DEVELOPMENT OF AN EXTENDED REALITY (XR) TOOL FOR EARTH SCIENCE VISUALIZATION

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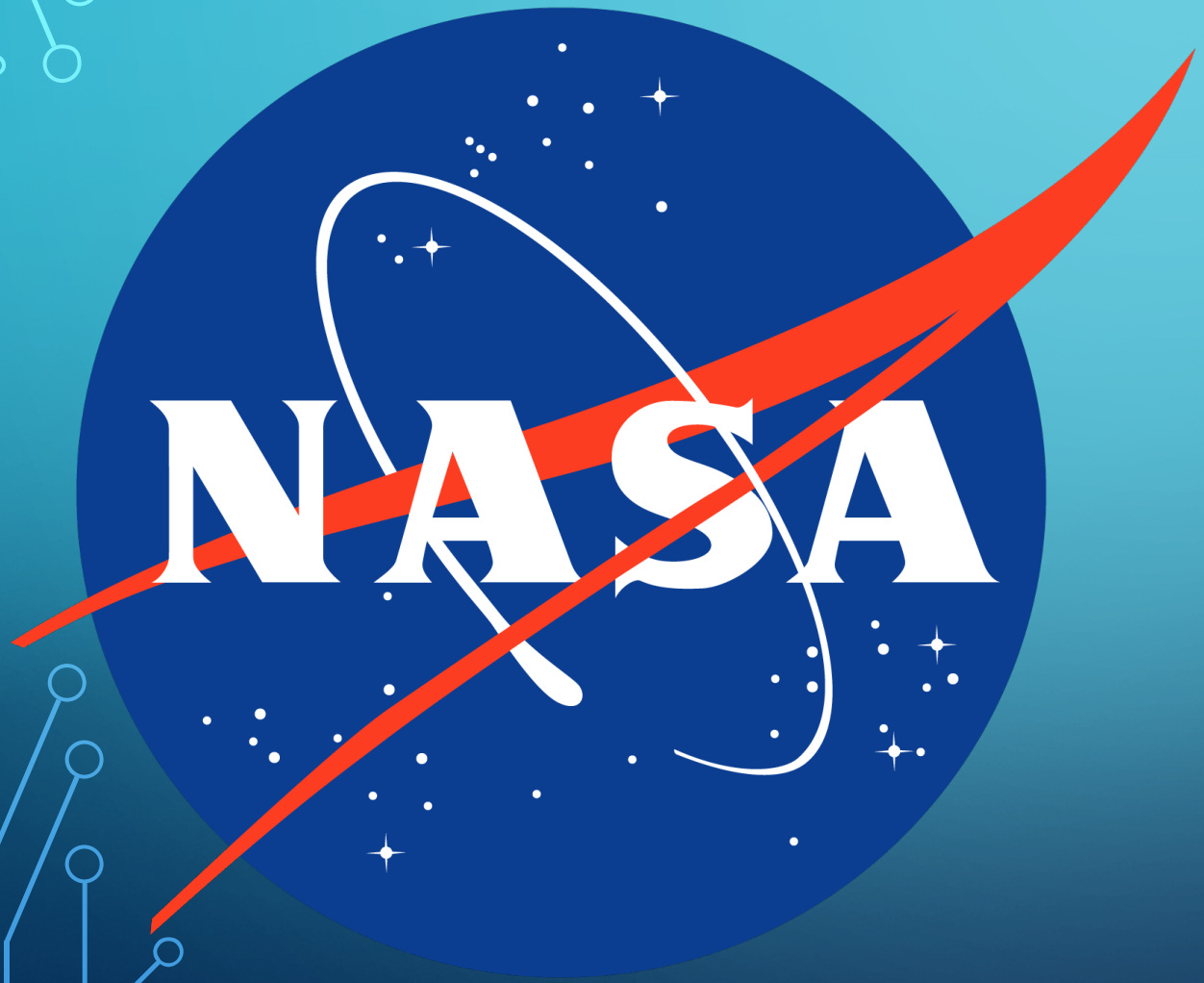
APL XR SYMPOSIUM, JULY 11

