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Spatially Immersive Visualization Domes as a Marine Geoscientific Research Tool

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Abstract

This paper describes the development of a series of four spatially immersive visualization environments featuring dome projection screens, a concept borrowed from digital planetariums and science theatres. We outline the potential offered by domes as an architecture and a mature visualization technology in light of current challenges in marine geosciences. Still though, science visualization in domes has historically been focused on narrative rather than exploratory workflows required by scientific visualization. The lasting advantage proven by all of our spatially immersive setups is their potential to catalyze scientific communication.

CCS Concepts

• ***Computing methodologies*** → ***Computer graphics;*** *Graphics systems and interfaces;* • ***Human-centered computing*** → ***Visualization systems and tools;*** *Displays and imagers; Scientific visualization; Collaborative interaction; Visualization application domains;*

1. Introduction

Spatially immersive visualization environments more or less fully enclose viewers in some array of projection screens, monitors or other display devices that create the omnidirectional illusion of presence in some virtual environment. Yet, at the same time, they form quite a physical environment that confines the audience to that particular structure. Famous examples from the field of scientific visualization are the CAVE [CNSD*92] and later refinements such as the YURT [Cam16], the StarCAVE [DDS*09] and many others. The big advantage of such spaces is their combination of virtual and physical (mostly bodily) perception that could be described as a kind of mixed reality (XR [MK94]). In contrast, head mounted displays completely replace the perception of the physical world by that of a virtual reality (VR [Yoh01]).

What are the implications for visualization as part of the scientific workflow? From a purely logistical perspective, head mounted displays (HMDs) are orders of magnitude smaller and less costly than room-scale spatially immersive laboratories. Though, the full economical context is bigger than that. Following van Wijk's [VW05] generalized cost-revenue analysis for any sort of visualization approach, any new method must prove itself in light of existing tools. This is the case if the frequent profit of many users exceeds their combined cost of building, learning to handle, and operating a visualization tool.

Science has a strong social component, though: advances are made through the exchange of ideas [Abe80]. Thus, efficient scientific simulators should be catalyzers to communicate and negotiate individually gained insights towards a common interpretation among a group of users, preferably in real time. This works best when users are in the same room together and physically perceive each other with their own senses, talking face to face. Therefore, until the physical, social and psychological aspects of fully virtual worlds such as the metaverse [PK22] have been perfected, we argue that spatially immersive simulators accommodating audiences rather than individuals have a clear advantage through their natural communication channels.

This paper gives an account of the concepts, methods, and experiences developing of a series of four spatially immersive visualization laboratories at GEOMAR throughout the last 15 years, all relying on variations of a hemispheric (dome) projection screen. They borrow concepts and technology from the field of astrophysical visualization practiced in planetariums, but expand and adapt those for the use in the field of marine geosciences. As quantitative studies on usefulness and usability were beyond the scope of the first three developments, and such studies are yet to be carried out in the most recent project, accounts on user feedback have to remain anecdotal.

The main contributions of this paper are:

1. A characterization of domed visualization in astrophysics and marine geosciences

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2. A technical description of four complementary hemispheric dome simulators
3. An account of content developed for each platform and its reception
4. A qualitative merit assessment of domes for ocean science visualization

The paper is organized as follows. We first give an account of related work and underlying concepts, followed by the consecutive description of the four simulator architectures, with a focus on the first three that led up to the development of the current laboratory which still is under construction. We conclude the paper with a summary and future outlook.

2. Domes in Planetariums and Science Theatres

The history of spatially immersive visualization stretches far back in time, even once we limit the definition to audiovisual experiences involving moving imagery. A prominent example are the animated projections of the night sky at planetarium domes, dating back a century to the introduction of the projection planetarium by Zeiss in 1923 [Bau57]. Planetariums have always fulfilled van Wijk's equation thanks to the large audiences (of laypeople) they educate, even in light of their great cost.

Yet, the illusion is never perfect. The simulated stars of the night sky (or any other virtual environment) are not perceived at infinity but on the curved dome screen. This introduces an unfamiliar form of nonlinear distortion which is highly dependent on the position of a viewer relative to the dome screen. The closer to the dome center, the smaller is the distortion effect. Still, all members of the audience experience a certain amount of such distortion. Individuals close to each other share quite a similar impression, supporting their discussion of the experience. In summary, the larger a projection dome becomes, the better it can simulate large environments to large audiences, but even small domes offer interesting compromises dependent on audience size and kind of content.

