Visualization brings them together at the Gates Planetarium

Daniel Neafus
Planetarium Operations Manager
Ka Chun Yu
Curator of Space Science
Denver Museum of Nature & Science
2001 Colorado Boulevard
Denver, Colorado 80205 USA
Abstract: The Gates Planetarium has been open for four years as a digital fulldome theater. Although the majority of the public shows are in the form of 20-minute pre-rendered movies, we continue to explore visitor programming of longer duration featuring live presenters. To support these alternative shows, specialized software has been developed in house and by contractors, allowing us to investigate opportunities that would not have been possible in a traditional planetarium. We also continue to embrace the use of new tools, techniques, and hardware. The ongoing evolution of visualization hardware has enabled significant improvements to be made over the original 2003 installation. Because of these subsequent updates, we are in a stronger position than ever to offer continuing innovation in science education and artistic programs. Our systems now have long-term sustainability, and with each improvement, the potential for expanded programming increases. Although many of the ideas that we have adopted are not unique to the Gates Planetarium, collectively they may serve as an example for other digital planetariums and suggest how domed theaters can evolve and stay relevant for the 21st century.
The Gates Planetarium at the Denver Museum of Nature & Science (DMNS) reopened in June 2003, after a four-year renovation. The original facility, built in 1968, was a level 50-ft (15.2 m) dome with concentric seating and hosted a Minolta optical mechanical star machine. Construction of the new Gates Planetarium was constrained by the existing DMNS building. Structural supports confined the dome to a diameter of 55.5 ft (16.9 m), but it is now tilted by 25°, with the audience placed in a unidirectional seating arrangement. Fundamental to the theater design are the performance stage and an array of theatrical hardware, including automated spotlights. Sixteen channels of surround sound and a Lake Huron 3D digital sound processor were installed to complete the immersive aural experience.

The modular video, audio, and lighting systems are controlled via a single 12-in Crestron touch panel (Conte 2003), which allows the audience experience to be finely tailored for each show. As soon as a visitor enters the dome, he is welcomed with colorful imagery for each show. As soon as a visitor enters the dome. As the main program starts, the audience placed in a unidirectional seating arrangement. Fundamental to the theater design are the performance stage and an array of theatrical hardware, including automated spotlights. Sixteen channels of surround sound and a Lake Huron 3D digital sound processor were installed to complete the immersive aural experience.

The innovative programming that followed was not only made possible by this move, but could only have happened in a digital fulldome environment. The Gates Planetarium itself has become an important resource for many of the departments at DMNS, which have started to rely on it for programming needs. Our repeat audiences also recognize its value, with many returning time after time to participate in ever-changing and diverse offerings.

As we are guided by our experience from the last several years, we see a promising future where toolsets will continue to be refined; collaborations are built with a wide range of individuals and organizations; and technical challenges are resolved to allow us to evolve and move forward. These various efforts allow us to maximize the potential of the facility and expand the breadth of visitor programming.

1. Theater Operation

DMNS management required that the Gates Planetarium be a multi-use environment with unique features. A streamlined staffing and operations model made the planetarium fit within the new organizational structure of the museum. As of this writing, only the operations manager (author D. Neafus) and the planetarium systems administrator (Z. Zager) are dedicated to the planetarium on a fulltime basis, making it necessary to utilize the skills of many other individuals, both inside and outside of DMNS.

The other author, K.C. Yu, is a curator within the Research and Collections Division at DMNS, and can devote less than 20% of his time to planetarium operations. Media developer M. Brownell is another DMNS staff member who can dedicate nominally 25% of his time, yet has been crucial in designing and creating many of the secondary systems and operational procedures.

Finally, J. Schoemer spends 15% of her time as program manager for the pre-rendered shows. The relatively small operations group has been quite successful, leveraging available resources and cross-training staff, so that any one person has multiple skills that may include projector maintenance, video alignment, audio patching, re-programming light settings, and computer systems administration.

A dedicated group of DMNS volunteers have also been instrumental in helping to maintain the systems. Since the start of the Gates renovation, we have contracted the work of specialists from beyond the traditional planetarium community, including lighting designers, high-end audio specialists, sound editors, and Crestron control programmers.
2. Real-time Astronomy Shows

When the old Gates Planetarium was demolished in May 2001, there was only one effective way to create real-time virtual environments which could be shown in a high resolution, multi-channel display environment. SGI had pioneered the Reality Center, an immersive display wall using two or more edge-abutted projectors (Helsel 2000). Graphics software running off an Onyx (or comparable) class computer could generate frame-synchronized imagery as viewed from different camera angles. By matching these virtual camera angles to the view frustums in the display system, a high-fidelity virtual reality (VR) scene could be generated for the display surrounding the observer. In addition to the hardware, the creation of immersive environments requires specialized software.

Cosmic Atlas was a DMNS in-house project started in Fall 2000 to create real-time interactive software that would replace the mechanical star machine. The virtual solar system (and eventually, the Milky Way galaxy) would be built using standard simulation techniques, written in ANSI C and using SGI’s proprietary scene graph Performer OpenGL (Eckel & Jones 2000). The software would run on the Onyx that was previously planned for the Gates Planetarium, as well as on other platforms for which Performer releases were available, including, at the time, Redhat Linux.

