can be simply described as: "To get people into them". This being the case, the next question must be: "Why do we want people to visit them?" This is where the differences start.

Depending on the objectives of the facility the answer could be: 1) We want them to visit so that we can share our passion for astronomy, space and the universe; 2) We want them to pay to visit a facility and the planetarium/dome is an attraction; 3) We want to teach astronomy/science and the theatre is a tool to help achieve this. My belief is that most facilities fit under one or more of these descriptions.

If we agree that the purpose of planetariums or digital domes is to get people into them, then we perhaps need to look at what experience people get once they are in. Do they get a canoe ride up a beautiful river or do they get overcharged to stand in lines all day? I doubt that there are many people reading who would deliberately want the latter.

When it comes to discussing the application of any technology, new or old, towards enabling a specific end-user experience, we really have to put technologies into the category of tools that have various inherent capabilities and functions. First and foremost you need to understand the job to be done before you can begin to understand the appropriate criteria for the selection of the right tools. This is why there is not one type of technology that is 'better' than another. The tool that does the job is the best one! When looking at all of the dome/planetarium projects that I have been involved in past and present, there are no two that have identical objectives and philosophies, and as a result, no two that have received the exact same technology package. Many new planetariums, such as the Morrison in San Francisco, are now opting to have both star projectors and video display systems to achieve the best of both worlds.

While on holiday on a Greek island earlier this year, I had the pleasure of witnessing the night sky with very little light pollution and it was breathtaking. I sat outside for hours watching the August meteor showers and marveling at sights I'd only ever seen previously simulated in planetariums. It is very important to note that I enjoyed what I experienced much more than I ever could have had I not had the opportunity to have been in so many planetariums. I spent some time playing with the zoom on my video camera to get some excellent images of the moons craters. I had to go through the usual 'Dad, you're such a geek' thing from the aforementioned kids, but it was well worth it!

Until this experience of witnessing a clear dark sky (remembering that in England it's not often clear and when it is, it's not very dark where I live), I hadn't realized quite what I'd been missing. I wonder how many other people have actually witnessed very dark skies without deliberately traveling to find them. This I believe is where the star projector has its greatest strength. Traditional star shows using a star projector, when done well, can be the canoe ride down a beautiful river. Although perhaps more of a guided tour by a trained captain, the scenery and marvels of the night sky are there all around you to experience. There is time to absorb the wonders being described and room left between for you to use your imagination to fill in the gaps. A truly wonderful experience. These presenter-led shows also allow for the opportunity to have interaction between the audience and presenter, as well as allowing the freedom to explore specific entities. It will be a long time before this specific tool is finally replaced, but certainly it will eventually be replaced. I can only hope that when the day comes that this tool itself becomes outdated and is replaced that its replacement offers at a minimum the same quality of experience but is able to then go beyond and extend and enhance the quality of both the user's experience and imagination.

Visualizing the Night Sky

The simulation industry has been simulating ground and sea terrains with moving objects for many years. In the early 1990s technologies from this industry were applied to new markets and thus set into motion the visualization market. The simulation-based technologies were put to use in oil and gas exploration, automotive design, architectural fly-throughs as well as many other areas. During this same period, video projection systems utilizing the simulation industry techniques such as blending and image distortion that were being perfected for the creation of large scale immersive environments, were introduced into the planetarium markets. The numbers of companies that are now capable of delivering the technology behind the high quality full dome display systems have grown significantly and there is now plenty of choice as to who to work with. The technology is tried and tested and the number of deployed and operational full dome video systems is rapidly growing.

The new California Academy of Sciences. Picture courtesy Renzo Piano Building Workshop / California Academy of Sciences.

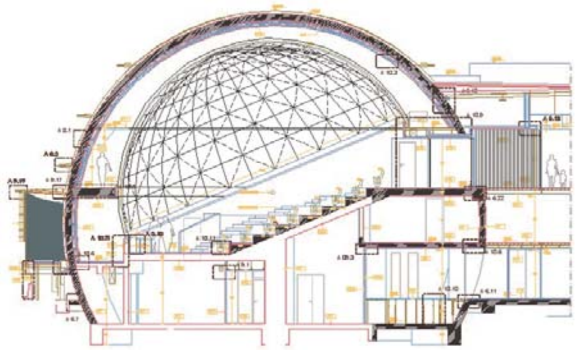
As with all industries, the visualization market is constantly striving for higher resolution and better image quality. Inside the planetarium however the star projectors can provide star fields that have greater than eye limiting resolution. It would take in the region of fifty off-the-shelf video projectors to begin to approach this near eye limiting resolution on a hemisphere. With digital cinema effectively setting the standards for video projection, and these standards likely to be adopted worldwide, there seems little incentive for projector manufactures to exceed this benchmark for just a few special purpose sales. It is likely that the drive for higher resolutions will come from the other industries like simulation where training to identify friend or foe before they can see you is a thin but critical advantage. Already from this sector we are seeing the introduction of laser projectors with very high resolutions that may be able to achieve this Holy Grail of exceeding eye limiting resolutions when tiled together. The timeframe to general affordability, overall quality and operational reliability of such extreme resolution systems will have to remain to be seen.

Beyond the measures of starfield quality and "infinite black", there are a wide variety of capability and versatility measures which quite strongly favor the video projection systems. Now, instead of needing arrays of clunking slide projectors, the images can be produced and presented digitally, and the portability of digital media is becoming fairly straight forward. Video projection systems also have the capability to enable a 3rd dimension to be understood such that the newly available data sets of the stars, mapped as accurately as science will allow, can be flown through and viewed from different angles and perspectives. The ability to provide a new three-dimensional map of where we are in the universe and dynamically be able to see what is around us, is a truly stunning capability that immediately captures the imagination and allows, in a way that was previously impossible, the dynamic depiction of what is really meant by the infinite depths of space. I have heard many people, with no specific interest in astronomy, rave about these presentations. This capability is enabling the planetarium community to teach the most recent discoveries and pass on the very latest in scientific knowledge. This has without argument added a new dimension to the capabilities of planetarium education.

The Diversified Dome

When discussing planetariums and digital domes with clients and prospective clients I have been surprised and saddened by the number of facilities that cannot financially justify a planetarium with astronomy as its sole purpose. This in some cases has caused planetariums to close and in other cases provided an opportunity to diversify the use of the planetarium as a digital theatre, thus enabling astronomy to continue but with other subjects utilizing the immersiveness and perceptual benefits of the dome for high impact teaching. The number of different subjects being taught or planned around domed theaters is constantly growing. There are a growing number of dome user groups that are not astronomy based. Already in domes, material has been produced as either playback shows or real-time data sets for a wide range of new subjects that have traditionally only been viewed on flat screens or smaller immersive environments. Some of the subjects I have discussed with various Universities for the presentation of coursework and research in their dome are life sciences, bioscience, architecture, ancient Greek archeological reconstruction, digital art, meteorology, marine biology, geology, mission planning and briefing, simulations and virtual field trips. As you would suspect, this is only the tip of the iceberg. There are many, many fields of study that will discover what astronomers have known all along, and will now begin to be able to leverage the dimensionality, immersion and experiential aspects that are native to a domed theater.

In addition to the diversification of existing planetariums there are an increasing number of digital domes being designed and built with no astronomical aspirations at all. It is in everyone's interest that the effort put



Foundation of the Hellenic World - Digital VR Dome cross section

into creating a presentation on specific scientific research/knowledge should be as transportable as possible so that the science can be delivered to the largest possible audience. In order to achieve this, the onus is on the vendors and advisors for technology and content to ensure that common standards are adopted wherever possible. The advantages of this diversification are that a dome now no longer needs to be funded solely from the astronomy budget. Suddenly there are many different interested parties and it is reasonable to expect that they contribute to the running costs of the theatre as well. Whether they buy time, pay an annual contribution, provide staff and materials, bring other sponsors and donors to the table, or just donate a part of their annual budget, the introduction of other users to the dome does usually distribute the financial burden of the system.