Following a century of research and development on the above aspects, a solid body of work [Yu05, SRW08] describes the educational impact of planetariums and the well-established educational and visual best practices to achieve it. Today, planetarium domes worldwide number several thousands [Kwa17], by far outnumbering academic visualization laboratories of comparable investment, sharing a common minimum of technological standards through the use of a curved dome screen, and connected through a global network of professional organizations. With the introduction of panoramic or even hemispheric video projection (Fulldome Video) throughout the decade after the millennium, planetariums morphed from star theatres to transdisciplinary natural science theatres, broadening their thematic scope.

At the same time, little effort has been made to leverage their potential for direct scientific workflows, less due to organizational hurdles, but more profoundly due to the fact that these institutions offer explanatory (e.g., narrative) rather than exploratory (e.g., interactive) visualization workflows [YLT18]. Still, there exist (often anecdotal) reports [KF21] of purposeful scientific insight from planetarium visualizations particularly in the field of astrophysics (which has the longest tradition of providing content to planetariums). A Decadal Survey white paper [FSW*19] outlines the potential of planetariums for astrophysical research. In 2005 an early demonstration of a digital model of the cosmos using the Uniview [KHE*10] planetarium visualization software, particularly its ability to display dynamic animations of large datasets across arbitrary scales and in a georeferenced context inspired our conception of a domed visualization laboratory dedicated to the geosciences.

3. Immersive Visualization for Marine Geosciences

The earth sciences, and the marine sciences in particular, share a number of unique prerequisites with the fields of planetology and astrophysics: The realms studied cover orders of magnitude commonly perceived as too vast to grasp without auxiliary mental concepts; the objects of study are physically remote, thus their actual (robotic) exploration is expensive, highly time-critical and hardly repeatable; in many cases there is no preconception of situational awareness readily transferrable from our everyday lives (such as terrain texture, or "up" and "down" in open space or the water column).

Moreover, academic education particularly in the geosciences heavily relies on in-person field work and the construction of mental models based on the actual, physical presence in, and experience of an environment with one's own senses [LT12]. Oftentimes, such workflows hardly transfer to robotic exploration of the submarine environment, failing to construct the required situational awareness. As GEOMAR is one of Europe's largest multidisciplinary marine science institutions operating its own fleet of marine robotic platforms, our researchers frequently encounter such effects. From 2007 onwards, we thus conceived the concept of "Virtual Fieldwork on the Seafloor" [KHDK13], relying on holistic, high-resolution surveying using hydro acoustic and photogrammetric methods in order to create a photorealistic 3-dimensional digital model of seafloor outcrops. The study of these digital models back ashore in a virtual environment, free of the immediate constraints of seagoing research, motivated the conception of a series of spatially immersive simulators up to the present day. In hindsight of the four major simulator projects discussed below, the main features of an ideal virtual seafloor simulator can be summed up as follows:

1. It should yield a persistent, unique and quantitative added value for the scientific workflow, e.g. insight manifested in metadata as direct basis for publications.
2. Obeying van Wijk's value scheme, it should be easy and fun to use.
3. It should accommodate several users akin to a field work party of four to five.
4. The dome as a central hub with satellite nodes using head mounted displays should facilitate federated real-time remote collaboration.
5. Repeatable, swift construction of situational awareness should facilitate synoptic studies of large environments.
6. It should both display raw data (e.g. high-resolution film footage) and facilitate interactive real time computer graphics.
7. It should yield nested, georeferenced digital models across arbitrary scales, allowing local to global contextualization of stud-

ies: a single digital globe puts projects of various disciplines in context to each other.
8. With a prime focus on original research, it should nevertheless facilitate the derivation of highly curated outreach, formal and informal education visualizations through the introduction of an intuitive visual language (e.g., support “Exploranation” [YLT18]).

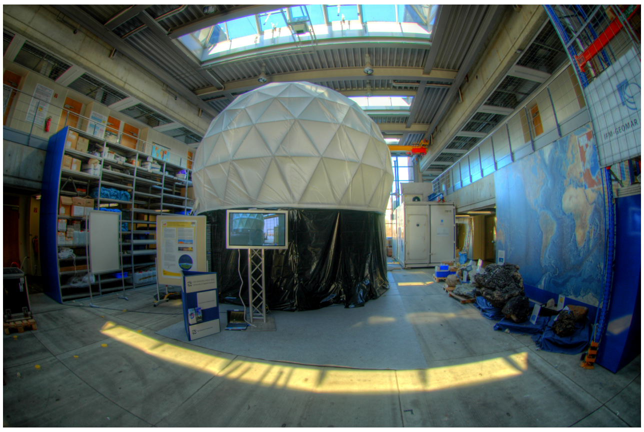

Figure 1: *An external view of the GEODOME with black curtains attached to block stray light.*

4. GEODOME

A privately financed sub-project of a master thesis in geosciences, the GEODOME was the first implementation of a visualization dome at GEOMAR (figure 1). It was the direct outcome of the realization of growing capabilities of early fulldome real time planetarium simulators, and thus heavily relied on direct planetarium technology and workflows.