The Cosmic Atlas (CA) team consisted of project managers (one of the authors, Neafus, and H. Cook), a graphics programmer (N. Jenkins of Nebulus Design), and a scientific programmer (one of the authors, Yu). The program model was in part inspired by, as well as expanded on, the achievements of the Digital Galaxy project at the American Museum of Natural History (AMNH), and was later adopted by SGI for their Digital Universe software that was eventually installed at the Beijing Planetarium. CA was built with emphases on scientifically accurate object ephemerides, flightpath- and timeline-based show development tools, and a software architecture intended for use in the dome as well as on standalone Linux machines and hence for on-floor interactive museum exhibits (Yu & Jenkins 2004). Its replication of traditional optical/mechanical star machine functions required sophisticated orrery functions for the solar system, advanced options for showing constellations and deep sky objects, and the ability to toggle unique didactic information and grids (Yu 2004). Show development tools included capabilities for saving out camera flightpaths in the form of keyframes, a timeline-based show editor, and the ability to render out show frames.

These features were used to create visuals in the tour of the solar system show, Cosmic Journey, which opened the new Gates Planetarium. Since the Performer OpenGL libraries were available on Linux, virtually all of the software development could be done, before the purchase of the SGI Onyx, on inexpensive machines running the open source Redhat OS. To prototype shows and prove the viability of the proposed digital display system, DMNS contracted with SEOS Ltd. to provide a miniature 3-m version of the dome. This “mini-dome” generated a great deal of attention and was popular for DMNS fundraisers in addition to its primary software development purposes. Not only could the CA software be tested within an immersive multi-channel display system, but the flight paths utilized in the opening show could also be refined within a domed environment. Once the full-sized theater was operational, the mini-dome became obsolete and has since been donated to a local university.

2.1 Post-Opening Challenges

The original plan for playback was to stream the frames of our first show, Cosmic Journey, from the Onyx. A custom movie player program was written to pull the two terabytes of uncompressed 1280 x 1024, 60-fps, full-resolution frames from the hard drives for all 11 graphics channels. However, in the months after opening, technical issues surfaced that forced us to reconsider this approach. Video glitches appeared that would result in synchronization mismatches between adjacent graphics channels. Frame freezing in one channel might cause it to hang completely through the duration of the playback, ruining the show. Despite repeated efforts to track down the problems, neither the in-house technology team nor the SGI support engineers could pin point a source for the video bugs, which neither repeated in the same spot on the time code nor appeared with any apparent pattern. The complexity of the Onyx made it uncertain whether the synchronization errors originated in the disk drive reads or downstream in the individual graphics pipes. The unavailability of expensive spare parts limited our options for “experimental” swaps of hardware to test for points of failure.

Four months after the Gates re-opening, we moved the playback off the Onyx and over to a set of twelve QuBit DS digital video servers from QuVis, Inc. The new playback units were purpose-built, rack-mountable worksta-
tions which used proprietary wavelet compression algorithms (of order 10:1) to stream synchronized video from 144 GB SCSI hard drives at the required frame rate and quality. Despite the large outlay for this remedial technology, the QuBits units proved to be a wise investment by providing consistent playback performance day-in and day-out. Their swappable drives held multiple shows, and backup storage was in the form of inexpensive commodity drives.

2.2 New Opportunities

Having a reliable set of video servers meant that the daytime public shows ran consistently and nearly trouble free. And perhaps almost as important, liberating the SGI Onyx from regular show playback (anywhere from 15 to 21 shows per day) allowed us to explore and expand the programming capabilities of the visualization supercomputer. This allowed us to promote the use of the dome for non-traditional events during off hours, with experimentation and content development from both of our image generation systems.

The QuVIS servers were often utilized for special events. For example, a book reading and signing by Nancy Conrad, wife of astronaut Pete Conrad, was held inside the Gates Planetarium with a nearly two-story image of the book cover displayed behind the author on the dome. For another private event, a short fulldome animation was created by a local contractor and shown at an early morning marketing rally held at the Gates Planetarium by an international corporation for its employees. In December 2006, DMNS hosted astrophysicist John Dubinski for an evening talk, “Future Sky: A Whimsical Look at the Ultimate Fate of the Milky Way,” on the future collision between the Milky Way and Andromeda galaxies. Dubinski rendered out into domemaster frames a numerical simulation (lasting a billion years in simulation time) of the collision using 30 million particles representing both stars and dark matter particles. The viewpoint of the observer in the animation was located at the Sun, which, in this particular simulation, was ejected into a highly eccentric orbit where it would then plunge repeatedly through the merging galactic nuclei. The effect of this “yo-yo” orbit through the maelstrom of tidally-striped stars was a vertiginous experience for the audience. They were able to witness the galaxy collision as part of the action, instead of viewing it remotely, something possible only with a digital fulldome theater.

