National Science Foundation Study Grant Final Report

Development, Testing and Implementation of Digital Imaging Techniques for Enhanced Learning Applications in HD, 3D and Dome Theater Immersive Environments

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Introduction

There are two main components to this National Science Foundation Study Grant. First, the Advanced Imaging and Visualization Laboratory at the Woods Hole Oceanographic Institution (AIVL) in collaboration with Joel Halvorson and the Science Museum of Minnesota (SMM), set out to test the efficacy of emerging technologies for video acquisition of 3D and full dome. Second, the AVIL at WHOI and SMM evaluated how “live action” imagery could be incorporated into a variety of museum theater venues such as traditional 2D, 3D, curved and full dome planetarium theaters.

The Advanced Imaging and Visualization Laboratory at the Woods Hole Oceanographic Institution in collaboration with Joel Halvorson Science Museum of Minnesota have conducted a series of in laboratory imaging tests, field trials and public screenings of multi-format natural history live imagery in support of this NSF study. After a year of rigorous testing and constant evaluation in an effort to satisfy the goals of this study grant, AIVL and SMM have concluded that live action content is both feasible and cost effective for the science and museum communities.

Image Acquisition and Technique Development

The original proposal proposed a series of different images that would be captured based on several scenes for films that were and are in production by WHOI’s AIVL and SMM. Specifically, the productions were:

• “Shadows of the Sun” is a full dome production of the Minnesota Planetarium Society, featuring time-lapse, high speed and full dome terrestrial and oceanic cinematography of nature photographer Jim Brandenburg and the Woods Hole Oceanographic Institution’s Advanced Imaging and Visualization Laboratory.
• “Turning the Tide” (3D Marine Mammals) and “Deadly Beauties of the Sea” (3D Jellies-Invertebrates) are high definition 3D productions featuring the research results and imagery of the Woods Hole Oceanographic Institution’s Advanced Imaging and Visualization Laboratory. (See Appendix for treatments on each of these films)

The originally proposed set of tests intended to cover a variety of scenes that were thought to be critical to each production but had never been technically accomplished by other film productions in the proposed imaging formats and distribution venues (Table 1). Also studied was the development of an image acquisition technique to satisfy the requirements of both scientific imaging and filmmaking for broad general release.

Table 1. Original testing plan.

<table>
<thead>
<tr>
<th>Scene</th>
<th>Format</th>
<th>Tech specs</th>
<th>Production</th>
</tr>
</thead>
<tbody>
<tr>
<td>Underwater invertebrates</td>
<td>3D Full Dome</td>
<td>Standard angle</td>
<td>Deadly Beauties of the Sea Shadows of the Sun</td>
</tr>
<tr>
<td>Underwater and terrestrial</td>
<td>3D Full Dome</td>
<td>Macro lens</td>
<td>Deadly Beauties of the Sea Shadows of the Sun</td>
</tr>
<tr>
<td>microscopic creatures</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Whales from the airship, above</td>
<td>3D Full Dome</td>
<td>Telephoto</td>
<td>Turning the Tide Shadows of the Sun</td>
</tr>
<tr>
<td>water</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Underwater Whales</td>
<td>3D Full Dome</td>
<td>Ultra-wide format imaging</td>
<td>Turning the Tide Shadows of the Sun</td>
</tr>
<tr>
<td>Cloud movement, flower opening, ice</td>
<td>Full Dome</td>
<td>Time-lapse</td>
<td>Shadows of the Sun</td>
</tr>
<tr>
<td>melting</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Monarch in flight</td>
<td>Full Dome</td>
<td>High-speed</td>
<td>Shadows of the Sun</td>
</tr>
<tr>
<td>Loon diving</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

After initial review, this set of tests proved too ambitious to conduct within the confines of the budget of the study grant, i.e., a much larger travel and ship/aircraft budget would have been required. In order to simulate the scenes in the initial proposal, a larger number of tests were developed to represent the environmental conditions of the original scenes (Table 2). For example, airship and ship/sub time was not available during the study period, so previously collected image data was used for the study.

Table 2. Revised testing plan.

<table>
<thead>
<tr>
<th>Scene</th>
<th>Format</th>
<th>Tech specs</th>
<th>Proof of concept clips</th>
</tr>
</thead>
<tbody>
<tr>
<td>Underwater Invertebrates</td>
<td>3D</td>
<td>Standard angle</td>
<td>Corals St Thomas USVI Shown at ASTC</td>
</tr>
<tr>
<td>Underwater Invertebrates</td>
<td>Full Dome</td>
<td>Standard angle</td>
<td>Corals St Thomas USVI Shown at ASTC</td>
</tr>
<tr>
<td>Underwater and terrestrial</td>
<td>3D</td>
<td>Macro lens</td>
<td>Laboratory Bench Tests and Tests at MBL</td>
</tr>
<tr>
<td>microscopic creatures</td>
<td>Full Dome</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Underwater and</td>
<td>Full Dome</td>
<td>Macro lens</td>
<td>Jelly and Invertebrates</td>
</tr>
<tr>
<td>Monarch in flight</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Loon diving</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
terrestrial microscopic creatures shown at ASTC

Whales from the airship, above water

<table>
<thead>
<tr>
<th>Imaging Format</th>
<th>Lens Type</th>
<th>Screen Format</th>
</tr>
</thead>
<tbody>
<tr>
<td>2D HDTV</td>
<td>Normal</td>
<td>Macro-Standard</td>
</tr>
<tr>
<td>2D HDTV</td>
<td>Wide</td>
<td>Standard - Dome</td>
</tr>
<tr>
<td>2D HDTV</td>
<td>Ultra Wide</td>
<td>Panoramic- Dome</td>
</tr>
<tr>
<td>2D HDTV</td>
<td>Fisheye</td>
<td>Full Dome</td>
</tr>
<tr>
<td>3D HDTV</td>
<td>Normal</td>
<td>Macro-Standard</td>
</tr>
<tr>
<td>3D HDTV</td>
<td>Wide</td>
<td>Standard - Dome</td>
</tr>
<tr>
<td>3D HDTV</td>
<td>Ultra Wide</td>
<td>Panoramic- Dome</td>
</tr>
<tr>
<td>3D HDTV</td>
<td>Fisheye</td>
<td>Full Dome</td>
</tr>
<tr>
<td>Hyper Definition</td>
<td>Ultra Wide</td>
<td>Panoramic- Dome</td>
</tr>
<tr>
<td>Hyper Definition</td>
<td>Fisheye</td>
<td>Full Dome</td>
</tr>
</tbody>
</table>

Another test plan was developed to examine how the different image formats would play on various types of screen venues (Table 3). A key component of this test was to capture imagery that could be used for multiple applications, such as scientific purposes, museum films and documentary projects.