4.1. Hardware and Software Setup

With no formal institutional backing (yet), the system was designed as a mobile semi-permanent installation. Omittance of seating maximized the size of audiences, while a diameter of 6 m was chosen based on practical experiences with semi-permanent planetariums: Considering that the majority of the population is less than 2m tall thus their eye-level is below 2 m, the radius of 3 m opens a space not perceived as confining, particularly when projecting virtual environments to be perceived at close to infinite distances. Nevertheless, the dome was designed as a spherical frustum of 220° vertical field of view, to offer a geometrically correct view below the horizon line at 180°. This meant the dome already was beyond room scale and had to be housed in a hangar. The most cost-efficient solution to produce a smooth hemispheric screen was cotton-coated fabric sewn into the shape of a balloon. Avoiding an expensive and psychologically repelling airlock into the inflated structure, it was held up by an outer third-frequency geodesic PVC framework covered in turn by translucent nylon fabric. The volume between the fabrics was constantly evacuated by a high-volume blower while the diameter of the geodesic framework had been chosen such that the projection screen was held up by the negative air pressure in

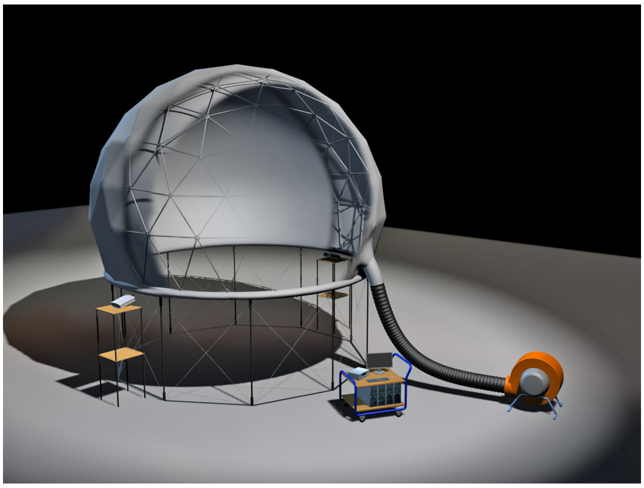

Figure 2: *Artistic cut-away rendering of the GEODOME with its geodesic strut framework, the inner and outer membrane attaching to the spring line. In front the blue mobile desk with computer rack for approximate scale.*

between the cloths. The dome rested free-standing on steel struts at 2m height in the leveled orientation of a classic planetarium (figure 2).

Projection was realized by a twin-channel system. Two Sony VPL-VW50 HD projectors opposed each other beneath the spring line of the dome, each equipped with a Raynox 185° fisheye converter lens originally designed for photography. Combined with a hard-edge mask, the built-in projector lens shift and an inclination of the projector of about 15°, this setup resembled the by-then state-of-the-art planetarium setup using two Sony 4K digital cinema projectors with custom fisheye optics. Thus, the system achieved a resolution of 1920 $\times$ 1920 pixels.

The visualization pipeline was driven by two separate twin-channel Windows PC clusters running the planetarium visualization software packages Uniview 1.2 by SCISS AB [KHE*10] and Digistar 3 by Evans and Sutherland, Inc. [LR02] respectively. While the former featured the above-mentioned digital globe from human to cosmic scales, the latter system was primarily used for playback of pre-rendered animations and live-action fulldome video. An array of video switches allowed switching between image generators at runtime. Calibration of the frustums, followed by warping and blending matrices to accommodate the curved screen was achieved by manual adaptation of templates provided for large 4K installations, merely leaving residual geometrical and blending imperfections across the zenith meridian where the projections met. A 5.1 channel home cinema sound system completed the setup.