3. Fulldome Post-Production

For its second pre-rendered fulldome show, DMNS licensed Passport to the Universe from AMNH. Although the program was reformatted for unidirectional tilt-dome theaters, the formatting was not done with the Gates Planetarium in mind. After consent from, and a subsequent thorough review by, AMNH production staff, the DMNS production team made slight edits to much of the show. This included re-tilting frame sequences in several critical scenes to bring the focus of attention closer to the Gates dome sweet spot; re-scaling domemasters to hide visible wedges of missing content that showed up as a result of the tilt work; and even moving inorganic animations from the center of the domemaster to the sides.

This post-production work was made possible by Remapper, a critical piece of original software written by N. Jenkins, who continued to write real-time software tools for show development for DMNS. Remapper is an all-purpose fulldome show editing tool, built with Performer OpenGL, and runs exclusively on the SGI Onyx. It is similar to other timeline-based video editing tools such as Adobe AfterEffects or Apple’s Final Cut Pro. It loads fulldome domemaster frames (Spitz 2005) from hard drives, but instead of displaying the frames within a video window, it re-proj ects them onto a virtual hemispheric dome. Using Remapper, the entire dome itself becomes a real-time, nonlinear editing suite. Not only could timeline-based scrubbing and scene transitions be previewed, performed, and seen in proper context from Remapper, but the domemaster frames could be manipulated within the virtual environment. Frames could be tilted by arbitrary angles, rotated azimuthally about the central axis, and scaled so that the edge of the domemaster stretched greater or less than 90° from its center. Keyframes for scaling and orientation settings could be saved and interpolated via splines to create seamless transitions for final rendering.

Like the vast majority of other planetariums, the Gates Planetarium is its own unique space. Other facilities will most likely not have the same seats, the same lean in the seat backs, the same seat row arrangements, and other environmental factors. Thus no single set of show domemaster frames can be universally run at multiple facilities without some compromise in visitor experience. We were fortunate to have Remapper to make slight visual tweaks to the frame sequences and optimize the viewing experience for our audiences. Our positive experience with this post-production step led us to use Remapper for editing subsequent AMNH shows, including Search for Life and Cosmic Collisions. Remapper also proved to be crucial for our own show development, for re-formatting raw frame sequences used during the production of Black Holes: The Other Side of Infinity (Yu et al. 2007a).

4. Innovative Programming

After the purchase of the QuBits players, the availability of the Onyx supercomputer led to a number of unique experiments with the real-time visualization system. These tests have stretched the boundaries of what it means to be a planetarium, and revealed the near limitless potential of fulldome theaters.

4.1 Education, Star Talks, and Classes

Although DMNS management had no
plans to offer frequent public star talks given by a live presenter, we continued part-time development and actively used the CA software after the 2003 re-opening. CA was extended beyond the solar system with a galaxy flythrough module. Instead of restricting the virtual model to the limited volume number of known surveyed stars in three-dimensional space (e.g., the 118,000 stars in the HIPPARCOS Main Catalog; Perryman & ESA 1997), the CA Galaxy statistically generates realistic stellar populations, allowing the user to navigate through a completely populated Milky Way. The original CA software, as well as the new Galaxy Flythrough module, were used in a number of experimental classes. Freshmen astronomy students from the nearby Metropolitan State College of Denver (MSCD) were brought in for two test sessions in Fall 2003. A year later, a six-week adult education course on general astronomy for DMNS members was taught relying on CA (Yu 2005). For these trial classes, regular sky motions, phases of the moon, and seasons were explained from both an Earth-bound perspective as well as from space. Comparative planetology could be done with flybys of the relevant bodies within the software. Galactic structure could be shown by examining the Milky Way from both within and from outside the galaxy.

As a result of these early tests, experimental star talks continue today and are run by the planetarium volunteers on a monthly basis as Colorado Skies. The preliminary success of using CA in astronomy instruction and in informal public outreach has also resulted in a parallel effort in educational research at the Gates Planetarium. The development of CA was instrumental in bringing in a National Science Foundation-funded educational research project to study the use of digital planetariums for teaching astronomy. Astronomy Learning in Immersive Virtual Environments (or ALIVE; NSF ROLE #0529522) is led by author and Principle Investigator Yu, and completed the first semester of in-dome datataking in Spring 2007. This collaborative study with Kamran Sahami, assistant professor of physics at MSCD, will help identify the best ways to use visualizations like CA to teach astronomy within an immersive setting. Quantifying the effectiveness of such techniques for this new technology will help justify the use of real-time visualization software and fulldome theaters in general.

