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Experiencing a Slice of the Sky: Immersive Rendering and Sonification of Antarctic Astronomy Data

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Abstract

We are creating INSTRUMENT: One Antarctic Night, a performative, multi-participant, and reconfigurable virtual reality artwork. We describe development of a large scale immersive star field from data collected by the AST3 (Antarctic Survey Telescope) robotic telescopes at Dome A of 817,373 astronomical objects from within the Large Magellanic Cloud within a game-engine based virtual environment. Real-time database queries, selections, and filtering operations enable participants to collaboratively interact with the star field to create dataremixes from astronomical data. Additionally, they facilitate collaborative creation of a soundscape via ambisonic audio spatialization and interactive sonification of the data utilizing data-driven granular synthesis. We evaluate the scalability of our approach and demonstrate that it maintains interactive frame rates at datasets with millions of astronomical objects, with each object being both individually manipulable or selectable and manipulable within subsets. Our user interface/interaction prototypes include a controller-attached UI and a wave/ripple based interaction where users grab hold of the star field and propagate waves and ripples throughout the virtual world. Our work arises from the art-science practice of dataremix: the appropriation and recombination (remixing) of data in any and all states along the continuum of its transformation from raw to processed to create new meaning.

One Antarctic Night: 4 Months

INSTRUMENT: One Antarctic Night (IOAN) is a performative and reconfigurable artwork that engages open astronomical data in combination with data generated by robotic telescopes in Antarctica. The environment at Dome A, the highest point on the Antarctic Plateau at 4093 meters above sea level, provides excellent conditions for astronomical observation: cold, dry, calm and dark for almost four months each year. The robotic Antarctic Survey Telescopes (AST3) was collaboratively deployed in 2012 by Texas A&M and the Beijing Astronomical Observatory. Designed for wide-field sky surveys its robotic mechanism captures an image every one to three minutes throughout the 4 month long Antarctic night [1]. The telescopes 10K x 10K sensor is the largest single CCD chip in use [2], [3]. The AST3 survey lead by Lifan Wang [4] is contributing to understanding phenomena such as the nature of dark energy, variable stars, exoplanets and the structures of supernovae.

IOAN, as an art-science collaboration and artwork explores the expressive potential of dataremix within an immersive context. In prior work[5, p. 4] we define DataRemix as: “the appropriation and recombination, (remixing) of data in any and all states along the continuum of its transformation from raw to processed.” Appropriation, recombination and re-contextualization of pre-existing material has a long tradition in the arts, spanning collage to DJ culture. Lessing argues that digital remix is as much a 21st Century literacy as is reading[6]. Dataremix makes use of aesthetically-impelled data-driven multi-modal mappings between data and formal elements of its representation that are neither hypothesis nor problem driven. Irrespective of the modality in which they are instantiated, the formal elements of visual, auditory or interactive mappings convey content which can relate to or comment upon some aspect of the data, its production or broader significance. Given this meta-level function of the representational and interactive idioms, the mappings may, but do not necessarily always, represent the data in a manner similar to scientific or information visualization, sonification or analytics.

Envisioned as a mechanism for questioning the broader narratives framing large scale data creation and representation, within dataremix data is considered a cultural raw material existing along a continuum from raw to processed. Its behavior is conceptualized as reversible along the continuum and having multiple states and transitions between states. State transitions can be trigged by any type of manipulation (algorithmic, analytic etc.) or decision that drives action upon the data by the designers or users of the system of representation in which the data is embedded. Multi-modal mappings externalize the continuum making it available to be remixed, creating outcomes different in intent and form from those envisioned by the original creators of the data, or the domain or problem-specific data-to-knowledge processing pipeline from which the data originated. Aligning with Navas's concept of regenerative remixes "juxtaposing two or more elements that are constantly updated, meaning that they are designed to change according to data flow [7, p. 8]” within dataremix, data is conceptualized as "behaving akin to a flux, flow, element or fluid [5]." As in more generalized forms of remix, the process of dataremix includes mechanisms for extending, adding, subtracting, and deriving data-driven content to create new work that stands on its own. As a process, dataremix results in "*datamades*" which are envisioned to function analogously to Duchamp’s *readymades*. The artwork appropriates astronomical data from multiple sources, remixes them to create a new context for the source data sets, and then recursively utilizes the appropriated/remixed data as source for a virtual instrument within which participants collaboratively create datamades through visual and auditory data remixing.

Here we present two aspects of ongoing work in creating the IOAN artwork: development of an immersive star field within a commodity game engine incorporating visual and auditory interaction with data from over 800,000 astronomical objects.