4.2. Content

Early on it was realized that the desired production quality of scientific visualizations to be judged as meaningful by scientists would have to be produced offline and rendered as linear computer animations, given the time frame of a master thesis [Kwa08]. Thus,

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using the 3Dstudio Max 6 software, a number of animations was created around the topic of the Central American subduction zone and related on-land, submarine and subsurface phenomena:

1. An animated 3D illustration showing isopachs [KFP08] of the Central American Volcanic Arc originally published as 2D graphs;
2. Allsky panoramic imagery of volcanic outcrops of the Ilopango Caldera, El Salvador (figure 3), along with animated fly-throughs of photogrammetric outcrop reconstructions including 3D fault system annotations;
3. A pseudo-volumetric animation of a 3D seismic survey [DRT*11] of the subducting oceanic crustal slab beneath Central America;
4. An animated 3D arrangement of an (originally 2D) multimodal benthic habitat survey on the Costa Rican shelf [KSH*14], including georeferenced standard definition video billboards of the original remotely operated vehicle (ROV) footage at relevant sites;
5. A fulldome video live action sequence shot aboard the German research vessel RV Alkor in 2006 off Helgoland Island using an analog Konvas 2M 35mm cinema camera with a Nikon F 5.6 6 mm fisheye lens adapted to 35mm academy format.

All sequences were mastered using Adobe After Effects to a resolution of 2048 $\times$ 2048 pixels at 30 FPS, amounting to a total duration of 12 minutes.

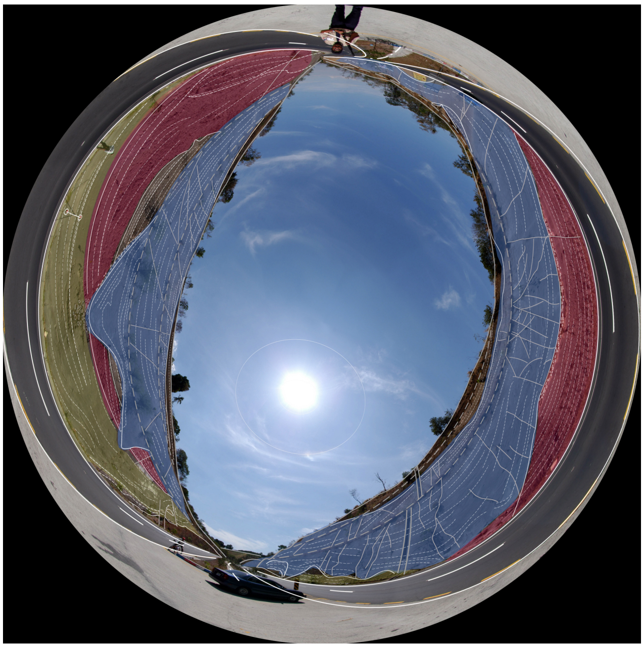

Figure 3: *Annotated allsky panorama of an outcrop of the Ilopango Caldera, El Salvador. Corresponding volcanic deposits are color coded blue, red and green.*

4.3. Deployment and Usage

The GEODOME system was constructed in 2007 and sporadically used throughout 2009 when it was sold to serve as themed entertainment. Content was produced in December 2007 and had a premiere screening the following year at the second evaluation of the Collaborative Research Centre 574 “Volatiles and Fluids in Subduction Zones” by the German Science Foundation, at a total audience of close to 100 viewers.

Anecdotal audience response suggests that the resolution was already deemed sufficient for the productive interpretation of photographic outcrop panoramas. Given that all other animations were reworkings of already published data, those outcrop visualizations yielded the greatest novelty, providing situational context on top of the large-scale outcrops they featured. A serious obstacle proved to be the effort required to prepare terrain or any other data to be loaded into Uniview (which therefore was not attempted and the software remained in its basic configuration). Its design philosophy dictated that data would not be loaded at runtime, apart from web mapping services.

From the point of usability, it was noted that the high position of the dome screen was unergonomic even to a standing audience and that, in contrast to the stars of the night sky, the orientation of geoscientific data should be looking downwards not up, to match human intuition. The strongest criticism though was directed at the fact that all presentations took the form of linear movies and there was no interaction with the content, lacking concrete, quantitative added value for the scientific workflow. Any insights gained would have to be replicated and manifested on established desktop workflows.

5. ARENA

Primarily to overcome the criticism of unintuitive orientation of geoscientific content in an upright dome, the next simulator was designed as a lower hemisphere, i.e. a bowl rather than a dome, inspired by a concept developed by Courchesne et al. [CLM06]. With a focus on collaboration, it was dubbed “Artificial Research Environment for Networked Analysis – ARENA”.