4.2 Black Hole Flight Simulator
Andrew Hamilton, an astrophysics professor from the University of Colorado at Boulder, spent a year-long sabbatical working with N. Jenkins at DMNS in 2001-2002. Starting with visualizations and computer models that he had created prior to this, Hamilton followed the Cosmic Atlas model and built his Black Hole Flight Simulator (BHFS) using Performer OpenGL, allowing it to run on both Linux and IRIX platforms. The BHFS is a real-time interactive flight simulator that allows the user to pilot an imaginary spaceship around a black hole, with realistic depiction of special and general relativistic effects, including gravitational lensing, redshifting, and time dilation. In addition to a simple Schwarzschild black hole, the BHFS implements a charged black hole using the Reissner-Nordstrom formulation, allowing the user to explore the mathematical possibilities of wormholes to parallel universes (Hamilton 2004). The BHFS became an important resource for securing National Science Foundation funding, as well as generating visuals, for DMNS’ Black Holes: The Other Side of Infinity planetarium show that has been licensed by digital planetariums worldwide.

4.3 The IMAGE_PAN Viewer
The Spirit and Opportunity Mars Exploration Rovers landed on Mars in January 2004. As public excitement and interest in the missions grew (e.g., Harmon 2004), we wanted to be able to show the large format images that were being released to the public on a regular basis from the mission websites without compromising the original resolution and detail. Using a scene graph framework that had been designed by N. Jenkins, author Yu wrote a general purpose image viewer in Performer OpenGL that would run on the in-dome Onyx system and on Linux machines. IMAGE_PAN, as this was known, allows high-resolution images to be displayed on appropriate geometries within a virtual environment. A user navigates the environment in real-time, with camera movement approximating zooms and pans. The image size is restricted by limits on texture resolution (4096 x 4096 on the Onyx InfiniteReality4 graphics pipes). By judicious use of geometries for texture mapping, both “flat” 2D images as well as in-the-round image sets, such as those intended for display as cylindrical or spherical panoramas, can be shown in their correct perspectives. An in-dome presentation can thus be made with a live narrator who uses IMAGE_PAN to show PowerPoint-like explanatory “slides” and single images, as well as panoramas which in the immersive Gates Planetarium can literally transport the audience to Mars.

IMAGE_PAN has been used for a variety of presentations. It regularly appears in our 60 Minutes in Space program, which is given by curators in the Space Sciences Department at DMNS. The audiences to these monthly events learn about the latest astronomy and space science news in the planetarium while exposed to full (or near full) resolution images shown via IMAGE_PAN. The SGI Onyx and IMAGE_PAN were featured at a high-profile presentation, “Recent Star and Planet Formation in our Galactic Neighborhood,” given by John Bally, a professor of astrophysics from the University of Colorado at Boulder, during the Western
Alliance Conference (WAC) of planetariums in September 2005. Bally pointed out high resolution detail made visible by IMAGE_PAN’s camera zooms, and relied on all-sky panoramas to show the locations of objects in the context of the entire sky. The sky, as photographed in the optical by Axel Mellinger, and mapped by 2MASS, IRAS, WMAP, and the Columbia University carbon monoxide (CO) surveys, provided yet more vivid contrasts from throughout the electromagnetic spectrum. In July 2006, noted amateur astrophotographer Axel Mellinger himself came to DMNS to give his lecture “Starfire, Dust, and Dreams: A Panoramic Image of the Milky Way,” on his photographic techniques with a highlight being a tour of his all sky map on the Gates dome.

4.4 Spherical Panoramic Travelogues

DMNS has long offered lectures given by world explorers. They share stories, pictures, and films from their adventures to museum audiences. At the same time, panoramic image creation has interested photographers long before digital photography became widespread (Meehan 1996), while similar techniques were shared previously by artists to create the landscape dioramas found at DMNS and other natural history museums (Wonders 1993), and in the even earlier medium of panorama painting (Comment 1999). Digital photography has made image panoramas much easier to create and distribute to a wide audience in compact formats like QuicktimeVR. Author Neafus has wished to expand on past travelogue offerings by utilizing the immersive qualities of the Gates Planetarium as a backdrop to the lecturer, and IMAGE_PAN. PAN turned out to be an appropriate tool for such a task.

One of the panoramic photography field’s most noted practitioners is Greg Downing, who presented four sold-out lectures, “Around the World in 360 Degrees,” showcasing his panoramas in the Gates Planetarium since 2005 (Bienas 2005). Downing’s talks were virtual travelogues, taking audiences to dozens of locales around the world via his high-resolution immersive photography. Working with author Yu, Downing choreographed the motion of each panorama, determining which part of the panorama an audience would face initially and how the view would be panned to reveal previously hidden parts of the image. A significant benefit of the interactive nature of IMAGE_PAN was demonstrated by the presenters when they went off script to follow audience requests to examine portions of the panorama in more detail.

Similarly, Barry Perlus from Cornell University’s Department of Art demonstrated his panoramic photos of the 18th century Jantar Mantar astronomical observatories at Jaipur and New Delhi, India for the WAC 2005 conference. Perlus gave a tutorial on how these mammoth stone structures were used as astronomical instruments, to track the movements of celestial bodies, and to tell time. But more importantly, the presentation was foremost an immersion within high resolution recreations of the observatory spaces. It placed the audience inside the unique architecture, which contained arcing ramps, inverted bowls, cylindrical loggia, and other non-rectangular forms.