Table 3. Formats for different venues.

<table>
<thead>
<tr>
<th>Imaging Format</th>
<th>Lens Type</th>
<th>Screen Format</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2D HDTV</td>
<td>Normal</td>
</tr>
<tr>
<td>2</td>
<td>2D HDTV</td>
<td>Wide</td>
</tr>
<tr>
<td>3</td>
<td>2D HDTV</td>
<td>Ultra Wide</td>
</tr>
<tr>
<td>4</td>
<td>2D HDTV</td>
<td>Fisheye</td>
</tr>
<tr>
<td>5</td>
<td>3D HDTV</td>
<td>Normal</td>
</tr>
<tr>
<td>6</td>
<td>3D HDTV</td>
<td>Wide</td>
</tr>
<tr>
<td>7</td>
<td>3D HDTV</td>
<td>Ultra Wide</td>
</tr>
<tr>
<td>8</td>
<td>3D HDTV</td>
<td>Fisheye</td>
</tr>
<tr>
<td>9</td>
<td>Hyper Definition</td>
<td>Ultra Wide</td>
</tr>
<tr>
<td>10</td>
<td>Hyper Definition</td>
<td>Fisheye</td>
</tr>
</tbody>
</table>

Note 1: All HDTV Imagery was in ITU-709 Standard 1920 by 1080 Pixels.
Note 2: Hyper-definition Tests included non-motion digital still cameras.

Imaging Systems Developed to Facilitate Testing

WHOI also developed under separate funding, image acquisition systems capable of collecting the following formats of images simultaneously in underwater, aerial and terrestrial applications.
The following are WHOI AIVL image acquisition and recording systems:

- 2D HDTV
- 2D Hyper Definition
- 3D HDTV
- 3D Hyper Definition
- 2D HDTV Full Dome
- 2D Hyper Definition Full Dome
- 3D HDTV Full Dome
- 3D Hyper Definition Full Dome
- Digital Still Camera Time-Lapse

**Tests Performed and Locations**

WHOI’s Advanced Imaging and Visualization Laboratory conducted tests relating to this study in the following locations. These tests were often conducted in parallel with other efforts and scientific missions and with outside funding.

Imaging tests conducted for this study occurred at the following locations:

- Optical Lab Tests at WHOI
- Dock Tests at WHOI
- NASA Neutral Buoyancy Laboratory in water tests, Johnson Space Center Houston, Texas
- High Speed HDTV Tests conducted by WHOI in collaboration with Lockheed-Martin, NASA, SAIC at the Kennedy Space Center in Cape Canaveral, Florida
- Shallow water wreck site off Rhode Island; 150 foot water depth
- Shallow water wreck site off North Carolina; 150 foot water depth
- Shallow water wreck site off the island of Kea, Greece; 500 foot water depth
- In air tests Athens, Greece
- Deep water dives with DSV Alvin at the 9 North Hydrothermal Vent site at the East Pacific Rise; 8000 foot water depth, Pacific Ocean
- Shallow water coral reef and cave tests in St. Thomas, USVI; 100 foot water depth
- Macro HDTV and 3D Tests at MBL Marine Resources Facility
- Flume and Lab Tests at WHOI and at Benthos-Teledyne; 20 foot water depth
- Time Lapse tests in the lab and using Jason ROV at JDF Hydrothermal Vent Site; 7000 foot water depth, Pacific Ocean

**Science Museum of Minnesota Image Tests:**

- Time-lapse tests done in Alaska with Digital Still Camera
- Computer visualization demonstrations of Earth and astronomical data
Dome Lens Testing

Prior to the field tests in Athens, WHOI’s AIVL evaluated several dozen off-the-shelf and custom made, high definition lenses for their optical quality and field of view. Eight lenses were eventually chosen for initial field testing that AIVL felt would allow for the greatest versatility in shooting for the different venue and screen types (Images 1-8). The lenses ranged from standard wide angle to ultra fish eye. In addition SMM tested several fish eye lenses and chose one for the still photography shot in Alaska (Images 9-12). Below are examples of the lenses evaluated.

Examples of Dome Lens Testing Performed in Athens, Greece 2006

Image 1. Still image from a Nikon 15mm lens.
Image 2. Still image from a Fujinon 4.5mm PF lens.

Image 3. Still image from a modified Fuji 7mm lens.
Image 4. Still image from a modified Fujinon fisheye 7.8mm lens.

Image 5. Still image from a modified Fujinon Argus II lens.
Image 6. Still image from a Nikon 10.5mm lens.

Image 7. Still image from a Fuji fisheye lens.
**Image 8.** Still image from a Sigma fisheye lens.
Digital Still Camera and Time Lapse Tests

Image 9. Still Image from Nikon Lens
Image 10. Still Image from Nikon Lens
Data Visualization Example

Image 11. Still image from data scaling visualization using Uniview

Results from Early Testing

Preliminary test screenings in dome theaters quickly pointed out a number of expected and unexpected results. These can be broken down into two main categories:
1. Viewer issues due to viewing angles and screen geometry of the dome
2. Image fidelity issues relating to both image acquisition and dome physical characteristics
Viewing Angles and Geometries

There are many differences in viewing angles and geometries for domed theater venues due to the differences in overall size, i.e., diameter and tilt angles. The size of the dome, which can be anywhere from a few to 30 meters, greatly affects how the audience perceives the imagery being presented. Further complicating this issue is the tilt of the dome theater screen, which also varies from horizontal in panoramic display venues to vertical in planetarium venues.