5.1. Hardware and Software Setup

For lack of practical experience with inverted domes, and officially still unfunded, a proof-of concept demonstrator of 5 m diameter was devised (figure 4). The cotton canvas was duplicated yet adapted, sustained by a tent-like strut system. At a radius of 20° around the nadir, an observation platform was left out of the screen for viewers to stand on. The screen could be closed to allow full surround vision. To maintain resolution, two projectors were mounted at the ceiling close to the spherical center of the screen. Though obstructing the view by their presence inside the simulator, viewers would only cast shadows on their feet, illuminated from above. At the same time, the ARENA was only about half as high in construction as the GEODOME, fitting into a normal office.

With projectors close to the center, the image generation was simplified to half a polar (fisheye, or dome master) panoramic image per projector with a favorable aspect ratio of 2:1 each. Two different approaches for projection optics were tested: (1) two down facing projectors with shifted fisheye adaptors close to the center, which left a hard edge similar to the GEODOME blend and (2) two

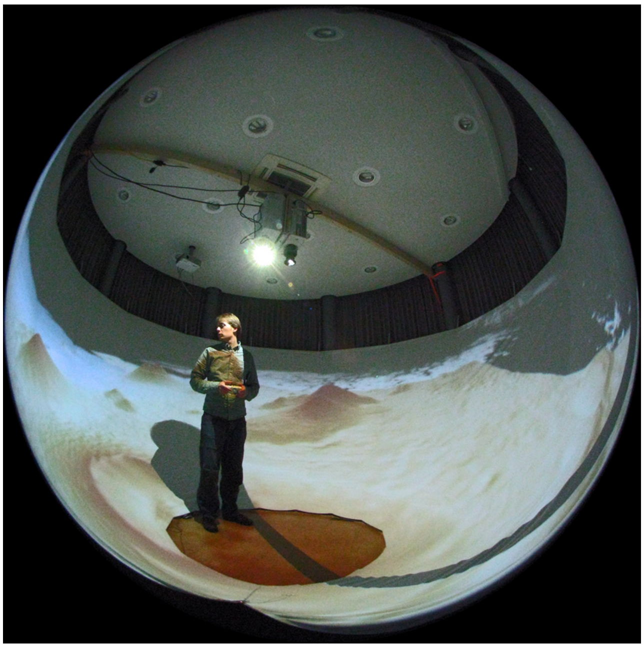

Figure 4: *A visualization of bathymetry using WWT in the 5 m diameter ARENA prototype. Note the black gap between projections, as blending was not achieved.*

horizontal front-facing projectors which image was deflected by a mirror prism downwards into a single fisheye adaptor.

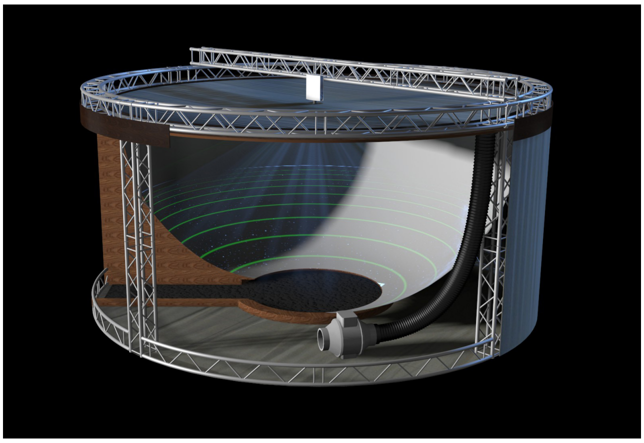

Figure 5: *Artistic cut-away rendering of the 6 m diameter ARENA design with the evacuation fan in front and part of the entrance to the left (brown).*

The following final design of the ARENA simulator enlarged the concept again to 6 m diameter (figure 5). The cotton canvas was once more shaped by negative pressure created inside a 6.5 m diameter drum of aluminum struts, with an airtight floor and perimeter made of nylon fabric, evacuated by a low-noise fan. It featured a sector of 0.8 m width sealing the low vacuum by two walls, forming an entrance stile, or gate, into the simulator. Again, the screen over the stile could be closed up. A black suspended cloth ceiling shut off any external light, effectively focusing peripheral vision to the screen.