Although they have yet to give public lectures at DMNS, we have also tested panoramic photography from Carla Schroer and Mark Mudge of Cultural Heritage Imaging, and Tito Dupret from the World Heritage Tour. Now that panoramic imagery can be easily displayed with a program like IMAGE_PAN (as well as via features available in vendor software like Evans & Sutherland’s Digistar 3, SkySkan’s Digital Sky, and SCISS’s UniView), the fulldome theater is no longer restricted to visual content from just the space sciences.

4.5 Geology Visualization

In an effort to demonstrate how the planetarium could be utilized by the museum curators, DMNS geologist Marieke Deschene was able to convert the 3D GIS-based geological model of the Denver Basin that she was building with colleague Bob Raynolds into a format that could be imported into IMAGE_PAN. The Denver Basin model is based on analysis of over 100 wells, and represents the geometry of the Laramide synorogenic sediments built up over the last 75 million years beneath the Denver metropolitan area. The model is an innovative tool for rapidly growing communities reliant on the groundwater contained

---

2 www.gregdowning.com

3 Perlus’ panoramic photographs and 3D visualizations form the core of c-www.jantarmanantar.org, a web-based research center about the observatories.

4 www.c-h-i.org

5 www.world-heritage-tour.org
in these sediments. IM-PAGE PAN had the capability of loading 3D models, using software functions from Performer OpenGL. This allowed us to import a variety of source models from geology, geography, and chemistry, allowing the Gates Planetarium to be used as a general-purpose VR theater. The three-dimensional structure of the sedimentary layers revealed by the Denver Basin model was shown to geology classes as well as oil industry basin modeling professionals in 2005-2006.

Geology visualization in the dome from a more entrepreneurial standpoint occurred in October 2004, when Landmark GeoProbe® software was showcased at DMNS in an event tied to the Society of Exploration Geologists (SEG) conference that was held in Denver that year. Landmark, a brand of Halliburton Drilling, Evaluation, and Digital Solutions, is a leading supplier of visualization tools, software, and optimized computing solutions for the upstream oil and gas industry. Since Landmark GeoProbe® software was designed to run on multi-channel SGI machines, it only took a small effort to reconfigure this application for the DMNS Onyx. The presentation, designed and coordinated with software engineers and marketing personnel from Landmark, was shown to oil company executives at a VIP event, as well as to a group of SEG conference attendees on the following day.

5. Linux Visualization Cluster

In the years since our purchase of the Onyx 3800, the graphics processing unit (GPU) industry has expanded at an accelerating rate. Driven by market forces from the multi-billion dollar video game industry, GPUs now have processing power that surpasses that of the CPU. A 3 GHz Pentium 4 can theoretically calculate 6 billion floating point operations per second (6 gigaflops); an NVIDIA GeForce FX S900 Ultra card, however, can return a 20 gigaflop performance (Buck & Purcell 2004). The steady increase in processing speed of GPUs, in fact, is faster than that given by Moore's Law, 6 ensuring that GPUs will continue to outpace CPUs for the foreseeable future.

The fast evolution in performance of consumer-level graphics cards has led to the obsolescence of Onyx 3800 hardware in many performance categories. The increasing capabilities of standard PCs compared to the cost of its high-end workstations was a blow for SGI (Preimesberger 2005), and was a strong factor in its Chapter 11 bankruptcy filing (Kawamoto 2006). But even in Spring 2005, before these turns of events, our DMNS planetarium technology team had another set of problems to deal with. The hardware support contract for the Onyx was too expensive to maintain indefinitely. A new solution for in-dome real-time visualizations would be needed.

After consultation with the Infiscape Corporation, we decided that PC workstations sporting high-end GPUs were capable of matching our interactive real-time needs while possibly even exceeding the graphics performance that we had come to expect from our Onyx. The cost for acquiring such a system, moreover, would only be a fraction of that of purchasing the SGI equipment. Maintenance costs would not only be significantly reduced because of the use of commodity components, but we would not have to rely on individuals with specialized training to troubleshoot and fix problems. Instead, the knowhow would exist among the IT staff at almost any moderate or large institution.

To get the proof that this was the right direction to go, we needed PC workstations for testing. In December 2005 we acquired three Hewlett-Packard xw8400 workstations, each with a dual-core AMD Opteron 2.4 GHz CPU, 2 GB of RAM, and dual Nvidia Quadro FX 4500 GPUs. In January 2006, Infiscape engineers installed the Fedora Core Linux OS on the machines, as well as a host of VR applications based on OpenGL, open scene-graph architecture, and the VR Juggler application virtual platform. Each machine had four video channel outputs (two from each graphics card), meaning the three machines could provide output to all eleven projectors in the Gates Planetarium plus one additional channel as the control port.

VR Juggler is a VR application development tool. It allows the same application to be run on any VR system, with arbitrary display configurations as well as cross-platform support.

6. Windows Visualization Cluster

The success of the small cluster built from Linux boxes led us eventually to a donation from Hewlett-Packard of a full 12-node PC cluster running Windows XP. This new set of xw8400 workstations were driven by dual Intel Quad-Core processors from the Xeon 5300 line, with 3 GB of RAM, and Nvidia Quadro FX 5500 GPUs (Greiner 2006). The dual quad-core chips meant a total of 96 processors in the twelve machines.