Even with the increasing number of companies involved in the sales and marketing of dome video systems and an ever-broadening diversity of technological backgrounds being brought into the mix of what is available for dome theaters, there are still elements from other media which are available to new digital domes that are slower to become adopted. The star projector and video projection systems appeal only to our visual sense, while standard stereo and 5.1 audio is limited in its ability to reproduce natural and dynamic sounds. The virtual reality, simulation and theme park industries go to great lengths to go beyond just simple visual plus aural displays to stimulate as many senses as possible in order to provide more dramatic multi-sensory experiences to their customers. While VR and simulation are designed to create a perceptually compelling environment or situation for learning and experience, the theme park industry simply and intentionally tricks our sensory systems in order to provide us a thrill. The new Digital Dome at the Foundation of the Hellenic world is planning 3D stereoscopic presentations with audience interaction and will not be used for astronomy.

As one example of new technologies coming available, there are now a number of vendors coming to market with spatial audio systems that go far beyond the 5.1 or 7.1 surround model, and enable sounds to appear to be dynamically attached to visual objects and thus move in conjunction with the object around the theater. These systems allow for the ambient sounds of animals moving about a rain forest all around you, listening to a bird fly past your head, following conversations amongst a group of people as they walk by, or listening to rain drops falling onto various sized leaves all around you add to the realism of what the audience is seeing and provides a deeper immersion into the environment being shown or studied. One science centre project intended for children's scientific education considered special seating to enable wind (hot and cold), smell, water spray, leg ticklers, seat drop, and seat shakers / butt kickers. These traditional theme park ride effects were considered in order to make the learning experience in the dome as much fun as possible while actually delivering some fairly complex and very serious science. In addition to the variety of sensorial stimulation technologies available, there are also a wide variety of feedback and interface devices available that begin to change the role of the individual from an observer to a participant. These technologies range from hand-held selection devices to in-seat control panels and joysticks, and can be leveraged to create a much more dynamic relationship between the presenter and/or content and the recipient.

Field trips for schools, colleges and universities have become riddled with regulations and restrictions that make the thought of them frightening to many educators, administrators, and parents alike. The insurance alone has caused many schools in England to drastically reduce the number of field trips they provide. Using the dome to re-create these field trips has been regarded as second-best, but a significantly better option than no field trip at all. These virtual field trips can include video and audio recordings of the places that the students would have previously traveled to by coach. The advantages of the field trip within the dome include both cost and safety; however, by allowing the presentation to be done with a highly experiential medium, the learning extends far beyond what they would get from a book or slides. The teacher has the whole class within earshot at all times and can use supplementary material to provide more information than the students may have picked up on their own in the field. A pre-field trip briefing scenario being developed by a university in England is designed to provide marine biology students with pre-dive information on the equipment they will use, what they can expect to see, and details of the aspects of the dive that will be of specific interest. This educational model is designed to provide for a greater educational impact when the student is underwater, and subsequently with only minimal modes of communication available between the student and the teacher.

Hope for the Future

At the beginning of this article, I discussed the highly experiential and imagination-provoking outing where my family and I wound our way through the quiet countryside and struck out by canoe into the river for a day's adventure. It is this sense of adventure and discovery combined with the mysteries and infinity of space that has until very recently been the mainstay of nearly all presentations and educational experiences inside a planetarium. With new tools coming into the forefront of the dome presentation toolkit, it is important for all persons associated with planetariums and domed theaters alike to strive to maintain and improve upon this experience. New technologies promise to further engage our senses and allow us to participate more directly and more experientially than ever before in what we want to see and how we want to see it, but there is a danger that if not well maintained, not well considered, that these technologies could simply usher in the 90-second show at the end of that long line that makes us wonder if our money and time were really that well spent. ☆

It is this sense of adventure and discovery combined with the mysteries and infinity of space that has until very recently been the mainstay of nearly all presentations and educational experiences inside a planetarium. With new tools coming into the forefront of the dome presentation toolkit, it is important for all persons associated with planetariums and domed theaters alike to strive to maintain and improve upon this experience.

The Powers of Ten with a Steering Wheel on the Global Visualization Superhighway

Carter Emmart
Director of Astrovisualization
Rose Center for Earth and Space
American Museum of Natural History
79th Street at Central Park West
New York, New York 10024
carter@amnh.org

Powerful three-dimensional exploration, demonstration and description of the measured universe across all scales has become a spectacular reality now with increasingly affordable technology upgrades for planetariums. From the largest to the smallest domes, some digital systems can now be run in real-time and networked together. Broader networking of domes to common desktop machines will enable a worldwide audience to share in guest lectured, tele-collaborative immersive presentations, interactive instruction, and discussion. The revolution is being televised.

The future global planetarium

While it may be confusing enough to consider the exciting potentials of going full-dome video from your old reliable star ball, I would like to offer a glimpse of a step beyond that which is not so far off. I offer this as one who weathered the transition at the Hayden in New York, yet confess that my perspective is not coming from a traditional career in planetariums, but rather from one of data visualization and scientific illustration. My role, however as director for space shows and astrovisualization at the Rose Center has a lot to do with my inspiration and education at the old Hayden Planetarium as a child.

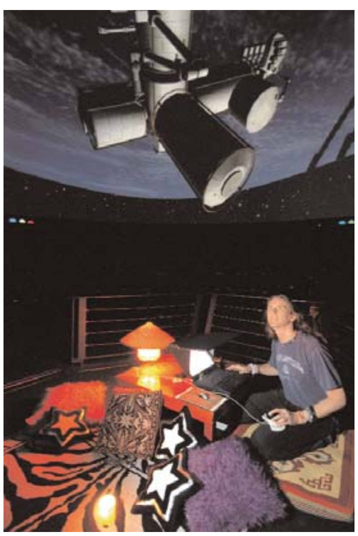


Fig. 1: The author with the "magic carpet" setup in the center of the Hayden Space Theater. Remote interactive operation of the full-dome video graphics is being made by a network connection from the laptop to the image generating computer in another part of the facility. Live navigation and manipulation is being done with a hand held space ball. Credit: Alex Bowles, photographer. ISS model: Takahei Toshiyuki, Riken Research Institute.

Imagine for a moment a future where we all have these new-fangled full-dome video systems, if for no other reason than the entry price has fallen enough and your trustees insisted that you keep up with the trend. (For some of you out there like us in New York, you've kept your star ball as well, you like its stars better, and frankly, you're attached to it - that's OK ...). We're all happy because we can now play the latest spectacular full-dome shows being produced by various places, and we can cut, splice, and re-edit this material in support of our own home spun programs. By this time, a 3D atlas of the universe with real-time "flight simulation" controls will be standard issue with your full-dome system of choice. You have been coached by the vendor on how to go on-line with the planetarium network where you can choose to join in the same virtual 3D space within the atlas together. You have also read the manual describing how to "drive through the solar system" and even "fly through the stars" and leave the galaxy, but all that still seems a bit alien above and beyond presenting the good old night sky.

Perhaps, you admit to yourself, "I would *love* to fly out there. I dream about it. I wanted to *be* an astronaut, but hey, I've got enough problems, and learning how to drive this new "Jetson's car" is a just bit too ... well, complicated. I'll stick to my diurnal motion, thank you very much. Besides, I'm sure not going to get lost and make a fool out of myself in front of a live audience .... I'll stick to those nice movie clips we now have." Perhaps, however, you also have a passion for the live presentation tradition in

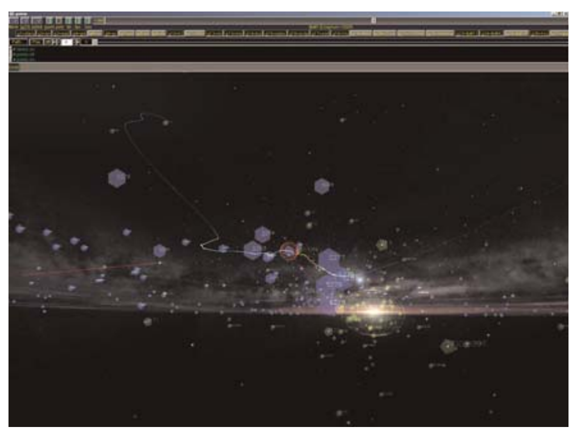


Fig. 2: Partiview software interface for single screen viewing of the Digital Universe, Milky Way atlas showing flight paths away from a red, 100 light year sphere around the Sun, Hipparcos stars, yellow globular cluster locations and blue stellar birth HII regions. Credit: author and NCSA.

planetariums that got you hooked as a kid in the first place, and it would be pretty cool if you could take people *through* the stars yourself ...