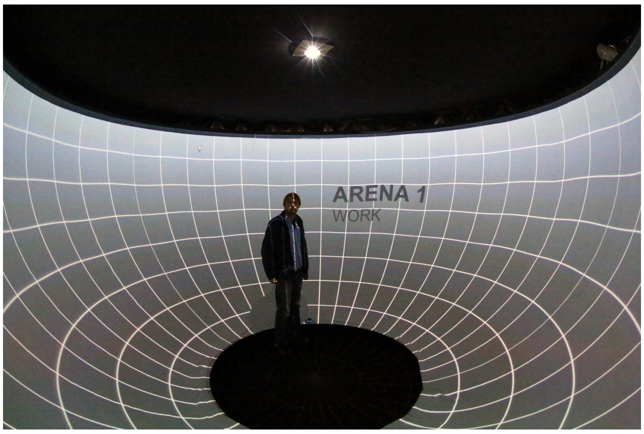

Figure 6: *Interior view of the ARENA with a geometric alignment grid displayed. Note the projector above.*

A single Projection Design F35 WQXGA DLP projector equipped with a dedicated Navitar 180° fisheye projection lens was suspended facing downwards from the spherical center (figure 6). Accepting a resolution drop down to 1600 × 1600 pixels, this meant a perfect image with no seams and minimal tuning effort by simply adapting the x and y shift of the lens mount in the projector. Again, a 5.1 channel home cinema sound system completed the setup. With the simplification of the projection architecture, the image generation pipeline could be reduced down to a single Windows PC playing back linear content using standard operating system media players. Real time graphics were generated using Worldwide Telescope (WWT, [Won08]), an open source planetarium software developed by Microsoft Research not only with astronomy but also earth sciences in mind. The virtual camera was oriented downwards according to the inverted screen orientation. A feature request enabled the geometric compression of the virtual field of view of 240° onto the physical screen of 180°, critically revealing a portion above the horizon such as mountain ranges. WWT not only introduced an open source solution, but also a full ecosystem of remote control, scripting, pre-processing of georeferenced terrain data to a local set of levels-of-detail as well as loading of photogrammetric 3D models and authoring of pre-scripted tours. Most importantly, it provides an interface for real time data exchange as well as a plugin for MS Excel. This meant that data plots on the digital globe in the dome could be manipulated and queried in real time, simultaneously to the immersive visualization.

5.2. Content

True to the Virtual Seafloor concept, we used the ARENA and WWT to interactively visualize seafloor outcrops for the first time in our project, browsing a diverse set of world-wide bathymetrical data sets produced in house as well as photogrammetric microbathymetry off the Cape Verdean archipelago [KHDK13] collected during RV METEOR cruise M80/3 in 2010.

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Moreover, a 12-minute fulldome documentary film tailored to the ARENA geometry and animated in 3Dstudio Max was produced in cooperation with the University of Applied Sciences in Kiel. It explained the geological mechanisms behind the formation of marine mineral resources, their abundance, economical potential and current plans to exploit them, with a focus on hydrothermal systems.

5.3. Deployment and Usage

In 2012, the final 6 m ARENA simulator was the first we built under a formal budget and the first to be conceived upon a fully developed theory of operation as part of a focus project on marine mineral resources. The preliminary 5 m screen diameter test installation of 2011 had been unfunded and its projection optics proved too complicated to justify further attempts to refine them. Although such a design would still fit an office, it was found too small as the relation of diameter and body height played an even greater role than in a planetarium dome:

First, the very limited space around the nadir for viewers to stand limits their number to four at most, with a comfortable limit reached with two viewers already, even within the 2 m platform diameter of the final ARENA design. Despite the effort that went into the production of the documentary, this meant that, beyond demos for individual stake holders, as a low-capacity venue the ARENA was too impractical for public outreach.

Even more importantly though, the position of the horizon plays a much greater role than for upright domes. It is visually much more tolerable not to see below the horizon than not to see anything above the horizon. In the 5 m demonstrator, one could almost peek over the perimeter of the screen, requiring one to sit on a chair.

The 6 m version, at its 3 m radius combined with the geometric compression of a 240° field of view, meant that the horizon line ran comfortably close to the eye line of a standing adult viewer. With the head close to the dome center, the minimized distortion was particularly convincing. With the ceiling obscured in darkness, there was no physical reference left for orientation, leading to a strong feeling of immersion which could lead to viewers losing track of the position of the entrance once it was obscured by the screen. The flipside of this effect were frequent reports of simulator sickness particularly by viewers who did not fly the simulator themselves, anticipating the virtual motion to come.