The installation of a Windows cluster was driven by the need for a replacement for Co-

[Image 133x527 to 477x756]
mic Atlas. Re-writing the Performer-based CA code would have taken an enormous amount of resources. The need to switch to a cluster architecture would be a significant expense, but so would the need for developing on a new scene graph, since SGI no longer supported Performer OpenGL. Instead we decided to license SCISS AB’s UniView software, along with the Digital Universe databases from AMNH (Abbott 2006). As part of a collaborative partnership with SCISS, Cosmic Atlas features and orrery code would be migrated to subsequent versions of UniView.

After the hardware setup and software installation, the first public demonstration of the system was for a book reading and signing event with author Dava Sobel in November 2006. The UniView software was used to provide a dramatic and topic-appropriate backdrop inside the planetarium during the reading. Four days later, Intel and Hewlett-Packard jointly held QuaDfest in Denver, a press event for launching Intel’s new Quad-Core chips. After a day-long series of talks and demonstrations, the gaggle of reporters and marketing personnel were brought to the Gates Planetarium in the evening, where UniView was used to take the audience on a real-time journey from low-Earth orbit out to the edge of the observable universe and back again. A follow-up event for visualization researchers and educators took place in January 2007.

Experimental lectures and special events make use of UniView in the dome have continued since then. These include a MSCD college astronomy class, brought in for four separate sessions in the Spring 2007 semester for the ALIVE research project (with more classes to come in the next school year); a lecture on sky motions and the shape of the Earth to a group of first grade students based on recommended science literacy benchmarks (AAAS 1993); as well as museum fundraiser and new member events.

### 7. Real-time Music for Fulldome

Some of the earliest experiments with combining music with visuals in a planetarium setting were the Vortex concerts by Henry Jacobs and Jordan Belson at the Morrison Planetarium. These involved a unique surround sound environment created by some dozen speakers (McConville 2007) with matched visuals created by specially-installed projectors that showed interference patterns, film loops, and kaleidoscopic designs (Youngblood 1970). Vortex was short-lived and ran for only a handful shows between 1957 and 1959. A longer-lasting tradition took hold in the mid 1970s with Laserium, which provided memorable planetarium experiences for many, including the authors. These laser-based rock music shows were pioneered by Ivan Dryer, and became a popular mainstay of live planetarium programming for decades. Planetariums have since also experimented with live musical performances within the dome with lighting and visual effects timed to the music (e.g., Kinsella 1984).

Options for music shows in the digital fulldome theaters have been limited. The once traditional laser systems became impractical, and in a tilted environment, potentially unsafe. Few fulldome shows with pre-rendered animations synchronized to licensed musical tracks exist. SonicVision from AMNH has received wide distribution, including at DMNS. The Mediendom at the University of Applied Sciences, Kiel runs multiple fulldome musical productions within their 9-m diameter facility.\(^7\) The Clark Planetarium runs hybrid fulldome animation and laser music shows with nonsynchronized sound: the *Rock on Demand* classic rock jukebox show and the *enTRANCED* show featuring club trance music.

In each of these cases, the visual, pre-rendered animation takes considerable time and effort to create, requiring a team of dedicated animators. The animations have limited use outside of the musical tracks that they were designed for, unless the new music has similar track length, rhythm, and pacing. A better alternative would be to create real-time software that would allow interactive input from a live video-jockey performance artist (VJ). With the right tools, such a performer could tailor visuals and effects specifically for each song, on the fly. Although such tools are just beginning to come into use (see §7.3), an option that occurred to us was to use our existing real-time software, such as Cosmic Atlas, for musical events.

#### 7.1 Live Music

We explored the use of our real-time visualization tools with live musicians in the dome within a month after re-opening. In July 2003, the Gates Planetarium hosted *Celestial Sounds*, with the Musica Sacra Chamber Orchestra conducted by Michael Shashberger. The 17-piece chamber group (including a string bass and timpani) squeezed themselves onto the stage in front of the first row of seats, giving performances of Haydn’s *Symphony No. 43* and Mozart’s *Jupiter Symphony No. 41*.

The dome’s display showed a projected live flight through the CA simulation to accompany the musicians. The use of didactic grids and markers in the simulation added further visual interest. For the finale of the Mozart symphony, we also made use of a new real-time Gravity Demo by N. Jenkins and Nebulus Design, that allowed the user to interactively control a particle-based numerical simulation of colliding galaxies. The user was able to interactively move the camera around the simulation, control the number of colliding objects, alter simulation speed, change particle size, toggle gravity off (leading to spectacular “fireworks” like effects), switch color tables (based on source galaxy, particle velocity, or particle acceleration), and turn on a faux motion blur that utilized OpenGL frame buffering tricks. The wealth of visual ploys allowed a live presenter to interactively create spectacular visuals that could be timed to match beats and highpoints in the audio performance.