Immersive Star Field

We provide detailed descriptions of the data and systems utilized in the artwork in sections below, but first we present a brief overview of the installation. We are prototyping IOAN within a 20-foot by 20-foot installation space outfitted with a 7-channel spatialized audio system. Multiple users can enter the installation space and interact with the system through tracked head mounted displays and controllers. Not only do users share the same physical space but they share the same virtual environment. Their physical locations and movements are matched in the virtual world. This hybrid physical/virtual space facilitates their collaborative interaction with the star field to create a remixed soundscape. In an aesthetic gesture that inverts the relationship of the human body to astronomical scales, the astronomical data is rendered as a field of objects, a literal and poetic star field, surrounding the users at hip-to-waist height instead of above the users in the skybox, with each object positioned according to its astronomical galactic (RA/Dec) coordinates. Users can freely walk throughout the star field, select star objects for examination, or manipulate individual objects through gestures to trigger analytical operations. For example, a user can pick up a section of the stars nearby and shake it (as one might shake a sheet of fabric) to create ripples across the star field and ultimately filter the data and reveal aspects of it in order to create a remixed soundscape. When a user enters the space, they are exposed to a general ambience of a soft, granulated soundfield. This invites them to explore, via movement and the relation of their body to the data, the star field represented in the virtual environment. Movement through the star field generates spatialized ambient textures driven by the displacement of the data points around the user. As the user interacts with objects or subsets of objects, such as sends waves across the space, the soundfield transforms responsively, immersing the participants in sound driven by their engagement with the data.

We are developing the IOAN virtual environment within Unity's game engine[8]. The built-in rendering and physics engines, optimizations for real-time interaction, user interface elements, networking, multi-player modes, sound, artificial intelligence, graphical primitives, lighting models, and GPU accelerated shaders enable Unity to reduce the development overhead of creating visualizations and simulations [9]. Yet it also comes with inherent limitations for working with large multidimensional data such as, network capacity, features for object interaction during visualization [10] or the ability to modify data structures to accommodate simulation of real-world astronomical dataset sizes, which run in the range of millions to billions of data objects[11]. Our system works around the game engine's object number limitations by using GPU shaders to manipulate and render data and provide simultaneous interactive access to 817,373 objects representing a portion of the Large Magellanic Cloud (LMC) from the AST3 dataset (and up to 7M) astronomical objects, with the ability to select and query each from the individual level up to subsets of hundreds of thousands in parallel, in real-time, with little impact on interactive framerate performance.

Related Work

As one of the first sciences to make extensive use and experience the benefits of big data, the astronomy community has made significant investments in developing international data standards, open access middleware, and open access databases. Requirements by funding agencies for data to be made public, and efforts such as the International Virtual Observatory Alliance [12]–[14] make it possible to combine data from different observatories, telescope types and time periods to facilitate research. Additionally, large scale survey data is made accessible via online repositories such as the GAIA catalog [15], the SIMBAD Astronomical Database [16] and VizieR Catalogue Service [17].

By combining data from multiple instruments and surveys, astronomers and researchers from a wide range of disciplines are able to make discoveries in the original data and address research questions not originally posed by those who captured the data. Unexpected discoveries can be made through the application of novel analyses or by combining data from different instruments. Additionally, there exists a large community of amateur astronomers and a burgeoning citizen science movement which are contributing insights. Examples include projects such as the Kepler exoplanet search mission's planet hunters program (http://www.planethunters.org/) or the many publications (https://www.zooniverse.org/publications) that incorporate results from citizen scientists.

Active education outreach fostered by NASA in the US has increased access to open data and has encouraged similar developments within the international astronomy research community [18]. This availability of data has resulted in a vast body of work in space-art with artists exploring and making use of open astronomical data [19]. Our work exists in this context of art facilitated by open access to astronomical data while it simultaneously intersects with the realm of game engine based virtual worlds, yet it does not lie within the realm of astronomical illustration or space art, nor does it fully fall within the domain of pure visualization and sonification of large scale data. It resides at the edges and intersections amongst these domains and arises from a lineage or works such as Legrady, Villegas and Burbano's *We are Stardust* [20] or Norimichi's *A plaything for the great observers at rest* [21], Kubli's *Black Hole Horizon* [22] Simiconductor's (Jarman and Gerhard) *Brilliant Noise* [23], and *Black Rain* as well as *Ecce Homology* [24] and *ATLAS in silico* [25]–[27], prior works in which we explore aspects of dataremix, including scalable aesthetically impelled data-driven, yet non-hypothesis driven data mappings, and development of scalable auditory data signatures [28]. Similar to [29] our work explores approaches for integrating spatial and non-spatial astronomical data, and utilizes shaders [30] to store and load into the environment particle indexes, positions and textures.