Our testing has shown that imagery collected in full dome must be geometrically corrected to fit the various sizes of dome screens. The resultant fields of view change during this process and the effect can most noticeably be seen as the imagery appearing too close to, or too far from the observer. Though this can be easily corrected using off-the-shelf software packages such as “Full Dome” and “Full Dome Plug In,” testing must be done with the original material in order to best fit each scene to the specific dome theater size.

As mentioned earlier, viewing angles due to dome screen tilt are more difficult to correct for. This is further complicated by the necessity to compose and scale shots differently for different types of horizontal and vertical venues. Studies suggest that there are optimum camera angles for different groups of tilted dome designs. As part of the lens testing WHOI worked with Sky-Skan to find the right camera tilt angle and to develop field guides for placing the subject of a scene into a “sweet spot” directly compatible with a variety of different screen tilt angles.

Examples of Tilt Angle Testing performed in Athens, Greece 2006
Image 12. Still from a Fuji fisheye lens.

Image 13. Still from a Fuji fisheye lens.

Image 15. Still from a Fuji fisheye lens.
One of the biggest issues encountered during these tests involved aerial and underwater imagery where the viewer’s inclination is to interpret the imagery from a down-looking perspective, even though they are forced to look up at it in a dome screen. Needless to say, this effect increases viewer discomfort as the tilt angle of the dome increases to vertical.

This issue was quickly realized and a more panoramic approach to filming underwater imaging was adopted (Image 14). This change in composition also helped to reduce overhead lighting issues that were prevalent in earlier tests. Controlling overhead lighting in a dome theater venue is critical to overall image quality as high light levels effectively wash out other parts of the projected image.
Tests were successfully completed using this new approach and plans are underway to mask and correct the underutilized screen space in this format. The screen space is limited to directly behind the viewer and is felt to be lower in importance, especially on a more vertical dome.

**Image Fidelity**

**Overall Image Quality**

Tests conducted during this study prove that image fidelity is key to generating a positive response from the viewing audience. Results from these test screenings seemed to indicate the following:

Studies have shown that at some point near HDTV ITU-709 resolution (1920 by 1080 pixels), human vision switches from detecting image quality as a measure of horizontal resolution to one of color fidelity and quality.

3CCD 2K Sensors can easily out perform single sensor CFA devices of over twice the resolution in subject testing. This was also described in a recent study by Kodak for the Society of Motion Picture and Television Engineers SMPTE. In this study, a 2k by 1k 3CCD camera image was compared with a 4k by 4k CFA Single sensor image on a 4k and 8k projection system. The study results showed there was little discernable image quality variation between the two images.
These studies appear to support the findings of this testing series that 3CCD imaging systems do perform as well as Single CFA sensor cameras of over twice the spatial resolution of the 3CCD sensors.

These findings contradict the current and popular trend of thinking that camera systems, such as the Red Camera, will revolutionize the manner in which we can collect imagery for full dome venues. We feel that the Red Camera will have an impact but that a much more controlled and systematic approach must be taken when acquiring imagery with CFA sensors than with 3 CCD Prism Block Sensors. In some cases, it is, therefore, expected that 3CCD HDTV cameras will outperform the Red Camera.

**Image Quality During Acquisition**

Throughout this study, we found a number of parameters that affect image quality during acquisition. They all seem to have a direct effect on the image quality and are not necessarily independent of each other. These parameters include the following items:

- Optics
- Sensor
- Recording Format

**Optics**

An important consideration when designing an imaging system is the design or selection of the main optical element, i.e., the lens. It is critical when trying to accomplish ultra-wide optical imagery that the lens resolving power match or exceed the resolution of the sensor. One means of determining this is to measure the MTF of the lens and camera combination. The optics selection was found to be a vital step towards assuring high quality presentation on the dome screen. In addition, anti-aliasing filters must also be matched to sensor and optics for best performance.

A known example of optical mis-match is the common HDV camcorder, whose small sensor size of ½ inch to ¼ inch creates an optical problem that cannot be solved with current lens design. The lenses on the cameras cannot resolve even 1440 pixels of the 1920 pixels in the horizontal specification of the format. This fact is often ignored as the format is not considered a true professional format and the compression system is so harsh that it masks any optical effects.

Wide-angle fisheye lenses are the most difficult to work with as they are inherently soft by design due to their extreme angle of image acquisition.
The imaging sensor is often believed to be the heart of an imaging system. We found, however, that even the best sensors available cannot compensate for poor optics and the effects of high compression recording and playback. Studies by Kodak for SMPTE have shown that color image fidelity is more important than resolution in high resolution imaging systems. The study supports what we have seen in our tests. The 3CCD 1920 by 1080 imaging systems appeared to outperform the single sensor color filter array imaging systems. This was true even when the single sensor imagers were of higher (2-4x) spatial resolution than the 3CCD Sensors. Table 4 illustrates the range of sensors and their resolutions that were evaluated during this study.

The dynamic range of the sensor is also critical in applications such as full dome and underwater imaging where lighting is often harsh and difficult to control. A sensor with high dynamic range, allows for the post-processing of compositional elements, such as sky-clouds, differently than those of the foreground content. This process is now possible in software packages such as Photoshop.