You check your email. At 8 AM tomorrow morning, the Hayden is giving a live on-line, 3D tutorial about the upcoming Europa Lander mission, and then tips on navigating out to the Hyades and Pleiades. Strange time, you think, but then you recall in New York's time zone it will be *8 PM*.

Next morning, you log in from home before you leave for work and follow the tutorial on your laptop which runs the same real-time, interactive 3D software as your dome. The live session is being archived on-line, so you can download and play it back in your dome later, but what seems a bit fuzzy to you now is how the view on your laptop might correspond to the dome and then you recall the fisheye and zoom settings in the software ...

Over coffee, you notice that planetarium staff from Melbourne, Tokyo, Taipei, Shanghai, Los Angeles, Chicago and Stockholm (wow, they're up late) are all on-line together (as well as teachers across America and some in India, up very early). After a few flight paths are shared and discussed, the navigation controls are demonstrated several times. A digital 3D model of the Europa Lander is displayed and described from all angles with demonstration of how to set it in motion along its simulated trajectory. Questions come in from around the globe as navigation control is passed off to those asking a question. You ask which receiving station on Earth will be picking up the feed as the Lander sets down. New York spins everyone's view around to Earth, zooms in and we can all see it will be Madrid. You start to get excited because, not only are you seeing a true layout of the mission, but you are being taught directly on-line, in 3D, and this is just a warm-up for next week's tutorial from a guest lecture by the mission scientist at JPL!

When the real thing happens, domes from around the world will all be logged on together to watch a combination of virtual simulation of the mission with latest images projected properly within the scene and running commentary by those who made it happen. You sign off and leave for work, but that was surreal ...

Later, after work in your dome, you download the rest of that morning's recorded session, then watch and listen how others learned to fly out to the Hyades and look back home. You try it yourself, get screwed up, and log in to see who's there. It's now 8 AM in New York, and someone is there, answers, and sets you straight. You are now confident in your flying. You see Hamburg is on-line too and you toggle on their marker which is out by Vega. You go there and find they're practicing some wild interpretive virtual ribbon dance for an upcoming event. From Vega, you try to find the Sun, and you can't. Toggling on the extent of the Oort Cloud suddenly highlights the position of our star – and wow, its dim from out here!

You select the International Space Station from the menu and go on autopilot to take you there. New York was at Saturn, but saw you coming in and joins you and you both fly in formation to the ISS. As we orbit our home, New York turns on yesterday's satellite images as we float over South America and view the smoke trails of the Amazon burning .... Beyond the limb of Earth we see the Moon and a blinking cross hair beyond that announces a news flash; the position of a gamma ray burst recorded an hour ago.

If all this sounds crazy, I can say that I shared a similar skepticism when I heard about the Hayden rebuild in New York, nine short years ago. I can tell you with assurance however, that what is stated above is a lot closer than you might think, and in crucial pieces, already exists. The key elements are full-dome video display, a 3D atlas of the universe, a real-time interactive atlas visualization tool that can work in both dome and single screen, and networking.

Extending our Presence and Seeing the Universe

On a muggy summer night in New Jersey, in 1969, I sat underneath the dinning room table next to our family dog, watching TV with the rest of the world and pledged I would be part of this exploration of space. The future never seemed to turn out like the movies, but perhaps Stanley Kubrick was onto something more in line with the realities of the early next millennium than was presented in his great film. Projecting our consciousness into space by machines has become a reality, by combining data from telescopes and robotic spacecraft into new immersive viewing schemes by means of advances in computational, graphical, and display technology.

Extending our presence throughout the limits of knowledge is part of our species' survival skills. Projection in space and time of a situation is key to hunting, gathering, and tool making (... and flying to other worlds). We "manipulate" an unfamiliar object with our hands to "examine" it. We roll it around to see its shape, how it's made, how it works, if it's dangerous. Its external reality is recorded internally in our brain as we map it into our consciousness. To "see" something is a process of internalization and registration within our consciousness, as our mind goes on autopilot to figure out the relationships.

For things larger and smaller than we can hold, we create models and maps of them that we can. We have maps for all scales and timelines that allows us to snapshot certain

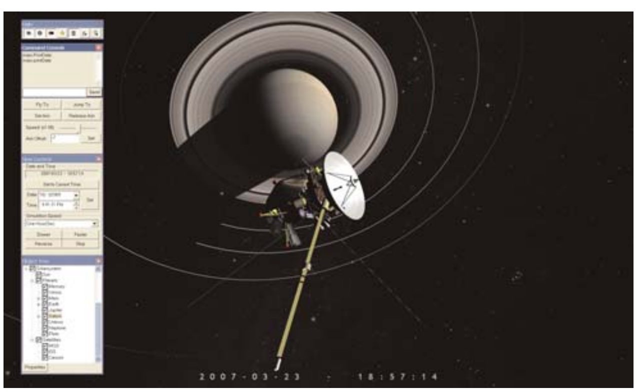


Fig. 3: Uniview single screen version interface with Cassini-Huygens spacecraft, just a small subset an atlas of the entire universe. This software can be run in fisheye mode or multi-channel for domes, as well as networked between domes and desk tops. Credit: author using Uniview by Sciss, AB, Sweden.

Fig. 4: Smoke from Amazon rainforest clearing by many individual fires. Picture take by MODIS satellite on September 17, 2005 and displayed in NASA's free World Wind interactive global Earth viewing software. Credit: author using World Wind.

resolutions of information and carry them with us. Such aids are really just abstractions that help guide us as reference for our internalized picture that frames our sense of presence within the perceived external reality.

The sky appears to be hemispherical (just like the planetarium dome), but because we can't touch it, or walk to it, we couldn't know its true dimensions and character firsthand. The mere fact we use a dome to model the night sky authoritatively may confuse children more than we might care to admit in their attempts to make sense of the real sky (as it did for me). Just as the study of astronomy struggled to obtain the third dimension and resolve the layering of what the sky presents to us, so too is the planetarium field now struggling to grapple with our three dimensional knowledge of the cosmos and present it to our audiences with full-dome techniques. The intrigue of full-dome spatial motion graphics is of course the very illusion of the third dimension that traditional planetariums' faithful duplication of the night sky lacks.

Technology has brought us to a new level of consciousness of our surroundings both in the amount of new information it enables us to gather as well as in the means it enables us to present these new findings with. We can barely keep up with the flow of data enabled by the new means of gathering it in almost every field. Faster computational and graphical systems evolved as a means of keeping up. The opportunity was ripe at the turn of the millennium to overhaul several major planetariums with full-dome digital display systems. In the case of the new Hayden, it was decided that an attempt would be made to update what a planetarium might be possible to achieve by combining the powerful three-dimensional illusion of full-dome display *with* a digital atlas of the universe depicted by means of data visualization. This new scheme was designed to be able to accommodate the flood of new information into it, placing it all in proper three dimensional context. It would be the basis of both real-time presentations as well as the foundation for in-house productions.

For the first time, we are now able to manipulate the view and examine the real three dimensional layout of the universe across vast ranges of scale. What is significant is that, for the first time we are "seeing" the universe in the form of the information we are able to gather from reaches across both space and time to distances we will never be able to travel to. Our accumulated knowledge across the centuries and beyond all bounds of human distinction, integrated and vetted by so many, distills into this plotting of the current limits of the known. On the dome, we set sail into it and get familiar with it in a whole new way. We become true star pilots, the real "astronauts". And while we may not be physically "out there", our familiarity of it is now "in here", in our brains, and in that way, or presence has been extended.

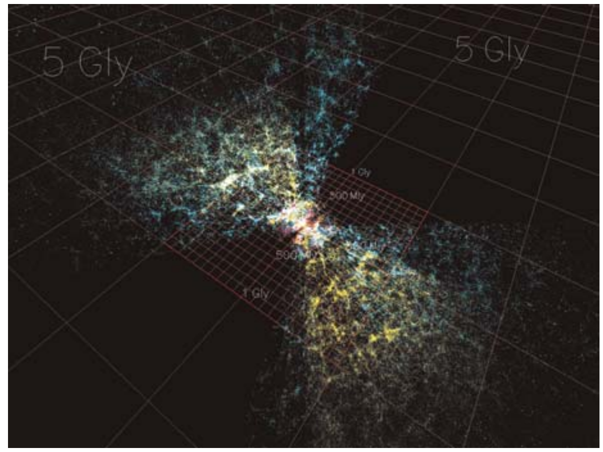


Fig. 6: Deep space 3D galaxy surveys out to several billion ("G" for giga) light years with nested grids for scale. Three data sets in view; Tully, Sloan, and Two Degree Field survey. Credit: author and Digital Universe, AMNH.