Immersive technologies that have demonstrated value to researchers for collaboratively interacting with large high dimensional data for complex analysis include HMDs and high-resolution tiled and CAVE displays. Consumer grade GPUs, computing and virtual reality hardware, and flexible commodity game engines (e.g. Unity 3D, CryEngine, Torque, Unreal Engine, Stingray etc., [31]–[35] are increasingly being adopted for non-gaming use in visualization and simulation [36]–[39]. For example: 1) Multiplayer features within Unity are utilized [40] to facilitate collaborative interaction and exploration of marine surface current data and potential renewable energy generation arising from marine currents; 2) Through partitioning genome data with an octree and utilizing multi-tier level of detail analysis and representation, [41]genomes are visualized in 3D across multiple scales (atomic, nucleosome, chromatin fiber) in a Unity game-engine based application that outperforms the state of the art 3D genome viewer.

These are but a few examples of a growing trend, yet game engines and virtual reality have long been used to interact with astronomical data. AstroVR, an early virtual environment for collaborative astrophysics research inspired by multi-user networked games (MUDs Multi-User Dungeons), linked both local and remote services, such as SIMBAD[42]. Connectivity and knowledge sharing were central in both the Meta-Institute for Computational Astrophysics (MICA)[43] and in AstroSim[44]. Both systems were created inside the Second Life platform during approximately 2008 - 2012 to explore the utility of virtual reality and immersive worlds for distributed collaboration and in-world astronomical visualization and numerical simulation. MICA conceptualized an immersive 3-D data cinematography for the virtualization of scientific research, used Open Simulator[45], linked to external data sources, and developed interactive in-world visualizations of multidimensional data[46]. AstroSim undertook the representation of stellar dynamics. Both faced limitations inherent to the SecondLife social networking platform: few features for object interaction during visualization, network capacity, and limited numbers of objects simulated (up to tens of thousands as compared to potentially millions or billions of objects in a realistic simulation). Donalek and Djorgovski[47] use virtual reality for immersive and interactive visualization of high-dimensional yet abstract data with an ability to visualize 10^5 to 10^6 data points. While frame rate and performance information is not provided, the implementation appears to reflect an evolution of the concepts underlying their prior work in developing the MICA environment. Efforts to harness the power of game engines for visualization and interaction with ever larger astronomy data sets continue[48].

Data

AST3

Our source data consists of time-series photometry (light curves) for 817,373 objects from the LMC observed in 4,183 images taken by the 10K x 10K CCD AST3 camera designed for multi-band wide-field surveys[49]–[51] (Figure 1).

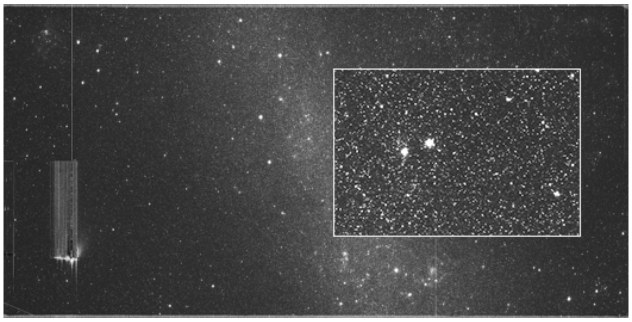

Figure 1: AST3 telescope image at timestamp 56048.0479629.

By registering and analyzing these partially overlapping images, astronomers have identified 817,373 astronomical objects with unique IDs distributed over 4,183 timed stamped luminance measurements, with an average of 927 measurements per object. Each ID has corresponding coordinates on the CCD sensor and galactic longitude and latitude (RA, Dec). From the luminance values, we derive secondary measurements such as mean intensity, binned magnitude and periodicity[52]. Figure 2 shows an openGL rendering of the catalogue data corresponding to the telescope image in Fig. 1. In Fig. 3 we overlay the catalogue render (now in red) onto the corresponding telescope image.