**Table 4.** Range of motion imaging sensors evaluated and/or used in this study.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Sony HDC-1500L3A</td>
<td>3CCD</td>
<td>1920</td>
<td>1080</td>
<td>10-12 bit</td>
<td>60</td>
</tr>
<tr>
<td>2 Sony HDC-950</td>
<td>3CCD</td>
<td>1920</td>
<td>1080</td>
<td>10-12 bit</td>
<td>30</td>
</tr>
<tr>
<td>3 WHOI HD-Mini-Cam</td>
<td>1 CFA</td>
<td>1920</td>
<td>1080</td>
<td>10-12 bit</td>
<td>30</td>
</tr>
<tr>
<td>4 Red Camera</td>
<td>1 CFA</td>
<td>4520</td>
<td>2540</td>
<td>10-12 bit</td>
<td>60</td>
</tr>
<tr>
<td>5 WHOI Mini-Dome A</td>
<td>1 CFA</td>
<td>2048</td>
<td>2048</td>
<td>10-12 bit</td>
<td>15-30</td>
</tr>
<tr>
<td>6 WHOI Mini-Dome B</td>
<td>1 CFA</td>
<td>4096</td>
<td>4096</td>
<td>10-12 bit</td>
<td>15-30</td>
</tr>
<tr>
<td>7 WHOI Mini-Dome C</td>
<td>1 CFA</td>
<td>2500</td>
<td>3580</td>
<td>10-12 bit</td>
<td>15</td>
</tr>
<tr>
<td>8 Prototype Hyper Definition Motion Camera</td>
<td>1 CFA</td>
<td>4008</td>
<td>2672</td>
<td>8-10 bit</td>
<td>15-30 with multiplexer</td>
</tr>
</tbody>
</table>

**Table 5.** Range of still imaging sensors evaluated and/or used in this study.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Fujifilm S2 Pro</td>
<td>1 CFA</td>
<td>4256</td>
<td>2848</td>
<td>12 bit</td>
<td>1-5 fps max burst</td>
</tr>
<tr>
<td>2 Canon EOS-1D Mark III</td>
<td>1 CFA</td>
<td>5616</td>
<td>3744</td>
<td>8-10 bit</td>
<td>1-5 fps max burst</td>
</tr>
<tr>
<td>3 WHOI Test Rig</td>
<td>1 CFA</td>
<td>4008</td>
<td>2672</td>
<td>8-10 bit</td>
<td>15-30 with multiplexer</td>
</tr>
<tr>
<td>4 Fujifilm S1 Pro</td>
<td>1 CFA</td>
<td>3040</td>
<td>2016</td>
<td>12 bit</td>
<td>1-5 fps max burst</td>
</tr>
</tbody>
</table>
Digital Still Camera Tests

Digital Still Camera testing was limited to time lapse and optics verification tests only. This was due to these cameras inability to acquire motion imagery at the frame rates required for motion imagery. The lowest frame rate tested and evaluated by WHOI for use in Imax type productions was 12 frames per second. This speed worked with very slow moving objects imaged from very slow moving camera platforms.

A variety of fisheye and full dome lenses were also tested and or evaluated in this study. Many of these lenses produced unfavorable results especially regarding optical clarity near the edges of the frame. This was observable as color artifacts produced by the lens and CFA Sensor combinations used.

Recording Systems

National Deep Submergence Facility (NDSF) Resolution Study:
A recording study was done using a WHOI HD-Mini-Cam on the Jason Remotely Operated Vehicle, in order to best assess the effects of recording system compression on image quality for both still and motion imagery. Table 5, illustrates the recording mediums used, their data rates and the amount of compression inherent to each medium. This test exemplified what we had seen during test screenings on the dome and has pushed us towards using lower compression recording systems for our field acquisition of imagery. Image data with lower compression not only resulted in high resolution and sharpness on the screen, but also enabled more sophisticated post-processing of the imagery. The post-processing included color grading and scaling to 8k pixel widths.

**Table 5. NDSF Recording Format Study.**

<table>
<thead>
<tr>
<th>Recording Format</th>
<th>Data Bandwidth</th>
<th>Media</th>
<th>Compression</th>
<th>Example</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 DVD SDTV</td>
<td>4-6 mgbytes/sec</td>
<td>Tape</td>
<td>Variable frame rate</td>
<td>Image 15</td>
</tr>
<tr>
<td>2 DVCAM</td>
<td>25 mgbytes/sec</td>
<td>Tape</td>
<td>Intra Frame</td>
<td>Image 16</td>
</tr>
<tr>
<td>3 HDV</td>
<td>25 mgbytes/sec</td>
<td>Tape</td>
<td>15 Frame Long GOP</td>
<td>NA</td>
</tr>
<tr>
<td>4 HDCAM Classic</td>
<td>175 mgbytes/sec</td>
<td>Tape</td>
<td>7:1 Intra Frame</td>
<td>Image 17</td>
</tr>
<tr>
<td>5 HDCAM SRW</td>
<td>440-880 mgbytes/sec</td>
<td>Tape</td>
<td>2.4/2.7:1 Intra Frame</td>
<td>Image 18</td>
</tr>
<tr>
<td>6 Raid Recorder</td>
<td>Above 880 mgbytes/sec</td>
<td>Hard Drive</td>
<td>No Compression</td>
<td>Image 19</td>
</tr>
</tbody>
</table>
Still Images from NDSF Recording Study

Image 18. Full frame still from DVD recorder.
**Image 19.** Full frame still from DVCAM recorder.

**Image 20.** Full frame still from HDCAM Classic recorder.
**Image 21.** Full frame still from HDCAM SRW recorder.

**Image 22.** Full frame still from RAID recorder.
Physical Characteristics of Dome Theaters that affect Image Fidelity

**Picture Height**

- Current standard definition television systems use a picture height to viewing height ratio of about 7:1 for determining best viewing distance.

- Current HDTV television systems use a picture height to viewing height ratio of about 3:1 for determining best viewing distance.

- Dome theaters generate a picture height to viewing height ratio of about 1:1 for audience viewing distance.

- Small portable dome theaters generate a picture height to viewing height ratio of about 0.5:1 for audience viewing distance.

These items demonstrate that higher quality imagery projection is required for small domes in order to maintain comparative image quality over larger dome venues. This, however, is rarely the case as most portable domes use lower quality projections systems and screens. In addition, the content is usually compressed higher than what is used in permanent theater venues. This is often overlooked by viewers due to the novelty of the dome environment and that the majority of content being displayed is coming from high-resolution sources, such as computer data visualizations. Live imagery will need to be 2-4 times the resolution of the larger dome theaters to maintain the same overall perceived resolution. This is currently not feasible which may result in a loss of image content fidelity in small dome theaters. Small domes do, however, represent an ideal demonstration and educational environment for data visualizations and similar visual media.