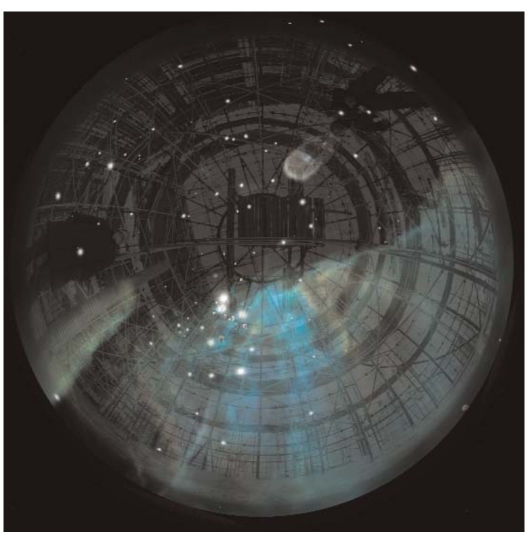


Fig. 5: Building new frontiers: composite of new Hayden Planetarium dome construction with Orion Nebula still from debut full-dome space show, "Passport to the Universe". Credit: The author, and Rose Center Production.

"The Powers of Ten" with a steering wheel

The nickname for this concept of data visualization across a range of scales that some of us adopted was '"The Powers of Ten", with a steering wheel' as a respectful nod to the seminal film by the designer couple Charles and Ray Eames in collaboration with the physicist couple Philip and Phyllis Morrison. We were certainly not out to replicate that classic film, but expand on what it introduces. Eames' idea was to animate scale change within a single sized frame, similar to the idea of how an architect develops a set of drawings for a project, each drawn at different scales, yet each fitting a portion of the project to a standard size sheet of paper. Whereas "The Powers of Ten" was a scientific illustration, based on the best knowledge of the day, the ability to move anywhere throughout current measured reality, and across many orders of scale was now possible with computer graphic visualization.

Data Visualization

Plotting "data" and making pictures of it is called data visualization. Data visualization is nothing new when we consider making a graph, an engineering drawing, or a map. Each one of these graphical representations relies on numbers and scale. Three dimensional data visualization allows us to create modeled environments, called "worlds", based on measurements. This can also be considered 3D mapping, and much of the graphical logic and analysis that applies to 2D mapping can be extended into the additional dimension.

Astronomical data visualization, or "astrovisualization" for short, allows us to examine the real size and scale relationships of the universe with visual depth cuing and continuity between locations by motion with the added abilities to highlight, threshold, group, delineate, and demonstrate across time in ways that were not available before. The transition for our profession to 3D is from concept artwork and illustration to astrovisualization. The "art" now is in the preparation, interpretation and presentation of the data where the computer frees us from much of the mechanical forms of constructing it as in the past.

A "Digital Universe"

At the Hayden transition, this meant dual research projects to assemble the data and visualize it. The data assemblage, or "atlas" amounts to a collection of academically published astronomical catalogs that have

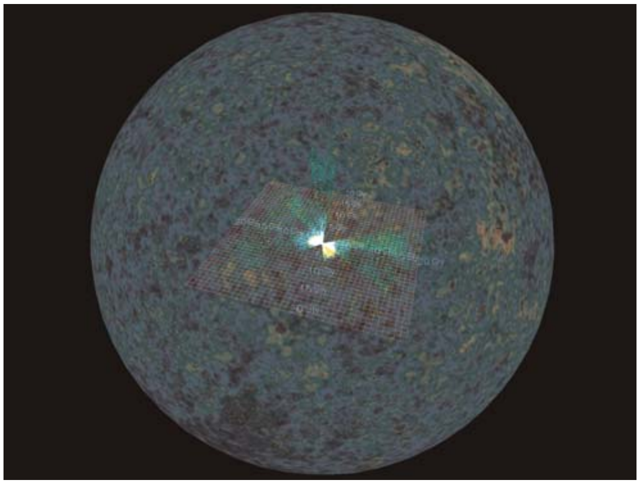


Fig. 7: The edge of the visible universe mapped spherically around our point of view at the center. Surface of photo decoupling, several hundred thousand years after the Big Bang imaged by the WMAP satellite of the Cosmic Microwave Background Radiation, encloses the deep surveys of individual galaxies. Credit: author and Digital Universe, AMNH.

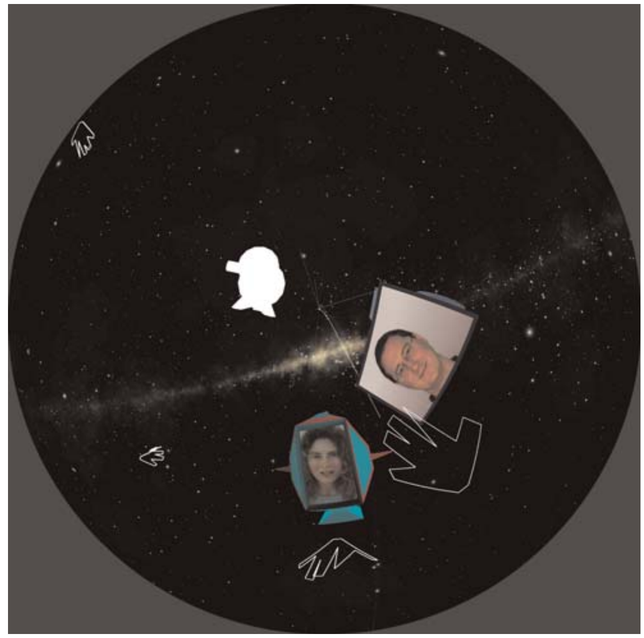


Fig. 8: Visitors in the sky at the Hayden. Donna Cox and Bob Patterson (Stuart Levy does not have his "skin" turned on) from NCSA say "Hello" with a wave of a virtual hand at session's beginning of remote tele-collaboration to build a flight path together for our second space show production. Credit: author and NCSA using Virtual Director.

distance information and then processing them to all fit the same solar centric, galactic Cartesian coordinate system. In 1998, NASA funded the initial Hayden effort which was then called the Digital Galaxy Project reflecting its limitation to plotting the known constituents of our Milky Way Galaxy. Since that time, we have expanded the scope of the atlas and renamed it the Digital Universe. Key to our NASA funding was making this atlas available to the community both in licensed by-products such as our full-dome space shows, and in free educational form now offered at www.haydenplanetarium .org/hp/vo/du with a freeware viewer called Partiview.

Virtual Director

The visualization of the Digital Universe has many stories in the development of a tool to accommodate the twin goals of doing both real-time operator driven interactivity, and production. For our first space show, "Passport to the Universe", we partnered with NCSA, the National Center for Supercomputing Applications, whose visualization team lead by Donna Cox had been working with researchers on the observed distribution of galaxies and the modeling of the large scale structure of the universe. In order to preview camera paths on our dome they were making through such data, we had them install "Virtual Director" on our system, a flight path authoring tool for use in the CAVE, or Computer Assisted Virtual Environment (see http://cave.ncsa.uiuc.edu). The CAVE is essentially a cubic room with rear projected walls of computer generated stereo graphics where an operator wears a head mounted tracker to accommodate the computer's ability to correct the perspective for any given viewing location within it. Instead of using a mouse, the operator uses a "wand", with another tracker on it so one can position, select, grab and alter items within the 3D virtual space. Our dome was not setup for stereo graphics, or tracking, so our first use of Virtual Director was meant primarily as a viewer to play back flight path scripts in real-time. Another feature of it, however, would indicate an interesting future.

Remote Tele-Collaboration

Perhaps the most intriguing function of the CAVE and Virtual Director was a capability we would not be able to use until the second show production; remote, tele-collaboration. In the Hayden rebuild, we had purchased an SGI Onyx II computer to run our seven video channel display, which was the same hardware that NCSA was using for their CAVE. While this investment by our museum in research-grade computer equipment would allow for us, in principal, to hook up with NCSA over the internet, its priority to both render and later deliver the show meant that it would have to be designed for total isolation from the grid. This was eased up enough by the second production because show playback had been moved off the Onyx to a separate Windows NT based, DVS system. Finally, we could logon to NCSA's CAVE from our dome, and both see the same virtual environment and "fly" through the atlas together.