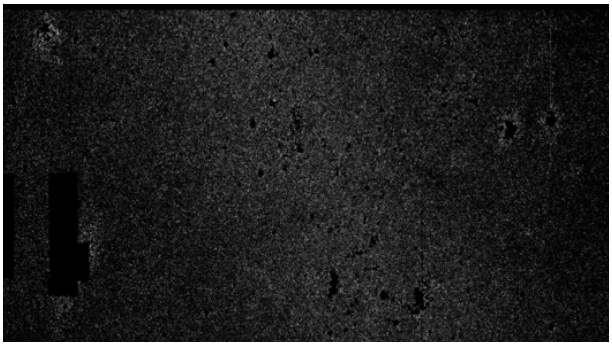

Figure 2: openGL rendering of timestamp 56048.0479629 from AST3 dataset.

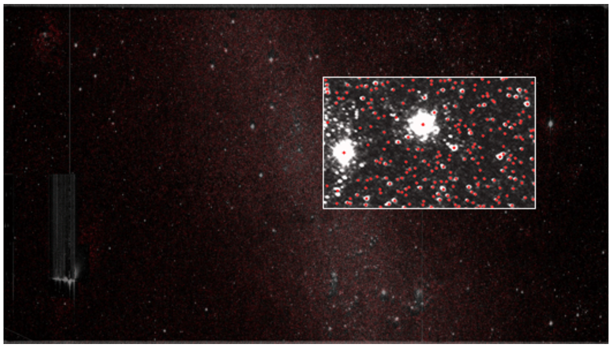

Figure 3: openGL render (red) overlaid on Fig. 1 telescope image (white).

Towards dataremix encodings and idioms

As an initial phase of dataremix, we annotate the AST3 objects with cross-referenced data from several large scale open access astronomical repositories, the GAIA Archive [15] and SIMBAD Astronomical Database. The GAIA mission aims to capture measurements for approximately one billion stars. The archive contains positional, photometry and spectroscopy measurements. The SIMBAD astronomical database provides information on astronomical objects that have been presented in publications. It cross-references measurements and astronomical data with bibliographic information. We compiled two additional databases by matching RA and Dec coordinates for objects in our AST3 data to objects in SIMBAD and GAIA by searching for nearest RA/Dec values with a very low failure threshold delimited to 1.5 degree radius to ensure accuracy. Data of numerous types including star type, magnitudes of different wavelengths of light, etc. was collected and compiled into new databases mapped to the global IDs of AST3 objects. The data is sparse both in that the SIMBAD and GAIA databases only contain data for 1/16th and 1/3rd of our astronomical objects, respectively, and that many entries do not contain values for all fields, yet it provides sufficient coverage to experiment with the design of expressive interactive auditory and visual representations incorporating multiple types of data in addition to the time series data from AST3.

In addition to cross-referenced annotations we calculate statistics including Lomb-Scargle (LS) periodograms [52]–[55] for all 817, 373 objects. LS periodograms reveal periodicity in irregularly sampled data and are utilized routinely in astronomy. Given the irregularly sampled nature of the AST3 light curve data, LS periodograms provide an entry point for algorithmic mapping and delineating auditory, visual and interactive structures within the dataremix engine for IOAN. While our work in scalable visual and auditory representations of this data is ongoing as part of development of the artwork, below we detail progress towards star field rendering and responsive sonification.

Slice of the sky

When encountering the AST3 telescope images initially we were struck by the high density of astronomical objects in each image and the relatively small slice of the sky as visible from Antarctica that the image represents. This motivated our approach to representing the data as a star field that one can walk about in. Within the framework of dataremix, we conceptualize the astronomical data collection as a form of abstraction that collapses vast distances and scales onto the 10K x 10K surface of the CCD, in a sense performing an initial phase of appropriation and re-contextualization of natural phenomena into digital data. Creating a star field from this slice of the sky allows us to convey the sense of scale and density of the number of astronomical objects. Placing the human body in this star field context such that movement displaces the astronomical objects and a distant horizon representing the edge of the data as it surrounds participants is simultaneously visible provides a sense of the unnatural boundaries that this abstraction creates.

Consistent with this concept, our objective became to include all of the AST3 objects for the LMC dataset that we were provided as part of the star field. Our challenge became how to present all 817,373 of the objects in the Unity based virtual world simultaneously, make them individually manipulable, make subsets manipulable, and the data accessible and remix-able instantaneously by multiple simultaneous participants as they collaboratively create visual and auditory dataremixes.

Audio and Sonification

The audio engine uses both individual data points and statistics to create an interactive and immersive sonic environment. This connection between large and small-scale data interpretations is important to provide a sense of the immense scale and detail of both the data and physical phenomena represented. Data statistics are mapped onto both fixed and stochastic variables for granular synthesis to sonify exploratory interaction of the entire star field. This analytic approach is mirrored by analyzing sample banks of audio files to retrieve timbral descriptors for sound grains, mapping data fields of the stars onto the descriptor space of the audio files used as material for granulation. Additionally, individual objects may be sonified into musical sequences driven by data of their light-curve periodograms and related statistics.