Results, Findings and Recommendations

**Initial Dome Screening Tests and Initial Results**

WHOI’s Advanced Imaging and Visualization Laboratory, with the technical assistance of Sky-Skan, Sony and Infinitec, developed and evaluated full dome stereoscopic imagery in planetarium dome theaters. The first 3D Full Dome HDTV was demonstrated by this team at the Athens Planetarium in December of 2006. Live action imagery in 3D and Full Dome was shot during the Conference of International Museum Directors, being held at the Athens Planetarium, and was presented onto the dome screen the following day for viewing and evaluation. This process showed unequivocally that it was possible to shoot 3D and Full Dome and present it to the public in a significantly shorter time frame than traditional IMAX acquisition techniques could facilitate. The Athens test, and others, were conducted to prove the efficacy of utilizing live imagery over computer-generated imagery for film projects being developed by WHOI and for the community as a whole.
Evaluation and Presentation Venues

WHOI and Sky-Skan have presented imagery at the following venues in order to inform the community of the work that is underway at WHOI, to enlist their support and get their feedback (Table 6).

Table 6. Evaluation and Presentation Venues

<table>
<thead>
<tr>
<th>Location</th>
<th>Format</th>
<th>Attendance</th>
</tr>
</thead>
<tbody>
<tr>
<td>WHOI’s AIVL</td>
<td>HD screen and 3D Viewer</td>
<td>50</td>
</tr>
<tr>
<td>Sky-Skan, New Hampshire</td>
<td>Full Dome and 3D</td>
<td>50</td>
</tr>
<tr>
<td>Athens Museum Conference, December 2006</td>
<td>Full Dome and 3D</td>
<td>350</td>
</tr>
<tr>
<td>NOAA NASA Demonstrations, February 2006 and April</td>
<td>Portable Dome</td>
<td>100</td>
</tr>
<tr>
<td>2006</td>
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<tr>
<td>Vancouver Sky-Skan, Spring 2007</td>
<td>Full Dome and 3D</td>
<td>150</td>
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<td>ASTC, Fall 2007</td>
<td>Full Dome, Portable Dome and 3D</td>
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<td>Gadget Off Conference, NYC, Fall 2007</td>
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<td>Standard Flat Projection and 3D</td>
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<tr>
<td>AGU, Fall 2007</td>
<td>3D</td>
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ASTC 2007 Presentation Results

An evaluation form was handed out following the presentations given by WHOI & SMM at ASTC. The presentations were done in a 30-foot negative pressure dome theater provided by Sky-Skan and Sony. Unfortunately, only a small portion of the 200 people in the viewing audience completed the survey. However, the majority of participants who completed the survey agreed on the effectiveness and value of live imagery, 3D and dome, and its use in immersive environments (Table 7). A small portion was unsure of the effectiveness of these formats, but no individuals disagreed on the potential of these formats to enhance the viewing experience.

A large percentage of those who did complete the survey felt that new content should utilize live image capture in both 3D and dome formats. The majority of those surveyed also strongly agreed that viewing natural science content in 3D or dome format would have a greater impact than viewing the same content on a traditional flat screen. The
majority of the surveyed audience strongly agreed that 3D content creates a more immersive environment than content presented on a traditional flat screen. Half of the participants surveyed strongly agreed that the dome content produced a more intuitive sense of place than what could be achieved on a traditional flat screen. These responses were also supported verbally at ASTC in addition to in informal exit polling done by WHOI and Sky-Skan at other presentation venues.

Many who did not fill out the questionnaire did comment positively on the presentations and even inquired as to the whereabouts of the complete shows. Two individuals reported difficulty viewing the presentation in 3D, but this was not an unexpected result. These individuals may be part of the 10% of the population that has trouble viewing images in 3D.

Table 7. Survey results from 3D and dome presentations at ASTC.

| Natural science full dome and 3D content has historically been computer generated. Based on the previewed content, new content should utilize live image capture in these formats. |
|---|---|---|---|---|---|
| Strongly Agree | Agree | Not Sure | Disagree | Strongly Disagree |
| 64% | 29% | 7% | 0% | 0% |

The dome content provides a more intuitive sense of place than similar content on a traditional flat screen.

| Natural science content on the dome would have a more lasting impact on the learner than the same content on a flat screen. |
|---|---|---|---|---|---|
| Strongly Agree | Agree | Not Sure | Disagree | Strongly Disagree |
| 50% | 36% | 14% | 0% | 0% |

3D content provides a more intuitive sense of place than similar content on a traditional flat screen.

| Natural science content in 3D would have a more lasting impact on the learner than the same content on a flat screen. |
|---|---|---|---|---|---|
| Strongly Agree | Agree | Not Sure | Disagree | Strongly Disagree |
| 64% | 36% | 0% | 0% | 0% |
3D Stereoscopic Effects

3D Stereoscopic imagery generates a number of desirable responses for the human vision system. The fusion of two discrete high resolution images by our brains increases the perceived resolution of the image content almost two fold. This case is particularly evident in the viewing of 3D Stereoscopic Underwater Imagery.

WHOI’s 3D Stereoscopic Camera systems also mimic the human vision system closely relying upon a more parallel optical arrangement and the use of fixed focal length optics over the more traditionally used variable focal length optics, i.e., zoom lenses. This design approach has actually made the stereo camera systems much smaller and easier to use in remote field locations and harsh environments. This design also eliminated the need for complicated opto-mechanical servos for adjusting inter-ocular distance, convergence range, and focal length of two lens in sync with the desired zoom setting. WHOI has found this approach to accurately mimic human vision and result in very low fatigue stereoscopic viewing.

One of the benefits of a parallel stereoscopic camera system is the ability for scientists to measure objects in situ. WHOI has been developing software with JPL and others to obtain very accurate measurements of objects large and small, in underwater and terrestrial environments.

Stereoscopic underwater imagery seems to be the best of all the imagery types tested, resulting in the greatest appeal by the screening audiences.