Once more a temporary and highly mobile structure, the ARENA was frequently used for demos throughout Kiel and was even shipped to the National Oceanography Centre in Southampton in 2014 for a screening of three weeks. Participation in the 1st Marine Imaging Workshop there brought a cohort of more than 100 viewers over the course of less than one month. Notably, though, scientific interest remained limited to a number of passive visualization and interpretation sessions. It became clear that, in the absence of powerful tools to interpret, query and annotate immersive models in real time on the dome, not in a spreadsheet, the benefit of the simulation was limited to enhanced communication of users while in the simulation session, leaving no artifacts. Still in 2014, safety concerns related to fire protection led the ARENA simulator into permanent storage.

6. ARENA 2

Since 2018 onwards the ARENA2 has been the latest iteration of spatially immersive visualization labs at GEOMAR. It is the result of three consecutive rounds of funding, each expanding a diligent technological concept built on a vision for marine data visualization serving GEOMAR and the greater Kiel based marine science community. At the core of this concept, the immersive visualization dome shall serve as a central hub of a scalable, federated visualization network of smaller platforms but also other domes, leverage the possibilities of telepresence on research cruises, and provide a portal not only for active research, but also for high-quality outreach and stakeholder engagement. Thus, it shall help to lead ocean sciences to new workflows in the digital age.

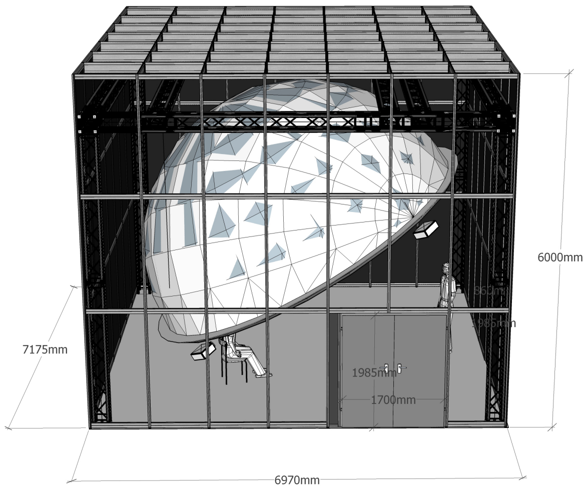

Figure 7: *Cut-away sketch of the ARENA2 with the enclosure (black), supporting strut system (black) and dome screen (white).*

6.1. Hardware and Software Setup

ARENA2 is the first (semi) permanent laboratory installation of our simulators. All aspects were realized, also for the first time, not in house but by a host of contractors, leaving the still massive task of integration and coordination to our team. The central element is a fiber reinforced hard shell dome of 6 m diameter that is flexibly suspended within an enclosure of 7 m × 7 m × 6 m (figure 7). At a nominal forward tilt of 21°, the orientation of the screen is variable in principle. Meeting room furniture accommodates parties of five scientists but can be removed for groups of up to 20 visitors at a time. A five-channel, stereoscopic WQXGA projection system of Barco F50 projectors is connected both to a pair of video playback servers and to a five-channel real time graphics PC cluster via an automated video switch matrix. A digital stage control system automates the entire laboratory. A four-channel passive OptiTrack motion tracking system allows real-time interaction with virtual environments. A semi-automatic calibration system determines the frustums as well as additional warping and blending matrices for each channel. The net resolution on the dome is 4.500 × 4.500 pixels, slightly above the still-valid 4K by 4K industry standard. The

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entire Microsoft Windows-based system is controlled by one workstation within the dome. Only the sound system has been inherited from the original ARENA lab.

The original concept foresaw a custom adaptation of the Unreal game engine by EPIC Games [San16] to serve as a universal visualization application. Much rather, a host of freely and commercially available software packages was implemented over the last four years, in order to accommodate the broadest spectrum of possibly requested use cases. This involves game engines, traditional clustered visualization software such as Paraview [Aya15] but also current open-source planetarium software such as Openspace [BAB*17] or Cosmoscout [SZGG22]. Moreover, it is possible to display the re-interpreted OpenGL-buffer of selected classic applications used in marine sciences, minimizing the requirements for data preparation (figure 8).