We chose an open multichannel speaker array to take advantage of high-order ambisonic spatialization techniques that are adaptable to any loudspeaker configuration. This enhances collaboration, allowing each user to experience the full soundfield while maintaining the capacity for voice contact, which may otherwise be hindered by a traditional binaural over-ear headphone mix. However, the software retains the possibility of producing a binaural mix output for a remote-user experience.

Large Scale Navigation / Data-Driven Granular Synthesis

The task of mapping such a large dataspace into an explorable soundfield presented several challenges due to the scale and relative completeness of the data. Because of the stellar object quantity and density, it appeared difficult to represent each data point sonically with a unique signature. To avoid over-saturation, we chose to generate statistical maps of available data fields for objects onto a quantized grid. When objects in a cell are activated by the user, these statistics are queried by the audio engine and generate a data driven grain cloud that spatially tracks and transforms as the user navigates the data.

The entire dataset is quantized into a 32x32 grid and run through a machine learning classifier to identify each cell as one of 10 possible classes. These grids are pre-computed and stored locally within the audio engine, to drive stochastic parameters for grain creation, and to avoid the need to make queries into SQL for every sound grain. Instrument type is chosen based on the most prevalent class in the current region an interaction occurs, while the volume of this sound scales with the intensity of the action. The instrument sample banks were chosen for their textural sound qualities, to highlight the sense of scale and granular detail associated with the data. We believe that timbre works as a better descriptor space for the multimodal data-mapping we wish to achieve.

Spatialization and Ambisonics

We utilize a high order ambisonic library for sound spatialization. Ambisonic spatialization works by algorithmically modeling a virtual space with sound sources and hypothetical microphones to simulate spatialization of objects across a loudspeaker array. Sources are encoded as a soundfield and decoded for a given loudspeaker configuration. This allows us to optimize our spatialization to the spaces of numerous installation environments. Effects and reverbs can be applied to the entire ambisonic soundfield through the library tools to enhance ambience and immersion.

System

The AST3, GAIA, SIMBAD and computed statistical data is stored in a MySQL 5.7 database residing on a Windows 10 workstation (AMD FX-8350 CPU, 16GB DDR4 ram). Via a default TCP/IP connection it is loaded into a shared 3D virtual space in Unity on a dedicated graphics workstation (intel i7 3570k, 16GB DDR3 ram) using a consumer grade graphics card (NVIDIA GTX 1080Ti). This is the core application, and additional users can connect either locally (on site in an exhibition space) or remotely/online with additional machines running the application. Fig. 4 shows a diagram of our system.

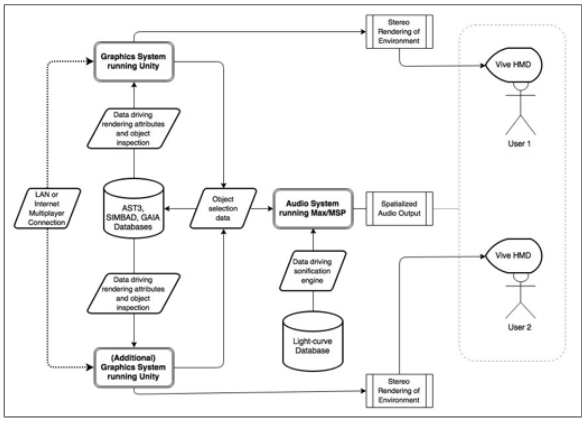

Figure 4: System Diagram.

In the virtual environment, objects selected by users query new data from the database to drive visuals and text data, as well as send information to a dedicated audio machine running

Max/MSP [56]. Here the object selection data is compared to an additional database of light curves – the graphs of each astronomical objects luminance over time – and this is used to drive HOA spatialization, note data, and VST parameters in a multi-instrument sequencer. The virtual instrument we use is Omnisphere [57].

This all combines to form the experience in the installation space, where the stereoscopic visuals are rendered through one or more HTC Vive room-tracking HMDs [58], while the spatialized audio is output through 6 surrounding satellite speakers and 1 subwoofer. The users perform object selection and filtering using the Vive hand controllers. All of these systems communicate over LAN, but the experience can also be accessed over the internet.