Time Lapse Imagery

Time Lapse testing was done both by SMM and WHOI during this study. Though the digital still cameras used were of high spatial resolution, the imagery often suffered when presented on a dome. The issue appeared to be a problem with the post-processing workflow and is one that needs to be constantly addressed by venue. It is imperative that the formats used in the field are of the highest quality (generally RAW) and that the integrity of that format be retained through processing to final projection.

Another issue to be addressed with time lapse is the aperture/iris drift and floating black levels from long periods of use in non-stable temperatures. These issues require even greater camera control and more significant post-processing when moving the still frames into motion sequences.

Macro and Stitching Imagery

Macro images are the most difficult to acquire especially for Full Dome venue. WHOI has tested a number of macro image sequences including some at the ASTC conference
which have been well received by the audiences. WHOI is currently looking at using image stitching and compositing techniques to bring macro imagery into dome theaters utilizing macro underwater imagery that contains either blue or black backgrounds. These types of images can then be tiled and composited in moving mattes around the dome creating a truly unique viewing experience.

**Post Processing**

During the course of this study, we discovered that the file formats and compression techniques used on various brands of image servers, especially in dome theater applications, represented a direct affect on perceived image quality. A comparison of widely used still image file formats used during slicing operations showed a wide range of subjective image quality and fidelity issues. During this study we have moved towards using the least destructive of the image file formats for processing, slicing and distribution.

**Post processing Pipeline Development**

WHOI is working with Sky-Skan Inc to develop a more efficient and higher image fidelity technique for the processing of images for Dome and 3D screen Venues.

An example of a post processing pipeline is as follows:

**Acquisition at Full Bandwidth Lowest Compression Recording**
- Preliminary Color Grading
- Sharpening
- Scaling
- Post Grading
- Projector Grading
- Sharpening
- Geometric Rectification
- Projector Geometry Correction
- Slicing @ RGB 12 bit Avoiding destructive image file formats

**Engineering Efforts**

During the course of this study, WHOI’s AIVL combined and refined its design of underwater imaging rigs capable of simultaneously capturing 2D, 3D and Full Dome. For shallow waters, a fiber-tethered system has been designed and built that carries up to 5 different cameras, all oriented for different image formats. The fiber carries the signal to topside where the cameras are controlled and images are recorded. Initially, divers were reluctant to be tethered and felt that their lack of personal camera control would
adversely affect the end product. After a year of shooting, all involved have found that the results are quite the opposite and the benefits of the tethered system are many. Some of the benefits to this type of tethered system are:

- By recording images topside, a higher quality recording medium with less compression can be used
- Remote camera control allows for much greater flexibility in image manipulation
- Divers can focus on setting up and framing the shots without having to deal with minimal camera control
- With all systems in one rig, there is a tremendous savings in production cost by capturing multiple formats and only having to shoot it once

The underwater system has also led to a hybrid topside camera system that shoots in the same formats in terrestrial environments. AIVL has also developed housings for these systems for full ocean exploration and imaging.

Benefits of this study to WHOI NDSF Imaging

WHOI’s AIVL involvement in this study grant has not only stimulated exchanges with many museums, content developers and producers, but has also initiated a dialogue amongst scientists and engineers at the National Deep Submergence Facility at WHOI as to how we can build cameras better-suited for documenting the deep sea environment and the ecosystems we wish to study. Plans are currently underway to incorporate the results of this study into the next generation of imaging system designs for Replacement Human Occupied Vehicle and for future human-machine interfaces for remotely operated vehicles.

Future Areas for Study

- Dome Rectification Study
  - Translating to various dome sizes and tilts
  - Develop universal optimum for non-vertical domes
  - Develop vertical dome display venue

- Image Processing and Pipeline Development
  - Scaling and sharpening algorithms
  - Grading

Recommendations and Conclusions

This study proves the effectiveness of live-action sequences and natural history imagery in not only museum venues but all immersive environments. This study also proves that the current crop of existing High Def cameras, lenses and recording mediums are sufficient to capture high quality imagery that can stand up to the demands of dome
theaters. This is not to say that the images will not get better as newer technologies emerge, but there is sufficient quality in present systems at AIVL to warrant full scale production at a very reasonable cost and timeline, especially when compared to traditional IMAX.

There are still some post-processing and projection issues to be resolved and studied, but these should in no way hinder productions from beginning or editing. In short, the tools are here and the community should be ready to go the next step and begin producing films.
Long Term Production Application Treatments

Minnesota Planetarium Sun-Earth Full Dome Production

Summary:
The new Minnesota Planetarium is preparing to produce a first of its kind, full dome planetarium program, featuring the time-lapse and high-speed photography of Jim Brandenburg and Neil Lucas. A Minnesota native, Jim Brandenburg is considered one of the world’s greatest nature photographers. Constantly re-inventing his craft, Jim currently is devising innovative time-lapse applications of digital media. Neil Lucas is a producer at the British Broadcasting Corporation (BBC), and is widely credited with many of the natural history time-lapse techniques in use today. Neil’s skills are beautifully illustrated in his critically acclaimed production “Shadows of the Sun”.

Being co-located with a library, the Minnesota Planetarium is a natural gathering place to tell stories around a digital campfire. The proposed opening show will embrace the science, but also include the cultural and aesthetic sense of the subject. The program will be dominated by the use of time-lapse and high-speed photography featuring, seasonal change, weather, northern lights, the night sky, and wildlife. Additional underwater full dome footage will be secured through the Woods Hole Oceanographic Institution.

Treatment
The opening scene will establish the sun-earth connection through a computer generated temporal traverse of space covering the first 15 billion years of the universe - from the grand unfolding (Big Bang) to the present. To avoid describing this scene in technical terms, the viewer hears the voice of a native elder telling an origins story to a group of children gathered around a campfire along a lake at dusk. You hear the story as you view the animation. As we traverse time and space, we fly into the Milky Way galaxy, into our solar system, and past the gatekeeper planet Jupiter. As we fly by the earth we see that it is early Pangaea (200 million years ago) with the continents drifting apart. We fly around the sun, and return to earth as though riding a photon. We ride this photon at a very skewed angle to a present day earth. It is twilight of the summer solstice as we ride this photon through the earth’s atmosphere, heading to northern Minnesota. As we drop in altitude, we are traveling over a pine forest, across a lake, as we come upon the campfire where the elder is seated telling the story.