How it works is that separate, but identical atlas copies are resident on each of the computers running their respective displays, so that all that the two remote operators need to share over the internet are relatively tiny data streams of position, orientation and occasionally other communication protocols such as display attributes. If you have ever played a networked game, like net-Quake, this is old news. On screen we could both "see" each other in the form of an avatar, or 3D graphical representation object that displays ones position and orientation. My avatar was of course a dome with a simplified model of the theater. Also, we each had a graphically represented outline of a hand which we would use to point things out and gesture directions. At the start of each session, we would join up close and wave at each other as depicted in the adjoining dome capture images.

We had a production necessity in our second show, "Search for Life: Are We Alone?" to visualize a dynamic simulation of turbulence within a molecular cloud of the interstellar medium to show gravitational collapse into stellar birth. We utilized NCSA's master of flight path creation, Bob Patterson, stationed in the CAVE in Illinois, eight hundred miles away from our directorial perspective in the dome for framing and careful attention to turning rates. Working together simultaneously, with audio steaming or phone for verbal communication, we were able to efficiently conclude a complex flight

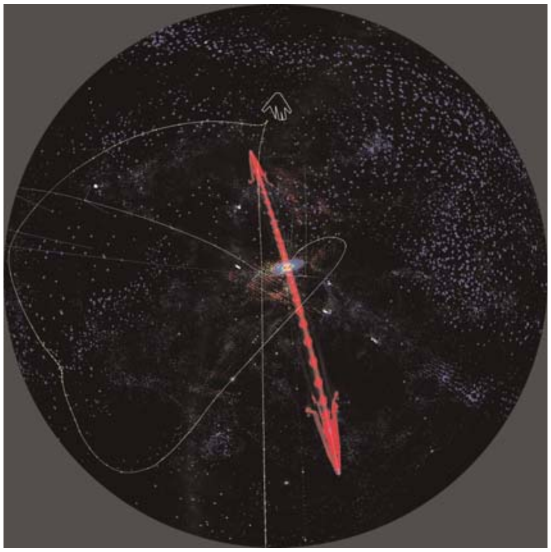


Fig. 9: View of completed collaborative flight path through dynamic molecular cloud to early Sun with proto-planetary disk and bi-polar jets. Credit: author and NCSA using Virtual Director.

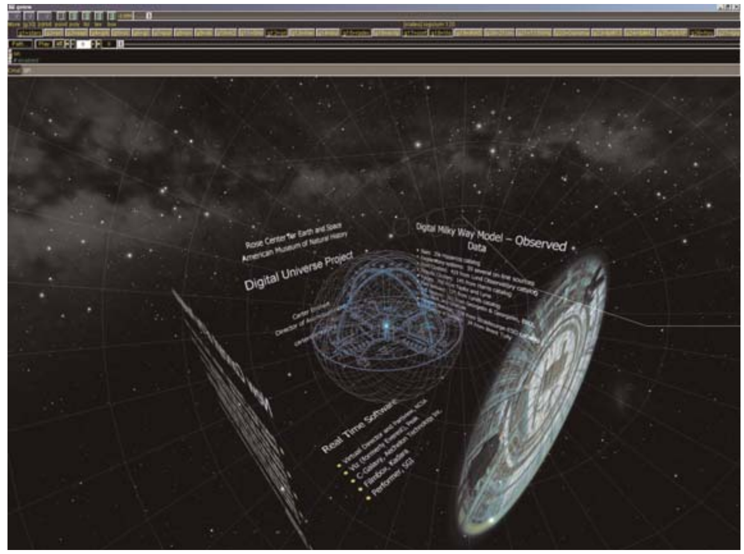


Fig. 11: Partiview 3D interface with Digital Universe data base and presentation slides loaded for a conference in Glasgow. Credit: author using Partiview.

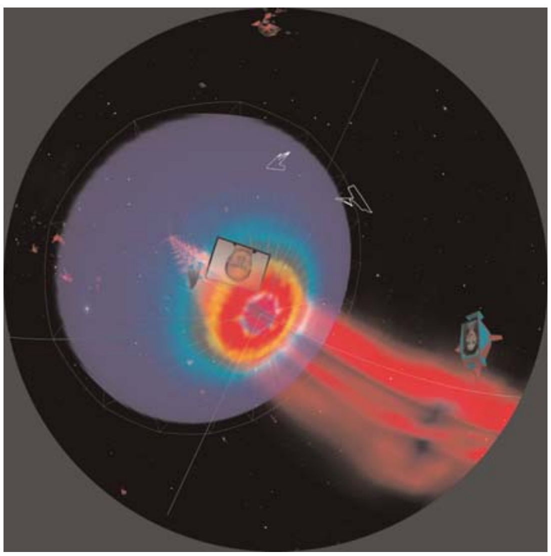


Fig. 10: Virtual Director full-dome image capture close to encounter with proto-planetary disk with collaborators, Bob and Donna from NCSA. Credit: author and NCSA using Virtual Director.

path together over several nightly sessions. During the work, Donna Cox and Stuart Levy, their visualization programmer joined the collaboration each on their own machines, making four of us within the shared virtual atlas.

Viz Tool Stopgap

For various reasons after our first production, we saw Virtual Director as a promising tool to display our data in, so we formatted the atlas to be read by it. We did not see Virtual Director as an end in itself, but rather a means toward an eventual, more specifically dedicated tool to visualize our atlas. We were helped allot by Stuart Levy to get the stars' apparent magnitudes behaving properly in real-time as we moved through them. He also helped us to understand the simple, yet extremely effective display commands to set attributes on multiple data sets. The interface left a lot to be desired for as it was designed to be "spoken to" with voice recognition software, which we never fully embraced, so it was all left to text entry with specialized command slang. Without a "wand" the navigation almost didn't exist, so we had to teach ourselves the "programmer debugging default navigation fallback options", which means "flight by mouse and control keys". For myself, I spent many nights alone in the dome forcing myself to learn this so that I could master the technique and get familiar with the data *from inside it*. NCSA was amused that we would even adopt Virtual Director as a "visualization tool stopgap", but lacking software development funds, we were determined to use this because we had it and it worked. Later, their team visited and complemented us on our navigation and told us they were seeing the data in ways they never saw before. Perhaps the art of presentation was a factor beyond merely the skill to operate it.

Partiview Portability

Stuart had shown us a single screen windowed spin-off of Virtual Director's display, called Partiview (short for "particle viewer") which he had authored with a simple graphical user interface that simplified much of the Virtual Director text commands. Because it did not work in the dome, we ignored attention to it in our focus to learn the Unix exclusive Virtual Director. At a conference with Stuart, I asked a question about data display in Virtual Director, and he proceeded to show me what to do in Partiview on his Windows laptop .... I was elated to see this tool in *Windows* which he intended as *freeware*. Since Partiview already read the Virtual Director format to which we had adapted all our data, this meant that we could release our Digital Universe to at least the Microsoft flavor of the world with Partiview to visualize it on single screens. This is what you can download as mentioned above, and there is now a Mac version, as well as the original Unix and Linux versions. We could now see, with this tool, what we used to have to go to the dome for, taking it with us on travel to work on it and present it off standard projectors. At IPS 2002 in Wichita, we presented a workshop on how to use Partiview to view the Digital Universe.

The Holy Grail of Unbounded Scale

One major lacking that we came up against very early in the Hayden project was the "precision issue" on the graphics processing end. In short, we could only fly through a limited range of scale before reaching practical bounds of numerical range that the processors could accommodate. If you zeroed in on an object too small and tried to get close to it, there was not enough numerical precision to define its position, so it would jump around. Flying up to the Earth was impossible if your map was as big as the galaxy .... Obviously we had a problem.

Embarrassing as this was, we got around it in production by making separately-scaled models to be rendered, then placing the renderings in proper orientation to one another and compositing them for needs of individual shots; "production magic" in short. Both of our productions only needed static renditions of the solar system, which were set for certain times on the basis of the shots. For that, we used the Jet Propulsion Laboratory's "Horizon's" webpage to generate ephemerides of the planets and their paths around the Sun to draw their orbits.