Audio

The audio engine is implemented in Max/MSP 7[55]. We selected Max for its robust DSP toolset, external libraries, VST hosting capabilities, and intercommunication with networked programs. Within the primary Max patch, the system communicates with Unity over UDP using the OpenSoundControl messaging protocol, receiving messages about user interaction and triggering events. The Unity environment updates Max at a synchronized rate from all client applications with information about user position, interactivity, and data engagement. Positioning and object IDs from Unity allow Max to query locally stored periodogram files and render them as musical sequences. Additionally, ambiance and interactive components of data exploration are spatialized to the user position within the multichannel soundfield. We utilize this method of networked packet exchange so that each user may affect the soundscape independently or collaboratively and have the sounds of their actions spatialized to their individual location, while retaining the ability to hear sonic responses from other users.

Sound sampling and synthesis is achieved through a combination of VST hosting and instruments coded within Max. Musical sequences are rendered with the aid of Spectrasonics Omnisphere, making use of its diverse and heterogeneous set of sampler and synthesizer instruments and parameter mapping capabilities to produce unique sonic identities for each object [59]. Exploration of aggregate data is sonified through a granular synthesizer coded in Max with a corpus of locally stored and pre-analyzed sound files. Sound file analysis is achieved with the aid of the MUBU library to return timbral descriptors for each grain [60]. Because we need the ability to adapt to both single and multi-user VR settings in a broad range of locations spanning home-based online users to exhibition spaces, a generative spatialization software solution was developed. We chose an ambisonic solution because of its ability to decode a soundfield to any speaker array or a binaural headphone mix. We use the HOA (high order ambisonic) [61][62]Library from CICM[63] to automatically generate an ambisonic decoder for the available loudspeaker configuration of a particular environment. The audio engine is run from a single Windows 10 workstation (Intel i7 6700k, 16GB DDR4) external to hosts and clients used for graphics. This is necessary for exhibition settings due to the high CPU and RAM usage needed for DSP tasks related to granulation and spatial diffusion of a 3rd-order ambisonic soundfield.

Virtual Environment in Unity

The virtual environment is implemented in Unity 5[8]. Our initial approach was to use Unity's game object structure to store each data point. Similar to scenarios reported in section 1 (above) we too encountered decreased performance when the number of data objects approaches 10^5 with this method. To overcome the limitations identified (above), and provide interaction at both granular and aggregate levels with a default data set of ~817K astronomical objects (that would eventually grow), we developed a point mesh based method where each object is rendered as one vertex in a large mesh. This method avoids the large CPU overhead that comes with managing a large number of Unity's game objects, and allows us to move much of the computational cost of manipulating the data in real-time to the GPU. Our current system represents the set of objects using a structure of composite point meshes, and distributes the access to contextual data between two different levels of interaction – one which uses an optimizable data structure for a few key database-wide fields, and one which defers the loading of the object-level data until it is requested.

Point Mesh Data Structure

We begin by computing a delaunay triangulation from the plot of all 817,373 objects, normalized on the RA/Dec axes and subdividing this triangulation into 256 parts. Each part is stored as a 2D mesh, allowing unity to render all data points as a composite mesh formed from these 256 models. A delaunay triangulation is a two-dimensional triangulation of a fixed set of points that maximizes the minimum angle[64]. This ensures triangle quality and allows us to use effective raycasting for individual object selection. The mesh computation was done in Matlab.

The submeshes are computed and stored in a custom file format which records the IDs (corresponding to our database) of each data point along with the vertex information. At runtime these IDs are loaded into an array with indices parallel to the vertex indices of the submesh, which enables them to be instantly accessed by raycast. These fields can used at runtime to drive graphical elements of the mesh, such as linking a specific color to a magnitude value for an object, or any other type of encoding of the original data and/or its annotations or derived statistics.

Prior to loading, a table of various other data fields can be pulled from the database and mapped to the vertex IDs. These fields can used at runtime to drive graphical elements of the mesh for visual encoding of the original data and its annotations.

GPU Based Data Manipulation

The pre-loaded fields are also used for our solution for high-performance data filtering. The data can be loaded into unused elements of the submeshes directly accessible by the GPU, such as the texture- mapping components. In Unity 5, the UV component alone can be used to store at least 8 floats per vertex. These elements are then used to drive shaders which can be supplied variables by the users in-game, allowing both parametric control as well as animation between shaders using a simple time variable. This enables users to perform analytic tasks such as quickly and smoothly moving all data points in the highest 25% average luminance to a virtual ceiling while dropping the rest to the floor, with minimal impact on performance.

Hardware: HMDs

Multiple HTC Vive headset/controller combinations are used for interaction within the installation. Unity integration is handled through OpenVR. We chose the Vive over the latest generation Oculus Rift with touch controllers for ease of room- level interaction. Another benefit is that multiple Vive HMDs can be used and tracked separately in one room with the same set of IR emitters.