We arrive to earth in an explosion of color, at a time when the photon driven relationship is at maximum energy. We celebrate this relationship and its impact on the natural world through the use of time-lapse and high-speed photography. The story’s protagonist, the sun, becomes the antagonist, and finally the protagonist again, as the impact of photons on the natural world changes the seasons. Using narrative stories, we watch several sun driven cycles unfold such as:

• Daily cycles: sun rise- sunset
• Temperature cycles: water to ice
· Water cycle: from clear skies, to clouds, to thunderstorm
· Plant cycle: green up and green down of plants and trees/ watching the food chain rebuild itself
· Seasonal cycles: A loon calling on a lake metamorphoses into a wolf calling on a frozen lake / northern lights / stars rotating around the North Star.
· Migration cycle: Migrating birds, whales, fish
· Lunar cycle: phases of the moon and moon rise and moon set
· Life cycle: from caterpillar to monarch / from egg, to hatching, to bird in flight.

The closing scene returns to the campfire. The viewer hears the elder telling a story about our water planet, the earth. As we listen, we fly up to the stars in an arc around the earth, and then to the moon. We descend slowing to the moon’s surface at a very skewed angle. As we descend to the surface we watch the earth set below the horizon of the moon. We see the dull landscape of the moon lit overhead by bright stars. The credits roll.

Production Schedule/Timeline
What does it mean to produce in a dome? Can techniques used on the flat screen, transfer to a domed environment? Can we successfully put terrestrial material on the immersive environment of the dome? What computer animation will work the best in the dome? These are just some of the many technical and content driven challenges of this program.

To address these challenges, and the need to shoot during all four seasons, a 36-month production schedule is recommended. This schedule will provide enough time to produce the program, test it in the new theater, and have it ready for an anticipated opening in Summer of 2009.
Every day on earth, new marine species face possible extinction. It could be from one, or any number of reasons--habitat destruction, pollution, climactic changes, hunting, or mysterious causes yet to be understood. But thankfully, virtually every year, scientists also gain new abilities and techniques to measure what is happening to our planet and the creatures with which we share it. Today, exciting new research techniques and developments are allowing scientists to do their jobs more thoroughly. A new millennium is bringing new ways to perform cutting-edge studies that just may turn the tide against the loss of biological diversity in the seas.

Today Northern right whales are on the brink of extinction. Only about 342 still exist, and scientists say that if we lose as few as two more a year to human causes, the population will disappear completely. Sadly, two pregnant females, Staccato and Stumpy, were killed by ship strikes last year, and with entanglement, over fishing, pollution and habitat loss, these magnificent creatures' ability to survive is severely threatened. This year the losses to date are between 7-12.

Only 5,000 blue whales--the largest creature that ever lived--still exist. The killer whale population in the Pacific Northwest is dwindling fast. From the cool waters of the Puget Sound to Iceland, New Zealand and Patagonia, whales are threatened by ship strikes, pollution, entanglement, over fishing and habitat loss. This means shifting food supplies, scary mass beachings, and finally, the loss of these gentle, powerful creatures forever. And we still know so little about them.

But there is hope. All over the world, scientists, rescuers, NGOs and even blimp pilots are pitching in with innovative ways to save the whales. Scientists, engineers, fisherman, and policy makers are collaborating in ways that were unthinkable just ten years ago. New technologies are being introduced at a frantic pace to gather data to better understand these mysterious animals. Researchers are studying the southern right whale's re-emergence for clues to help their northern brethren. Shipping lanes are being moved in Canada. Ordinary citizens are helping stranded marine mammals back into the sea, and rescuers are forming new partnerships to disentangle whales from fishing lines.

One example of these new and unique partnerships actually appeared quietly from the
Instead of hovering over stadiums and sports events, a blimp is now flying over the shores of Cape Cod, Florida, and the Pacific Northwest, helping scientists and rescuers identify, assess and disentangle whales. Just like the whales that the blimp is trying to help save, the airships themselves faced near extinction until recently. Now they are returning to service around the globe, used for monitoring and security operations. This merging of the older aerial technology and state-of-the-art imaging technology is unique. Already, this platform is credited with saving the life of one whale named "Trident."

To date, working with the Woods Hole Oceanographic Institution's (WHOI) Advanced Imaging and Visualization Laboratory, the Fuji blimp has made five scientific forays since 2002, assisting with three whale rescues and helping to survey and photograph over 150 animals. The brainchild of WHOI's Bill Lange and Fujifilm's Ty Atherholt, the program's stunning images are used to assess the animals and the state of the declining population.

In the near future, WHOI and Fuji plan to further push the frontiers of marine mammal research with their most ambitious project yet. WHOI, the National Marine Fisheries Services (NMFS), the Center for Coastal Studies, the Cape Cod Stranding Network and the National Oceanic and Atmospheric Association (NOAA) will use the blimp to document whale behavior, body condition and vessel interactions. And, for the first time ever, they'll gather stereo images that may provide data to show if the animals are losing weight and if their food supply is stressed. Researchers will also capture images of whales' scars to help determine how often ship strikes occur. This research will aid experts in developing long-range protective strategies.

The blimp is an ideal research and rescue platform. Stable and quiet, it acts as a complement to federal survey planes, allowing scientists and photographers to get very close. Helicopter noise spooks the animals at 1,000 feet, which is illegal, but blimps can dip down to as low as 500 feet without disturbing whale behavior. In Spring 2003, this allowed researchers to observe sei, fin and humpback whales and get unprecedented images. But perhaps most gratifying was the day when the blimp helped save a distressed creature from death. Trident, a humpback whale spotted off Cape Cod in August 2003, had fishing line wrapped around her fins and a net caught in her mouth. (Fishing gear can be deadly since it's capable of cutting through blubber right down to the bone. Shockingly, 70% of right whales bear its scars. These entanglements are extremely painful and can lead to slow death by starvation that can take years!) Overhead, the blimp crew was able to direct rescuers to where Trident was getting ready to surface, and WHOI imaging experts collected footage. On the water, a team from the Center for Coastal Studies (CCS) successfully pulled off the net. CCS directly credits the blimp's aid with saving Trident's life. The airship also helpful in identifying more entangled whales off Cape Cod that same year and in Florida, 2005.