The success of these two shows led to a second set of two concerts titled *Voices from the Silence*, in September 2003, and featured four
vocalists lead by Shashberger. The musical pieces chosen for these performances were for unaccompanied voice, and, as a result, the dome visuals were also kept comparatively low-key. CA was used to put the audiences in space in orbit far above Earth. Stunning, yet natural, acoustical effects were achieved with the sophisticated Gates sound system.

Voices were placed in virtual space to coincide with the actual positions of the performers as they periodically changed their positions, on and off stage. A startling effect was created when the performers were off stage and their poetic readings seemed to come from arbitrary locations in outer space, floating above the audience.

Live visual flythroughs of CA and the colliding galaxies visualizations were used for another event. A private, hour-long, rock n' roll party was held in the Gates Planetarium. VIP attendees had provided requests for musical selections, which were played in the dome with real-time visual accompaniment. Despite the success of these live musical events, the visual variety from CA and the Gravity Demo was still limited. Although we were able to utilize them for special events, the staff and systems could not sustain repeated offerings given over and over on a regular schedule.

7.2 Gaia Journeys

The addition of the more sustainable PC-based cluster and the installation of UniView altered the dynamic of what we believed to be possible. They allowed us to host the most successful and prominent of our live music events yet. Gaia Journeys was conceived by musician and filmmaker Kenji Williams, who was inspired by astronauts speaking of seeing a borderless world from orbit. Williams wanted to deliver this experience to museum audiences by surrounding them with photorealistic virtual depictions of the globe from near-Earth orbit, which would be tightly choreographed to live musical accompaniment (Yu et al. 2007b).

During each of the performances on February 15-18, 2007, Williams played the violin and keyboards, enhancing a previously recorded backing track, while the visuals came from UniView flown live by author Yu. The theatrical infrastructure of the Gates Planetarium provided superb sightlines for the audience, and colorful lighting on Kenji’s performance. The lighting was balanced with the vivid projections on the dome, providing enough illumination for the performance to be recorded in High Definition video for eventual release on DVD. UniView allowed the audience to simulate orbital flight with high resolution imagery and digital elevation maps of the virtual globe paging in dynamically. During the 50-minute program, excursions down to specific locations on the surface of the Earth were made to explore 18 separate, high-resolution spherical panoramic photographs by Greg Downing. The six tracks of audio were 3D spatialized to the 16.1 sound system using the Lake Huron, providing an immersive sound experience to match the visuals.

Gaia Journeys was a hit with our audiences. Although advertised almost exclusively through DMNS’ website and its Members Monthly magazine, the original three shows sold out within a week of the program announcement. A fourth show was added, which sold out within a few days as well. Audience reaction was very positive, with 70% of those submitting post-concert surveys rating the program either a 4 or 5 out of a maximum 5 points.

Of the responses to the question of what they enjoyed most about the program, one third specified only the space and/or panoramic visuals. Another one third cited the entire experience: both the visual and audio integrated as a cohesive whole. When asked what they would like to see changed, one quarter of the respondents found nothing wrong or would like to see more of the same. We found it encouraging that the remaining complaints (e.g., not having adequate information about the visuals, issues related to distractions or the viewing environment) could be mitigated in future performances.
7.3 PhonicFX

N. Jenkins at Nebulus Design created PhonicFX, a real-time interactive VJ tool for the multi-pipe SGI Onyx. Based again on Performer OpenGL’s scenegraph, PhonicFX has half a dozen different visualization modules with user control over the camera motions through these virtual environments. An arbitrary set of musical tracks could be used as source input into the VJ software. The musical beats, amplitude, and waveforms of the incoming stream would drive the visual effects with considerable input from the user.

PhonicFX was used in a handful of informal in-dome experiments, with the live VJ-ing done to user-picked pre-recorded musical selections. Despite the enthusiastic reception by the small test audiences lucky enough to sit in on these events, the software was never rolled out for any public programs. Some questions remained concerning the reliability of the Onyx hardware, but, primarily, Jenkins felt that there was yet again not enough variety in the visualization choices. Although promising to everyone else who witnessed it in action, PhonicFX was deemed not quite ready for the public. (As described above in §3, the evolution of computer systems would soon make the use of PhonicFX on the Onyx a moot point.)

8. 3D Sound Design, Experiments

In addition to the post-production video work discussed in §3, we also found it beneficial to optimize every soundtrack with an audio remix performed for our dome. Just as the projection may appear different from location to location, the sound also varies greatly between venues. Each soundtrack undergoes a final remix in the Gates Planetarium, utilizing a high end ProTools system to rebalance levels. The Gates team has also been quite successful in re-positioning the sounds around the audience, utilizing the Lake Huron to spatialize the sound into 16 channels, derived from the S1 surround mix provided by the shows’ producers.

In September 2005, sound artist Charles Morrow gave a demonstration at the WAC planetarium conference featuring a series of recorded 3D sound productions, varying from sound art to captured environments. These pieces were created using the MorrowSound™ True 3D toolset, which was used to spatialize native 3D sound assemblies, 3D B-Format microphone recordings, as well as binaural, stereo, and S1 sources.