Number of Objects	System 1: AVG FPS (Moving)	System 2: AVG FPS (Moving)	System 1 GPU Memory (Moving)	System 2 GPU Memory (Moving)	System 1 %GPU Load (Moving)	System 2 %GPU Load (Moving)
1	89.7	94.1	2502	2587	22	21
200000	90	94.4	2489	2596	24	24
400000	90	94.2	2423	2606	26	28
600000	89.6	94.2	2460	2616	28	31
800000	89.8	94.3	2569	2626	21	35
1000000	91.3	89.6	2226	2530	45	41
2000000	91.6	92	2342	2508	33	54
3000000	83.1	74.6	2367	2445	45	57
4000000	65.2	44.8	2476	2734	46	47
5000000	49	44.8	2591	2806	39	53
6000000	49	44.8	2667	2898	41	58
7000000	43.8	42.8	2792	2926	37	63

Table 1: Frame rate and GPU utilization comparison.

Evaluating Rendering and Interactive Performance

It is particularly important for VR systems to maintain a consistently high frame rate for usability. While our data set of astronomical objects contains approximately 800,000 objects, to evaluate how well the system we are developing for IOAN scales, we measure rendering performance with between 1 and 7,000,000 objects (each object is read into the system as a single vertex in a mesh but rendered as multiple vertices). Tests were performed utilizing two differently configured computers: System 1, an Intel i7 3570K with 16 GB of DDR3 RAM and a NVIDIA GTX 1080TI GPU and System 2, an Intel i7 6700K with 16 GB of DDR4 RAM and a NVIDIAGTX 970 GPU. We summarize results in Table 1 below.

We observe that the IOAN application is able to maintain framerates above 90 FPS with over 2,000,000 objects on both machines and over 45 FPS with up to 7000,000 objects. Offline (standalone user, non-networked) measurements were made with the headset initially positioned in the middle of the virtual environment. In the offline test conditions the orientation and position of the headset and controllers are subsequently moved and interaction occurs. In the online (multi-user, networked) conditions users are encouraged to move around and trigger interactions often. It is interesting to note that System 2, with its faster CPU and memory, outperforms System 1, with its faster GPU when rendering less than 1000,000 objects. Figure 5 below presents the differences in average FPS as number of objects increase for system 1 and 2 as shown in table 1 above.

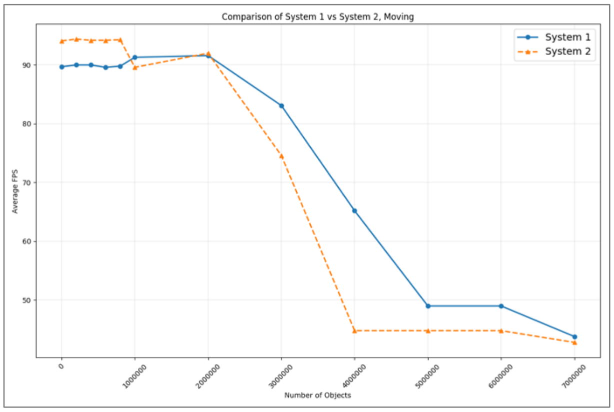

Figure 5: Frame rate as astronomical object number increases.

We also test the impact of the multi-user client server network architecture on framerates (Figure 6). Predictably, acting as the server has the strongest impact on performance for machines with a slower CPU. For this test condition System 1, exhibited a decrease of near 13 FPS. System 2, with the faster CPU, saw a decline of less than 5 FPS, between operating in a single player offline configuration and acting as a server for two clients (with a total of 3 players).

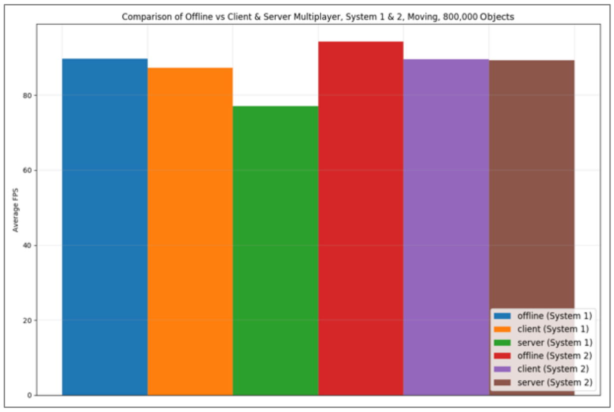

Figure 6 Frame rate in multi-user client/server configurations.
Blue: Offline system 1, Orange: Client system 1, Green: Server system 1
Red: Offline system 2, Purple: Client system 2, Brown: Server system 2

Tests were conducted with HTC Vive HMDs each with resolution of 1020x1200x2, refresh rate of 90Hz, FOV per eye of 11.814 degrees, and running SteamVR + Unity on system 1 and system 2 as specified above. In both test conditions, offline single user and networked multi-user the HMD was initially situated in the center of the virtual environment and users were then encouraged to move about freely and interact as frequently in as natural a manner as possible.