For our interactive Digital Universe, we left a detailed orrery out except for a simple depiction of the orbits of the major planets for two reasons. First, was that the solar system was too small to include in the visualization of the galaxy because of the precision issue, and second because its dynamical complexity and level of detail issues were perhaps best left to after the comparatively "easy" job of plotting the major static catalogs of objects beyond the solar system.

Because of the precision limitation, we also had to apportion Digital Universe in two major scale representations, one for Milky Way and one for extragalactic.

Accomplishing our goal of interactively spanning scales from that of spacecraft to the width of the observable universe was left as a future research project. To approach the interactive data visualization of the entire scale range of the universe all the way down to Plank length was the true "Holy Grail". Help came from Sweden in the form of an internship.

Uniview

At SIGGRAPH 2001, in Los Angeles, Ed Lantz pulled together a course entitled, "Computer Graphics for Large-Scale Immersive Theaters" of which I was a lecturer. Attending, was Anders Ynnerman, a physics professor from Linkoping University in Sweden who had founded a graduate program and laboratory for immersive scientific visualization, called NVIS. He came to visit us at the Rose Center in early 2002 with a contingent of his local city and business planners who were considering building a large scale VR theater of their own. Anders' twenty-week Master's program in visualization was producing talent, and he asked if I was interested in one of his star students. Staffan Klashed joined us that fall and immediately took on the scale limitation issue.

We had our Digital Universe which lacked a solar system, and a solar system model

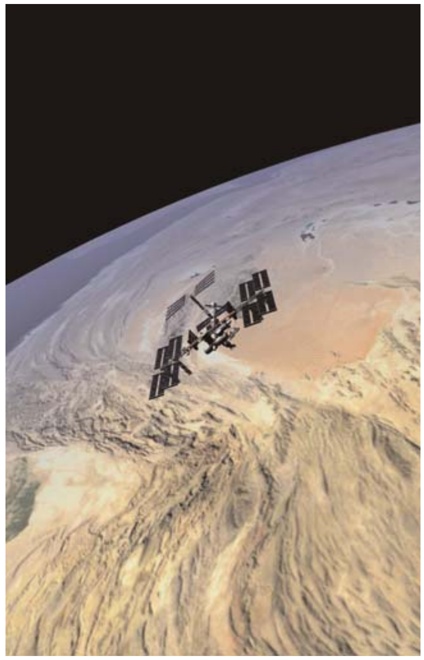


Fig. 12: In Earth orbit with Uniview. The International Space Station floats over the border of Afghanistan and Pakistan with 1km NASA "Blue Marble" Earth data for image and height map. Real time terrain generation is occurring in the software. Credit: author using Uniview by Sciss, AB, Sweden. ISS model by Takahei Toshiyuki, Riken Research Institute.

which had been shared with us from Japan, called the Solar System Simulator. Mr. Toshiyuki Takahei had constructed this very elegantly designed and versatile interactive "simulator" while he was still a student at the University of Tokyo, and was now working for the large Japanese research institute called Riken where he makes educational visualization applications that run off the innovations being made in their high performance computing division. Roughly one thousand teachers in Japan now use his Solar System Simulator (see www.sssim.com). We had hoped to collaborate in order to get his software running in our dome, but scheduling and supporting a few months visit proved difficult, so I asked Staffan to look into merging this solar system model with the Digital Universe.

Staffan's work addressed both the scale problem to fit Digital Universe and solar system together and the depiction of the dynamics of the solar system with a style that was informed by the design of Solar System Simulator, while not actually using its code. The concept allowed for separately defined scenes to each be placed into proper registration and scale with one another, such that one can seamlessly cross the boundaries between them and retain the view across them. Most importantly, this was a generic solution to the scaling problem such that an *arbitrary range of scales* can be defined across an arbitrary number of scenes, from quarks to quasars. Staffan named this "scale graph" and it worked beautifully. I suggested a more descriptive name to its function as a "universe viewer", echoing back a bit to our use of Partiview, or "particle viewer". Where "Universe" means literally "one statement" for everything, "Uniview" would mean "one view", or "one viewer" for all.

In the spring of 2004, we hosted two more interns from Ynnerman's program that Staffan had coached. Per Hemmingsson and Martin Rasmusson continued the work on

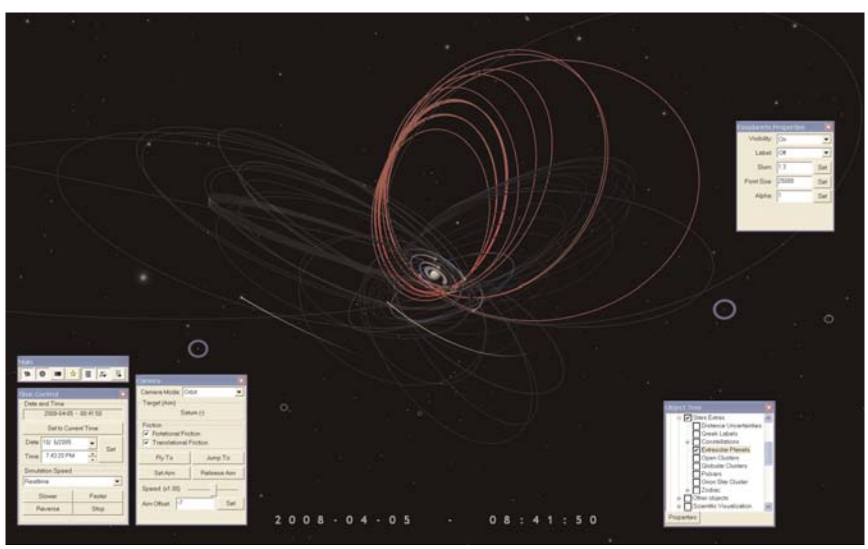


Fig. 13: Cassini-Huygen's four year Odyssey at Saturn, color-coded by mission phase in Uniview with background highlights of extra-solar planets. Credit: author using Uniview by Sciss, AB, Sweden.

Uniview which gave it a more solid foundation. Martin worked on improving the efficiency of handling stars and large high resolution planetary maps, and Per focused on a visualization of the Cassini mission, which I felt was not only topical, but would blaze a path toward visualizing all space missions. Dr. Kevin Grazier from JPL, who is an investigation scientist and science planning engineer for the Cassini-Huygens Mission gave us special assistance and coaching in the preparation of trajectories for spacecraft and moons at Saturn. Navigation had to be improved and simplified for the Cassini emphasis which helped a lot in general, and networking began to be integrated for remote collaboration.

In that same time period, Staffan founded the company Sciss based around Uniview. After their return home and conclusion of their degrees, Martin and Per were hired by Sciss with the first major assignment being a partnership with AMNH for the Digital Universe and SEOS of the U.K. for integration of a full-dome system at Chabot Space and Science Center.

The Network

Our positive experience of working tele-collaboratively with NCSA was a reference point in the development of Uniview. The idea being the scenario offered at the beginning of this article, namely that networking will enable useful teaching and worldwide lecturing by newsmakers perhaps in coordination with experienced operator / navigators. Dr. Grazier and I have presented the Uniview visualization of the Cassini-Huygens mission together on several occasions both in dome and also by flat screen single projection off my laptop. While these were non-networked, stand alone events, Kevin talked as I navigated, and since we were in darkness, the subject and the interaction was all in the graphics and audio anyway. Kevin and I might as well have been on the other side of Earth for how we were able to interact. As another reference point, I was also able to train Uniview to the operators of the interactive theaters at both NASA Ames Visitor Center and the University of Colorado's Center for Visualization over the phone, again without networking, but just by hand synchronizing our displays.

Uniview was originally developed in Irix on SGI multi channel Open GL based graphics hardware at AMNH, with network operations in the plans. Since the founding of Sciss, development has carried on primarily in Windows / Open GL, although Linux is also supported. While multi channel synchronization has been a hallmark of SGI, this was not the case with PC based systems. For the Chabot job, synchronization was developed for networking a PC / Windows graphics cluster which opens up the potential for much bigger networks. . The Hayden is now also running a new PC cluster donated by the NVIDIA company. Remote tele-collaboration between Hayden and Chabot could well be the first step. On a smaller scale, networking between the machines on our desks, to portable domes, and classroom projectors will create the ability for wide spread group teaching, training, lecturing, and demonstration.