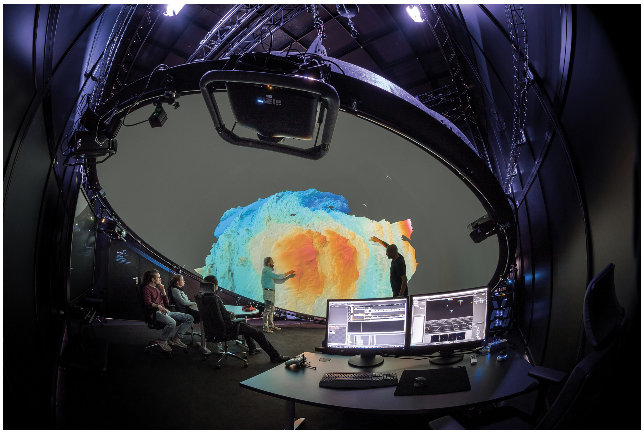

Figure 8: *Examination of a bathymetric data set in the ARENA2 by a scientific party of five. Control console with video playback and tracking software in front.*

To this day, all content is produced in-house. A hallmark immersive 360° video production of the ARENA2 lab has been a documentary on the 2020 RV ALKOR 533 cruise including sequences inside the JAGO submersible, which has been screened at several in-house and public events. Further documentary content came from our in-house aerial volcano monitoring group, operating over the Sicilian volcanoes. This material is currently being post processed.

A hallmark data set was contributed by the Schmidt Ocean Institute sponsored Virtual Vents project of 2016 [KKD*16], in which we could collect a holistic, comprehensive photogrammetric survey of an entire 500 m wide hydrothermal field in the northeastern Lau Basin, Tonga. Beyond the massive data set of 229.000 images, we also collected in-situ fulldome fisheye footage around the hydrothermal vents, which, integrated in a number of demos and short documentary clips, supports our case for the importance of real-time situational awareness on the seafloor.

6.2. Deployment and Usage

The ARENA2 lab builds on a solid number of GEOMAR projects related to or even dependent on the simulator. Critically, though, a large-scale marine science initiative in which the concept of the new simulator was to be embedded was not funded so that the envisioned marine science visualization network was confined to grass-roots measures on the working level. Consecutively, the pandemic practically prohibited the in-person use of the lab as soon as it became operational after a two-year construction phase. In the meantime, though, we entertain a series of academic and industrial projects ranging from computer graphics over marine geosciences and biology to physical oceanography and marine robotics, all the way to medical visualization. The lab frequently engages in high-level stake holder interactions, and has become a part of GEOMAR's corporate narrative.

The next major advances are planned in context of telepresence and federated immersive visualization, enhancing the value of seagoing expeditions and increasing our offers to stakeholders and the public.

7. Conclusion and Outlook

Attempting a transfer of planetarium-based dome visualization capabilities to the marine geosciences soon after they emerged in principle, we have come a long way not least due to the evident advances in general computer graphics. While head mounted display technology has become a consumer commodity and access to other spatially immersive infrastructures becomes ever easier, we still identify a unique value in domes, their sheer number and ubiquitous distribution, and also in their ties to natural sciences through planetariums and science theatres.

Any of the dome simulators we developed shared one strikingly positive effect, no matter how problematic the implementation: audiences immediately began to talk about their experiences as they happened. Domes are communication machines, and while this effect is hard to quantify, it is still vital for the scientific process. As such, all projects mentioned had a clear aspect of success.

Although planetarium-like implementations offer several advantages supporting scientific work, not only in communication but also visualizing complex, multimodal data sets, our experience revealed some recurring challenges that impede their adoption. It is especially the software frameworks, that (1) are too inflexible to allow either quick exchange of raw data and (2) often are not efficient enough to work with raw data rather than subsampled proxies. Focused on narrative formats, they never had to satisfy these requirements.

In contrast to planar immersive projection systems, domes have been, for the longest time of their history, monoscopic systems, owing their sense of immersion to the wide field of view and, recently, to motion parallax in video. The 360° field of view, lack of head tracking, and complex nonlinear warping of the dome screen have complicated the development of stereoscopy in this field. Most significantly, domes are aimed at groups of viewers, thus the use of head-tracked stereoscopic systems is greatly restricted. Ultimately, the additional investment in hardware is considerable, while stereoscopic workflows were informally rejected among the scientific clientele at GEOMAR. Consequently, we have developed our systems as monoscopic installations.

With the current ARENA2 simulator, we seek to overcome these hurdles, focusing on some of the same workflows (e.g. game engines) that the science theatres are turning to themselves, as today a whole spectrum of software platforms can be integrated into curved spatially immersive displays. What remains to be resolved is not so much the capabilities of computer graphics but the formulation and implementation of an objective, quantitative and repeatable scientific visualization workflow, alleviating the criticism towards visualization as a subjective method. The concept of spatial immersion as a catalyzer of communication and personal insight adds an exciting dimension to this task.

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