In Turning the Tide, we'll fly over the coasts of New England, Florida and the Pacific Northwest, participating in surveys, research and photo documentation. We'll see these majestic creatures as they breach, dive, feed and play. We'll talk to the pilots and researchers, rescuers and government officials, and volunteers and executives who have
joined forces to make a difference. And we'll assist a rescue team as they pull their small rubber boat up next to one of the world's largest animals and attempt to save its life.

Jeff Foster, the marine mammal expert who has overseen the rehabilitation of many endangered animals and has participated in countless cutting edge scientific survey programs, will be our guide to the pioneering research being conducted around the world. We'll see firsthand what state-of-the-art tracking tags and other tools are being used to study these creatures. In a unique journey, we'll travel the world with Jeff and the prestigious Woods Hole Oceanographic Institution's Advanced Imaging and Visualization Laboratory, seeing whales up close, underwater, right next to us.

The program will look at all the planet's great whales, including the mighty blues, graceful humpbacks and agile grays. We'll explore how they communicate, plus their family groups and behaviors. We'll also look at the smaller whales--unicorn-like narwhals, smiling belugas and sleek orcas, as well playful dolphins and porpoises. Then we'll look at endangered species, specifically the Northern Atlantic right whale, and ask why they're still dying even after whaling was outlawed globally in 1986. We'll investigate strandings--the possible causes, remedies, and why pilot whales are so susceptible. Just like on the hit television show, CSI, we'll see how tiny DNA samples are being collected from animals in the wild, hopefully unlocking some of the mysteries hidden from scientists for so long.

And what about captivity -- is it always a bad idea? When can it be beneficial? We'll learn about rehab programs for stranded marine mammals and the releases of Keiko, Luna, Springer and JJ. We'll see how human management of some species may be necessary to ensure survival.

With stunning high definition photography these beautiful animals will certainly come alive--breaching, diving, splashing--and serve as ambassadors to a deep blue world which is still mostly a mystery to us human observers. In HDTV Science Center venues we plan to expose the public to these unique creatures of the sea life size and in 3D. 'Turning the Tide' will give audiences an once-in-a-lifetime chance to see these awe-inspiring, mythical creatures up close. This may be our last chance to see...before they are gone.
DEADLY BEAUTIES OF THE SEA
A 3D HD Film from Silver Star Productions and
The Advanced Imaging and Visualization Laboratory
Woods Hole Oceanographic Institution

The Ocean contains a myriad of creatures that are completely alien to us. Among the most spectacular are deep-sea jellyfish and other strangely shaped animals, invertebrates without a bone in their bodies. These creatures seem straight out of science fiction: glow-in-the-dark jellies, blue-eyed albino octopi, squid that disappear into clouds of ink, and cuttlefish that can change their skin patterns to look like the opposite sex or any background. As enchanting as these species are, some are extremely deadly. Yet these dangerous, uniquely adapted animals are also at the heart of scientific studies that seek to relieve human suffering. With the world-renowned Woods Hole Oceanographic Institution's Advanced Imaging and Visualization Laboratory and the marvel of high-definition 3D, we'll meet the mysterious sea creatures that can either harm us or heal us.

They are beautiful
mysterious
and deadly.

But they just might save our lives.

The ocean contains a myriad of creatures that are completely alien to us. Among the most spectacular are deep-sea jellyfish and other strangely shaped animals without a bone in their bodies. We find ourselves helplessly drawn in by these mysterious invertebrates and their graceful, otherworldly appearance - yet some can kill.

Few people know that jellies form the largest biomass on the planet! In fact, if aliens came down and randomly sampled multi-celled life on Earth, they'd conclude that jellies ruled the world. They're found in every ocean and were recently discovered in fresh water, too. Endlessly fascinating in their colors and shapes, they range in size from the tiny, deadly sea wasp and blinking, glow-in-the-dark comb jelly to the Lion's Mane jellyfish, which has eight-foot umbrellas and tentacles that can stretch up to 200 feet long. They have been known to wipe out entire fisheries with their voracious appetites.

As enchanting as these species are, some are also extremely deadly. The Irukandji jelly is nearly invisible, but over 60 people a year are hospitalized with Irukandji Syndrome, and at least two have died. The blue-ringed octopus of Australia, which lights up when it feels threatened, contains enough venom to kill 26 adults within minutes. And you have virtually no chance of surviving a tangle with a box jelly.
Beyond jellies, the deep ocean hides other creatures that seem straight out of science fiction: Blue-eyed albino octopi, squid that disappear into clouds of ink, and cuttlefish that can change their skin patterns to look like the opposite sex or any background.

But these often dangerous, uniquely adapted creatures are also at the heart of scientific studies that seek to relieve human suffering. Jellyfish could provide the key to any number of major medical breakthroughs, from the treatment of arthritis to Huntington's disease. Marine sponges may just provide us with anti-cancer drugs. And a clotting factor in horseshoe crabs' blood can be used to detect bacteria in human blood, intravenous drugs and even prosthetics such as heart valves.

We'll travel the world with the prestigious Woods Hole Oceanographic Institution's Advanced Imaging and Visualization Laboratory, capturing images of these creatures in their natural underwater habitats. We'll explore how research on these animals is leading to medical breakthroughs. Through stunning 3D high-definition underwater imagery, we'll take on the prey's-eye view and look at jellyfish and rare invertebrates like they've never been seen before. Most people don't even know these animals exist, and even fewer have seen them up close like this.

Via Woods Hole's brand-new, state-of-the-art cameras, compelling storytelling, and filmmakers who are actual scientists, we'll go swimming with these eerie beauties and explore how they can both kill and cure, hurt or heal.