Compatibility

How might this work with "the rest of the world"? Obviously we will all need to be looking at the same data as a start. Could Uniview and Digital Universe work with the new Gates Planetarium's Cosmic Atlas or Celestia, Starry Night, Digital Sky II, or Digistar 3? Could a network be made to operate between these different systems, or will vendor and institutional rivalry keep this network dream a fantasy? Consider how many different brands of machines do we all use to get on the internet. The standards will likely develop in a way that can accommodate everyone, one would hope. I would offer that a software scheme that can work across these different systems and accommodate the entire scale spectrum of knowledge is a good beginning. Since we ARE a community, I am very interested in seeing us *all* benefit.

The Global Visualization Superhighway

The sea of data on-line is enough to drown in, but its there to be contextualized, and it's up to us to do it. Our immersive-full-dome-virtual-reality-visualization-theaters are the places to do it in. Placing information into a 3D context is what this "atlas of the universe" is all about, and sharing it by various means empowers us all to see relationships as never before.

Having a scheme to see across the vastness of scales and time that we can measure is essentially a new and very powerful library. Libraries and search engines allow us to locate information and see categories. Visualizations, such as maps and atlases let us see across categories to broader relationships. Plotting information across scales and time bring us even broader associations. As we gather more information, more imagery, and more 3D data at all scales, we can plug it into this multi-scale interactive viewer, and not just see a demonstration of scale range, but be able to dwell in a visualization of a particular subject with all its detail.

As a window on the future of using "distributed archives" brought together in a 3D graphical manner, download for free NASA's World Wind or Google Earth. You will be treated to seeing our planet at 15m resolution anywhere on the land surface with corresponding terrain mapped in 3D. Image and height maps stream across the internet depending on your view. Different data servers can be accessed simultaneously from different sites all brought together onto any part of the globe you choose to examine. Full color 250m resolution imagery by the twin MODIS satellites allows one to paste onto the globe yesterday's view. Google Earth even has selected higher resolution insets of popular locations from the company Space Imaging down to 1m resolution, although not as current as the MODIS

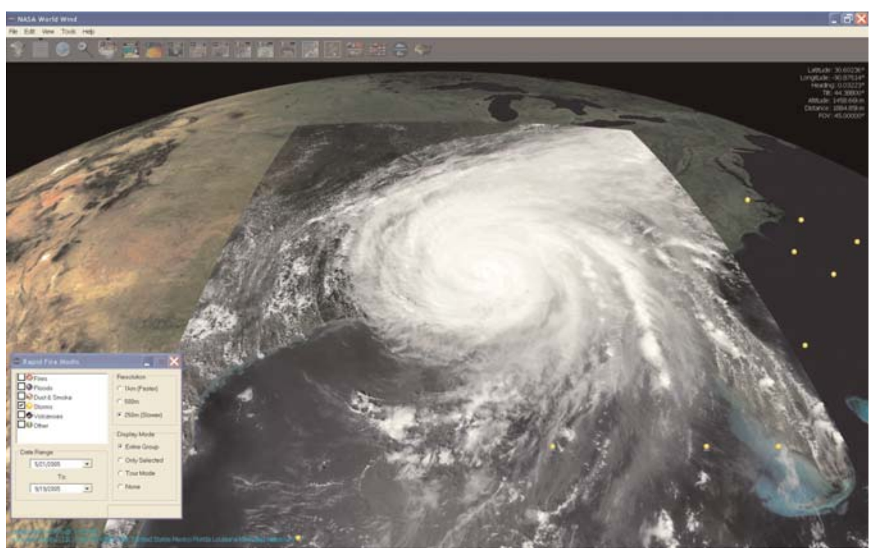


Fig. 14: Hurricane Katrina on August 29th, 2005. Another view from NASA's World Wind global viewer with MODIS satellite layering. Credit: author using World Wind.

imagery.

It is my hope that standards will develop for "information plug-in" to a multi-scale viewing scheme / tool like Uniview. The vastness of data is an opportunity to think creatively on how to fit a lot of it into such a scheme to make clear what might be self-evident to your trained mind in your particular field of study, but not to others. Making spatial and temporal data and visualizations accessible in standardized ways will allow this new library to grow organically as the internet did, such that access to entire new environments to explore should be as immediate as it has become for the rest of the world wide web; a global *visualization* superhighway. And like a highway, it shouldn't matter what make of car you're in or how big your windshield is, as we're all on that highway together.

Magic Carpet

Having built an atlas and a tool to view it with at the new Hayden, we immersed ourselves in learning it, like stepping outside for the first time and getting to know the neighborhood. After teaching a museum guard how to fly through it one night, we got in a very interesting conversation. The realization was that the tool worked well enough to break through to many of the revelations of astronomy that are at best, abstractions embraced and resolved by us few "astroheads". My conversation with that guard lead me to further discussions with others until I was bringing in friends, colleagues, and people I met anywhere for special Sunday night gatherings after hours. For these presentations / discussions, I fashioned a station of remote operations in the center of the theater atop the slip stage covering our Zeiss Mark IX projector.

I brought in a carpet and pillows so we could operate flight while we lay on the floor, staring straight up with the stars filling one's entire vision. We would navigate with a space ball one could hold on their chest. The spooky thing was, you really felt you were out there .... A lot of questions come up when you're out there, and these small gatherings were pretty special for that. Guided groups "seeing" the universe and responding as a discourse certainly helped us see it better as well. Steve Savage attended one of these evenings and dubbed it the "magic carpet ride" and he became convinced to adopt Digital Universe in Sky-Skan's Digital Sky II, where he's done a great job with it.

We have taken the show on the road around the world in various forms from flat screen presentations, to curved screens in stereo 3D, to small domes with fish eye projection.

Three years ago, I presented the Digital Universe to OPEC oil ministers in Abu Dhabi, and last year I teamed up with the company Elumenati to present at the Burning Man gathering on the Black Rock Desert in Northern Nevada. This year, at SIGGRAPH, we presented the atlas on Uniview at the NVIDIA / Elumenati dome, which also played back our full-dome productions. No matter the group, we have found the personal touch of presenting this material tends to connect well with an audience.

Our "magic carpet" evenings evolved into a monthly, live, interactive program called Virtual Universe at the Hayden (first Tuesday of every month, 6:30-7:30 p.m.). Brian Abbott, who manages the Digital Universe, Ryan Wyatt, who wrote last month's eloquent article "Planetarium Paradigm Shift", and I run these evenings and we three share a passion for the magic that lies beyond the night sky.

Fig. 15: "Bok Globule", Burning Man's "magic carpet", where tours of the universe were conducted nightly. This project was dedicated to our friend Dave Kennedy who built the dome, then passed away before ever seeing its completion. The exterior lighting was by Leo Villareal. Credit: Leo Villareal.

At the Hayden, our "tours of the universe" developed not only the skills of "how" to fly through it, but "how" to *present* the information. I do not believe we were even conscious of how this may in fact be a whole new style of presentation, but the whole medium is new, and we need more tour guides .... Sure, it's a lot of astronomy, but you can't step out into the universe without describing the relationships that suddenly jump out at you once you see them in 3D, whereas they may have taken centuries for scholars to deduce in abstract from the compressed view of the night sky.

With this new technology, planetariums are the locations to show humanity a view of itself, alone, afloat in space around one dim star in a vastness that shrinks before us as we fly away from it, spanning the knowledge worked out by our fellow human beings.

Far after the Sun inflates and spirals our planet into vaporization, we will hopefully have left a little more behind than Chuck Berry bolted onto Voyager. Our urge to go grows with our ability to hold the universe in our hands. The training starts in your dome. Come join the revolution. ☆

(*Last Light*, continued forward from page 68)

to borrow wealth. Oppressor classes use the present inequity at the subatomic level to justify inequity with wealth and credit at the human level.) With a strident activist approach, students will see social justice in action as oppressed photons, neutrinos, and other particles are finally given their fair share of mass and charge. Unless student uprisings and other people's movements succeed, the mass-rich (*e.g.* black holes) will get richer, while the mass-poor (*e.g.* interstellar hydrogen clouds) get poorer.