The native 3D works are characterized by strong, clear z-axis motion and by sound fields that extend beyond the brick and mortar architecture of the Gates Planetarium. These productions were played back on our 16-channel surround sound system, modified with the addition of floor level speakers. Eight channels from the MorrowSound system, representing the corners of a room, were positioned in virtual acoustical space with the Lake Huron. Once properly oriented, the sounds completely enveloped the audience, recreating the original acoustical environment. The technique holds promise for future presentations, allowing an audience’s sonic experience to be as rich as the visual one.

The Gates team has also been working with Leslie Gaston, assistant professor of music in the Recording Arts program at the University of Colorado at Denver to create a planetarium audio research group. This association of planetarium staff, sound professionals, and audio students (including a growing number of members from outside of Colorado), is exploring the transferability of surround sound from one planetarium to another.

The goal is to allow audiences at different facilities with different speaker arrangements to have similar audio experiences, and to create software that will make it easy for audio engineers to create such experiences. Acoustics, delivery methods, loudspeaker setups, seating arrangements, source recording, and mixing will all be considered along with the potential of current technology for achieving the goal of transferability. Resources exist on dome acoustics, spatial audio technologies, and B-format recording, but none are specifically aimed at exhibition in planetariums. We hope to provide the planetarium community with models for workflow and setup that will inform existing and planned audio infrastructures for dome environments.

In March 2007, the Gates Planetarium hosted the Denver section meeting of the Audio Engineering Society, with a presentation from Curt Hoyt of Trinnov Audio. The group heard Hoyt’s promising demonstration of the Trinnov Optimizer and its ability to identify and correct for acoustic anomalies created by multiple speaker arrays (the sort often found in planetariums). The group also auditioned a series of recordings made with Trinnov’s High Spatial Resolution Surround Microphone Array.
9. The Future

The reliability and sustainability of the visualization cluster has allowed us to move confidently forward with plans for future educational as well as artistic programming in the dome. With additional volunteer training and support, Colorado Skies may become an ongoing star talk that is officially open to the public before the end of the year. We are also starting to explore lectures using the same software, but given by researchers in non-astronomical disciplines that have an Earth systems focus, e.g., geology, resource use, and climate change. In the wake of Gaia Journeys’ success, the Gates team has started establishing collaborations with visual artists, musicians, and 3D animators. Among the goals of these artistic working groups are to nurture and guide local talent; create the infrastructure necessary to test and implement novel visualization technologies for the dome, and create a work flow and process by which pilot projects can be explored and developed, with the best ones eventually promoted as future public events for our visitors.

A cluster-based version of PhonicFX is being developed by N. Jenkins/Nebulus Design. This newer incarnation will contain many more visualization modules than had existed in the previous release, with a rich set of user options for each module. Additional source inputs will be available, as well as a host of new control devices for mixing and navigating the software visuals. We hoped to start testing an early beta release by Summer 2007, and afterwards to begin a viability study of its use for regular visitor programming.

IMAGE.PAN is the only significant piece of software on the Onyx that does not have a current analogue on the cluster. However, we are working with Infiscapes to help develop the next generation, cluster-based version of this tool. The new incarnation is called vPresent, and we have created a roadmap for its development, a detailed feature list, a website for developers, and have started building its core functionality with Infiscapes.

Our plan for vPresent is ambitious: create a tool for immersive data presentations as an Open Source project. The features that are planned for vPresent will make it attractive for use not only by planetariums and science centers, but hopefully for those in the arts and humanities communities as well. The Open Source nature of the software will allow a wide range of interested individuals and institutions to add to the project. Since such development is best facilitated on the Linux platform, we continue to see a parallel use of both Linux and Windows-based visualization clusters.

This broad focus of vPresent mirrors the general philosophy of DMNS and the staff who work with the Gates Planetarium. DMNS has six broad core disciplines in its research and visitor programs. Although space science and astronomy is one strong component, they are relative newcomers to a natural history museum when compared to anthropology, geology, paleontology, and zoology. As part of its decadal plan, DMNS will be installing new permanent exhibits on earth and health sciences. By exploring media and experiences that are not restricted to space themes, we can use the planetarium to test new ways of teaching these other subject areas. In addition to providing new and provocative planetarium programs, they also inform staff on how future exhibits can take advantage of new visualization technologies. Our hope is that such collaborative efforts will be fertile enough to result in a new wave of pioneering programs that continue to attract visitors to the dome.

10. Acknowledgments

The authors would like to thank Mary Cole, Carolina Cruz-Neira, Marieke Desciene, John Dubinski, Ed Lantz, David McConville, Charlie Morrow, and Barry Perlus for giving feedback on the text; Jan Warnstam for translation and music help; and Nigel Jenkins for providing screenshots of his software in action.

11. References

Abbott, B. 2006, The Digital Universe Guide for Partview; available online at haydenplanetarium.org/universe/duguide/
American Association for the Advancement of Science’s Project 2061 1993, Benchmarks for Science Literacy, NY: Oxford University Press.
McConville, D. Jan 16 2007, email communication.