Prototyping Interaction

In addition to developing the underlying framework and system components for integration of audio and graphical system components, our ongoing work includes prototyping multiple approaches for individual and collaborative interaction and dataremix. Users are free to move about the star field. As they do so they displace the data surrounding them, and can at any time select an individual data object to explore in detail. The ID of the selected object is used to query additional information from the database which is made available to the user. We have prototyped a controller-attached UI (Figure 7) and a set of collaborative data filtering and sonification interactive features. One of these features is the ability to select an individual object within the star field and pick it up with the tracked handheld controller, and along with that take hold of a portion of the star field, in essence making a subset selection (Figure 8). Once the user "grabs hold" of this portion of the star field, further motion with the controller generates ripples and waves that propagate throughout the star field and interact with ripples/waves created by other participants and create audio remixes from the underlying data.

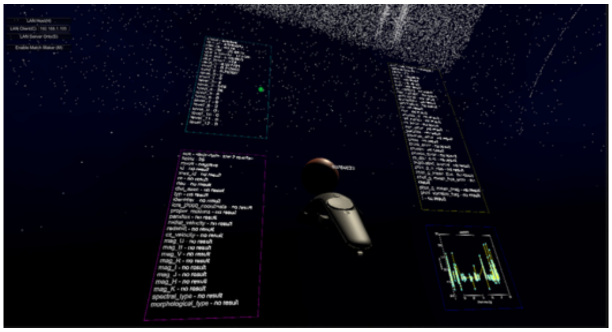

Figure 7: Controller-attached UI: A model of the astronomical object and a graphical UI displaying its data are attached to the controller.

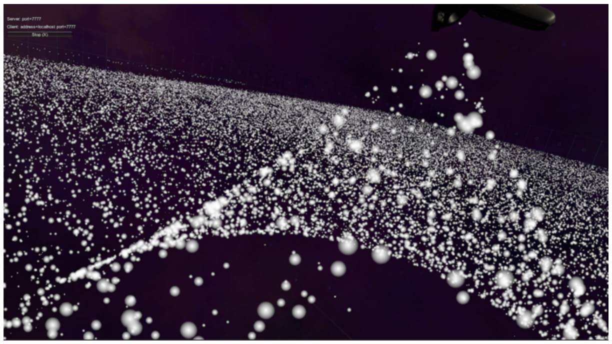

Figure 8: Picking up a portion of the star field prior to initiating a wave or ripple interaction.

Future Work

We are actively engaged in developing the IOAN installation and continue to prototype multiple alternative interaction modalities and visual and auditory encodings. Here we report on our progress in developing an interactive and immersive star field, with spatialized audio and sonification, comprised of 817,373 astronomical objects and a dataset containing lightcurves for each object, as well as cross referenced annotations from publicly available astronomical data archives. Developing IOAN is part of a series of works exploring how to operationalize the expressive potentials of dataremix[5], [65]. Building upon our prior work at the intersection of art, science and immersion[66] in developing procedurally generated scalable visual and auditory representations of large scale data in virtual environments[67]–[69], our future work will include developing the underlying dataremix framework so that it is extensible and generalizable for multiple types of data. Approaches we will explore to operationalizing dataremix include: 1) remixing in "noise" that has been removed from data throughout the process of refining the data during scientific analysis as a procedure to reverse processed data to "raw" unprocessed states, 2) multimodal representational strategies to externalize the operation of algorithmic processes at run time, 3) appropriate algorithms used for scientific analysis for expressive purposes, or 4) exploring the application of quantitative and qualitative listening modes[70], [71] for multiple layers of sonic representation, or 5) remixing data taken from multiple wavelengths and uncoupling time-based data from its original time series. This approach continues in the conceptual trajectory of art-science works that use raw or partially processed scientific data such as *Brilliant Noise*[23] or the genre of glitch art which creates meaning from imperfection. Ultimately, through developing IOAN as a datamade our aim explore the digitization of nature and culture as massive data and enable new meaning to emerge.

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