P482 – Feng Shui Physics, New Course in 2005!: Feng Shui, with its emphasis on the flow of energy, particularly *qi* energy, will first be explored in terms of Maxwell's formulas for electromagnetism to understand the basics of *qi* optimization, especially in kitchens and bathrooms. Students will then apply Schroedinger's equation to solve more complex problems, such as where to place a round table in a square room, or how many rocks are needed to make a rock garden look nice. Computational quantum chromodynamics in multiple dimensions will ultimately be invoked – *without* normalization – to lay a foundation for choosing the right wallpaper to maintain spatial harmony and to help a room look groovy. Extra credit will be given for Feng Shui-style body piercing, with generous discounts available at the campus piercing clinic for enrolled students.

And a last quote from the good doctor Einstein, with best wishes for a joyous and prosperous new year. "The ideals which have lighted my way, and time after time have given me new courage to face life cheerfully, have been Kindness, Beauty and Truth." ☆

Digital Frontiers

Ed Lantz
Visual Bandwidth, Inc.
1290 Baltimore Pike,
Suite 111
Chadds Ford, Pennsylvania
19317 USA
ed@visualbandwidth.com

Digital Frontiers

This is our second special topic issue with four invited papers on Digital Domes and Future of Planetariums. Carter Emmart, the "Von Del Chamberlain" of fulldome interactive storytelling, shares his vision for guest lectured, tele-collaborative immersive presentations, interactive instruction, and discussion. Carter and other digital dome storytellers and pioneering the movement away from straight pre-rendered shows to the more traditional planetarium style of interactive storytelling - backed by a powerful digital database, real-time simulations, and wideband interconnectivity. Chris Fluke and Paul Bourke of Swinburne University of Technology in Melbourne, Australia discuss the advantages of single-projector fulldome projection over multi-projector systems. In a separate article Paul goes on to describe in detail their mirror-based system which is simple, inexpensive, and especially well suited to small domes and portables. And Mark Matthews from independent fulldome consultant Visual Acuity Ltd. discusses digital domes and the viewer experience.

Please keep the fulldome papers coming. This is a great time to help define what digital technologies can and should do (or should not do) for planetariums. Debate is healthy and instructive and we'll all be the better for it. Also don't forget to check out Steve Tidey's *Forum* responses earlier in this issue to the topic of fulldome video.

This past year was witness to a flurry of activity in the fulldome world. Here are some of the highlights.

Spring was kicked off by the MAPS conference, held at the Fels Planetarium in Philadelphia, Pennsylvania. The conference was host to several fulldome vendor booths and demonstrations, including Sony's new SRX-R110 4096x2160 pixel, 10,000 lumen liquid-crystal-on-silicon (LCoS) projector. The projector was projected over a portion of the Fels' dome by Sky-Skan who is reportedly working on a fulldome version of the system utilizing two projectors.

DomeFest 2005 kicked off the summer with their third annual "fiesta de la dome" at the Lode Star Astronomy Center in Albuquerque, New Mexico, USA (see Jennie Zeiher's article "DomeFest 2005," *Planetarian*, Vol. 34, No. 3, Sept. 2005). In addition to many excellent fulldome art pieces (see www.domefest.com), we screened *Moleculariam: Riding Snowflakes*, a computer animated program that introduces the concept of atoms and molecules in an entertaining way with catchy songs and colorful characters. Produced by the Rensselaer Nanotechnology Center, in cooperation with Nanotoons, Molecularium is one of the finest children's educational fulldome programs, with an engaging story, catchy tunes and colorful characters that appeal to all ages. We also saw a preview of IMAX director/producer John Weiley's first fulldome project *Heart of the Sun*. John's pioneering interest in this new medium bodes well for us all.

The ACM/SIGGRAPH conference, held on July 30th to August 4th, featured two dome installations (www.siggraph.org/s2005). Upon entering the SIGGRAPH registration area, attendees were treated to the Full-Dome Animation Theater sponsored by Sky-Skan, featuring clips from DomeFest 2005 with

Immersive Cinema Workshop leaders enjoying Espinho's shopping district (from left to right: Robin Sip, Ian Dyer, Tim Florian Horn, Staffan Klashed, Ed Lantz, and Michael Daut). Photo Courtesy David McConville.

DigitalSky on a 9.1-meter dome. The theater was part of SIGGRAPH's Computer Animation Festival chaired by Samuel Lord Black. Another dome installation at NVIDIA's tradeshow was presented in cooperation with Elumenati (www.elumenati.com). A variety of content was screened including scenes from *Sonic Vision*, *Passport to the Universe*, and *Search for Life* from AMNH's Rose Center for Earth and Space, Molecularium, Scott Hessels and Gabriel Dunne's *Celestial Mechanics* (www.cmlab.com), Uniview from SCISS (www.sciss.se), and the Elumenati's *Optical Nervous System*.

Across the pond, the first Immersive Cinema Workshop was held September 12-16 at the Navigar Foundation's Centro Multimeios de Espinho located in the coastal city of Espinho, Portugal. The beautiful facility includes a planetarium, large format film theater, astronomical observatory and library, and exhibition gallery. A temporary definiti fulldome system was provided by Sky-Skan Europe. In addition to the workshop material and screenings, Mirage 3D debuted their new fulldome program *Origins of Life*, long time dream of Robin Sip. The show features photorealistic renderings chronicling the evolution of life on earth. The Navigar Foundation also showed excerpts from their ongoing fulldome production *Camping with the Stars*, produced in cooperation with Appia Films. Appia is using a unique rendering technique that reproduces a 2D cell animation style that was used in the original slide-projector version of the show.

The week-long Immersive Cinema workshop was attended by 18 students from 8 countries. Instructors included: David McConville, The Elumenati; Ed Lantz, Visual Bandwidth, Inc.; Harald Singer, Livinglobe; Johan Gijsenbergs, Sky-Skan Europe; Michael Daut, E&S; Robin Sip, Mirage 3d; Staffan Klashed, Sciss ab; Tim Florian Horn, Hamburg Planetarium; and Ian Dyer, Seos, Ltd. Selected workshop notes are available on the website at http://fulldome.multimeios.pt. In addition to an excellent course, the workshop proved to be a major networking opportunity for the European fulldome community. Workshop organizers encouraged lengthy dialog and debate regarding the impact of fulldome technologies on planetariums. Topics ranged from fulldome projection systems, pre-rendered and real-time 3D production, audio production, cinematic live-action, alternate fulldome venues and the history of immersive spaces. Many thanks to Navegar Foundation organizers António Pedrosa, Pedro Russo, Luís Calçada, Mariana Barrosa and all the lecturers and attendees. We hope this is the beginning of an annual European gathering for the fulldome community.

The IPS Fulldome Committee hosted a series of three industry forums and standards meetings led by Ryan Wyatt and myself. The DomeFest meeting attracted a number of fulldome artists and producers. In addition to advancing the developing standard for mastering and distributing fulldome programs, other needs were discussed including an IPS Guideline for Full Dome Production. This document would include guidelines for producing pre-rendered and real-time programming, including quality standards, market analysis, sample budgets and more.

This meeting was followed by two similar fulldome meetings, one at the Western Alliance Conference (DMNS in Denver, Colorado), and a second at the Immersive Cinema Workshop (Espinho, Portugal). Catch up with the latest on these fulldome meetings at Ryan Wyatt's website http://research.amnh.org/users/wyatt/Community.

On October 16th Ryan Wyatt led a "Future of Fulldome" panel at the Association of Science Centers (ASTC) at the Science Museum of Virginia. Panelists included Dr. Jeffrey Kirsch (Executive Director of the Reuben H. Fleet Science Center in San Diego), David Beining (Director of the LodeStar Astronomy Center in Albuquerque), and Alex Barnett (Director of the Chabot Observatory and Science Center in Oakland). The emphasis was on a CEO-level understanding of the fulldome medium in planetariums. The session was recorded, so if you'd like your CEO to listen to it, you can buy it online at http://www.conventionrecordings.com.

Also at the ASTC conference, Spitz, Inc. presented its second Fulldome Video Showcase at the Science Museum of Virginia's 23-meter diameter Ethyl IMAX Dome Theater. The 75-minute showcase launched Big Screen Day at ASTC. The theater was temporarily fitted with Spitz's ESky II fulldome video display system. Presentations included scientific visualizations, show trailers and excerpts, and experimental music and art productions and utilized the theater's surround-format audio system.

At last count on the Fulldome Compendium *ONLINE!* (www lochness.com) there were 161 fulldome theaters worldwide, with 80 of these in the U.S. The number of fulldome theaters now outnumbers the number of IMAX Dome theaters in the world! ☆