

Digital Planetariums for Everyone: Astronomy Visualisation in Reflection

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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, our recently developed MirrorDome uses light reflected from a spherical mirror to illuminate the dome, providing an affordable alternative that might change the way audiences experience planetariums in the future.

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

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

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 became 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 (Colless et al. 2001), 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: What a Star!*"

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

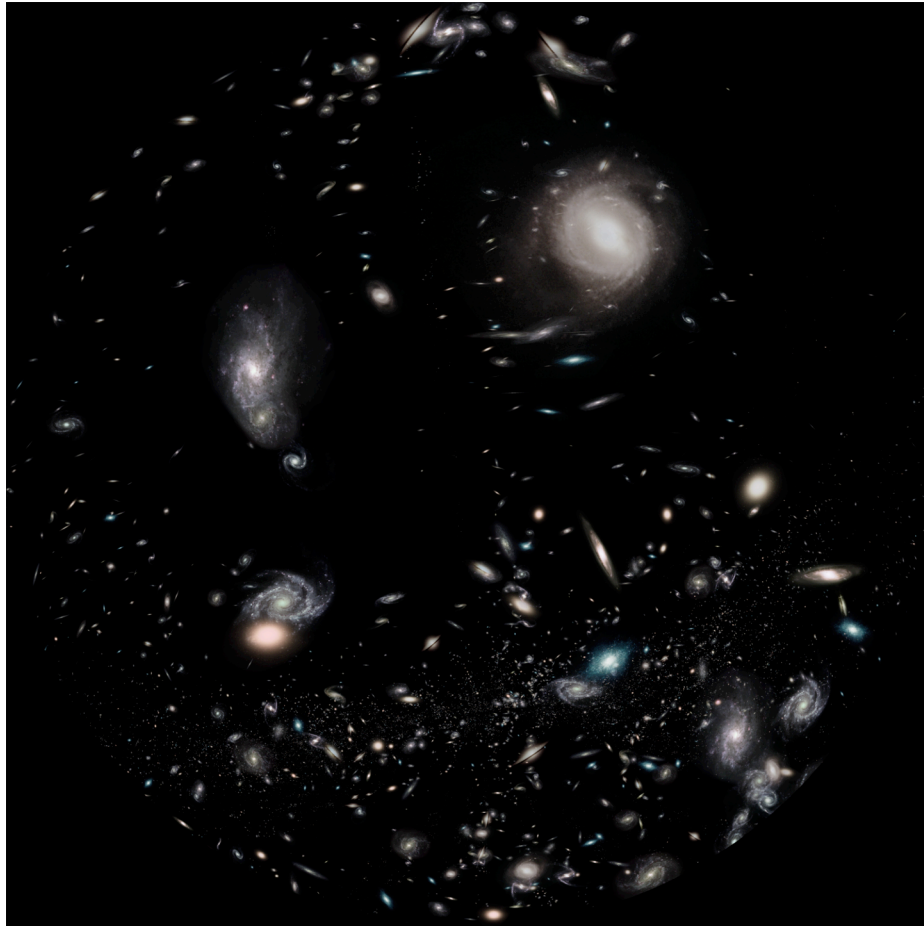


Figure 1: A Flight Through the Universe: a dome master from the 2dF Galaxy Redshift Survey sequence. Galaxies are in their correct spatial locations, but sizes have been scaled up by a factor of 100.

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,³ 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,⁴ and with the support of Spitz Inc, these shows were translated into Spanish for display at the Papalote children's museum in Mexico City. Then in mid 2004, Paul Bourke had an idea about dome projection...

³ <http://ftpwww.gsfc.nasa.gov/tharsis/mola.html>

⁴ At the time of writing the fifth show, "*Spinning in Space*", was nearing completion, and pre-production had commenced on show six.

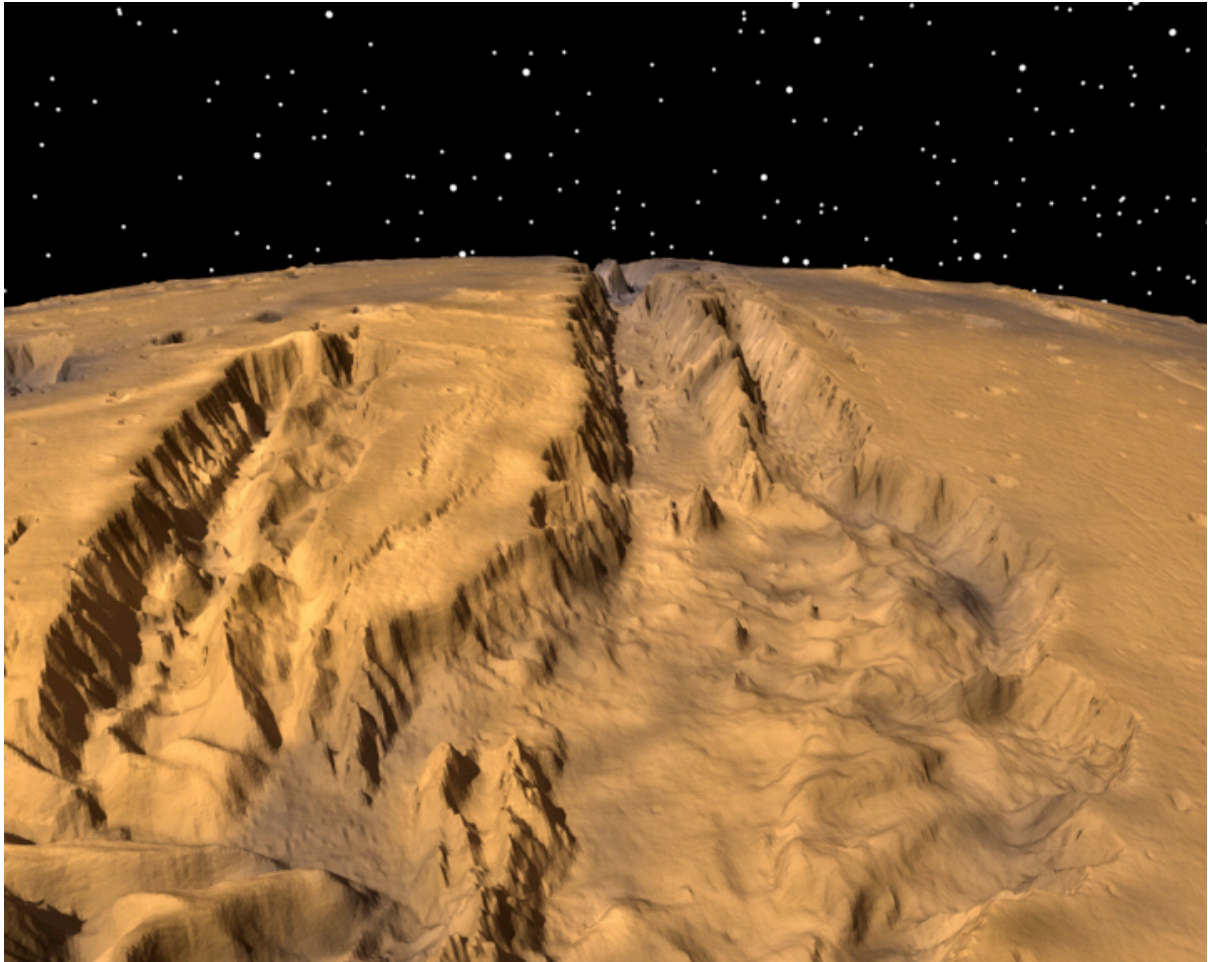


Figure 2: A view down Mariner Valley from the Swinburne stereoscopic production *Elysium 7*, using the Mars Orbital Laser Altimeter dataset of Mars Global Surveyor. This was the forerunner of our Mars sequence for *Infinity Express*.

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 (~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).

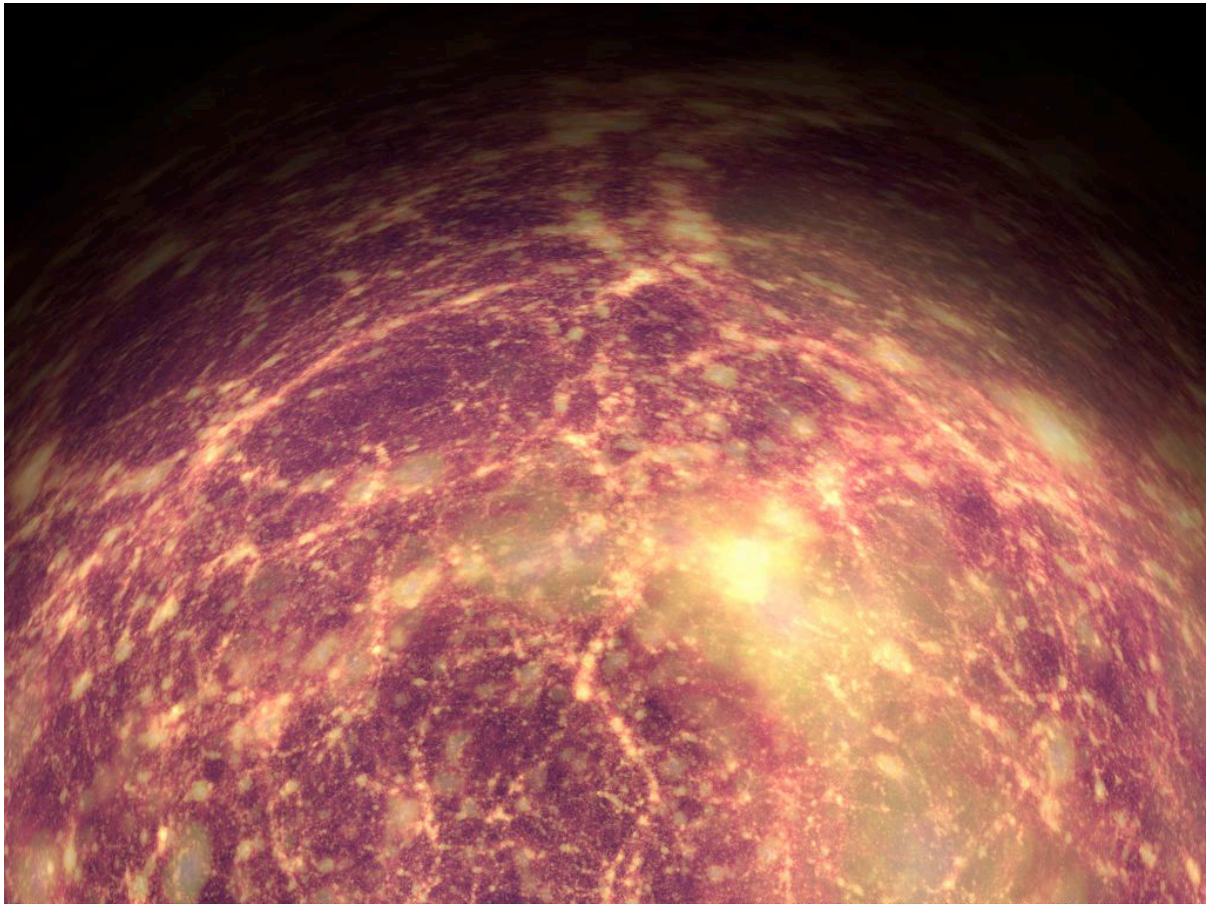


Figure 3: A warped image showing the large-scale filamentary structure of the Universe ready for projection with MirrorDome. Simulation by Dr Chris Power, visualisation by Evan Hallein & Paul Bourke.

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 Display⁵) using a plane mirror, a convex mirror and a single projector to fill a space 270 degrees horizontally by 100 degrees vertically (Iwata 2004). Images were filmed by reflection in a spheroidal mirror so they could be projected without distortion. 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.⁶ Although other people had tried similar ideas in the 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.

⁵ See http://intron.kz.tsukuba.ac.jp/vrlab_web/enspheredvision/enspheredvision_e.html

⁶ <http://www.arcscience.com/omni.htm>

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.⁷ 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, MirrorDome is 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.⁸ As of 5 September 2005, there were 1357 domes of known diameter⁹ (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

⁷ 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/>

⁸ Tallying The World’s Planetarium Attendance by Mark C. Petersen, Loch Ness Productions, available from <http://www.lochness.com/pltref/attend.txt>

⁹ We have excluded the 367 domes of unknown size

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.¹⁰

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 MirrorDome as we 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 future¹¹. 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 MirrorDome 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

¹⁰ For example, in the Swinburne VRT, we operate the projectors in economy mode rather than full brightness, as the contrast appears better.

¹¹ “The Past, Present and, Future of Full Dome, Full Colour, Single Projector Digital Planetariums.” Available from <http://www.fulldome.org/images/stories/IPS2004>.

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 MirrorDome affects 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 to MirrorDome here, as reflected light does not suffer from this refractive effect. However, we should not forget that MirrorDome is 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 MirrorDome 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 for MirrorDome 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 MirrorDome 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. Why give up the best seats in the house to the projector?
6. Capital costs, cost & ease of maintenance. Another win to SP, and MirrorDome slightly edges ahead of fisheye – in order to upgrade to a higher

resolution, brighter projector, the only change that is required is to swap the projectors over. For fisheye, it is usually necessary to purchase a new lens. With a less expensive upgrade path (remembering that the general trend is for projectors to increase in resolution and brightness, but fall in price over time), we believe that MirrorDome is a viable entry point for small domes who would like 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, there are no patent issues with MirrorDome - in fact, we would 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.

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 requirements 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, to account for differences in path length from 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.



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.

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 (e.g. Norris 1994).

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.¹² 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.

¹² 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.

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 (Abbott et al. 2003; 2004) and large-scale numerical simulations (Tueben et al. 2001)] 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 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 1000 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 ~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).

With the development of MirrorDome, 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.

As we write, our own inflatable dome has just arrived from Avela Corporation, and we have handed over the first MirrorDome system to Melbourne company Journeyman Cosmodome to be used in school educational and holiday activities. The future looks very bright for digital domes of all sizes, and we hope that our ideas will continue to help inspire a fascination in the Universe, through research and public education.

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