Funded through the NASA Earth Science Technology Office (ESTO) Advanced Information Systems Technology (AIST) Program

TEAM (NASA AND ACADEMIA)



- University of Maryland College Park
- University of Maryland Baltimore County
- University of North Texas

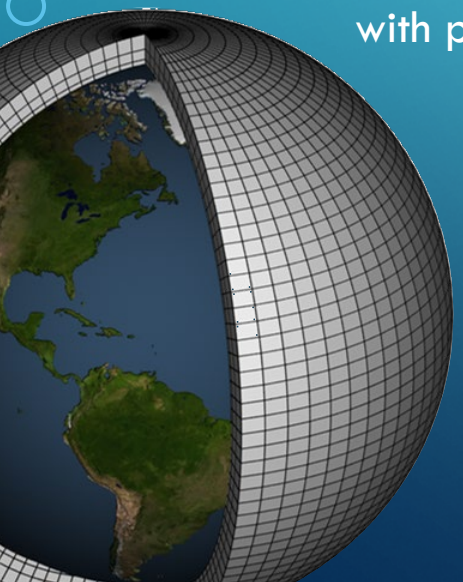
BACKGROUND

NUMERICAL CLIMATE MODELS

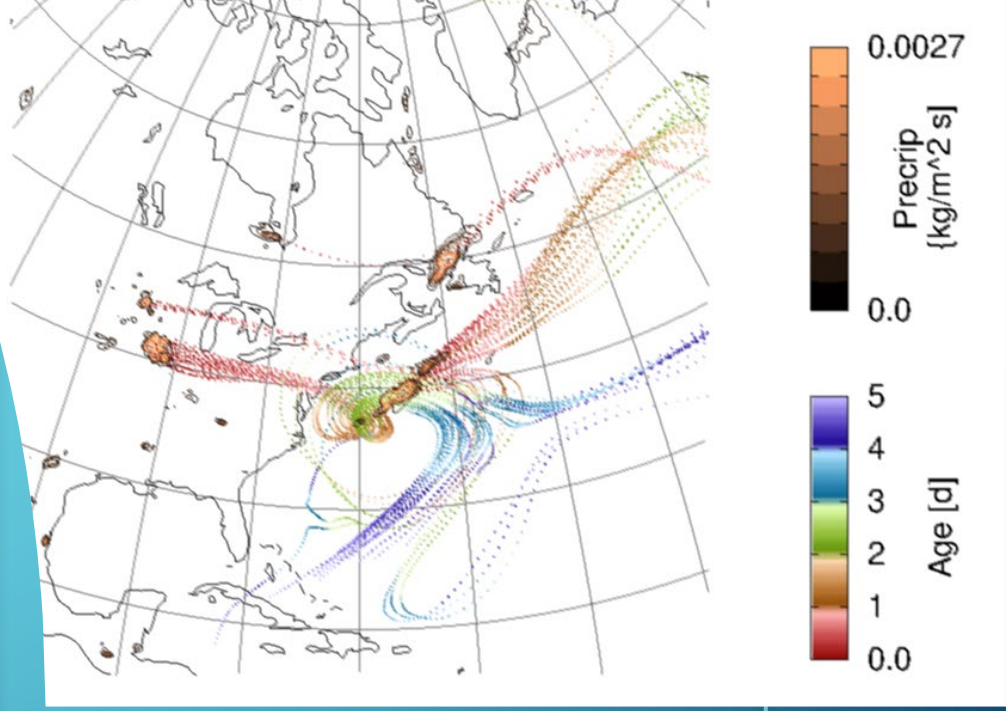
Traditionally, earth scientists view and analyze the result of calculated or measured observables with static 1-D, 2-D or 3-D plots.

Difficult to identify, track and understand the evolution of key features due to poor viewing angles and the nature of flat computer screens.

Numerical models, such as the NASA **Goddard Earth Observing System (GEOS)** climate model, are almost exclusively formulated and analyzed on Eulerian grids with points fixed in space and time.



However, atmospheric phenomena such as convective clouds, hurricanes and wildfire smoke plumes move with the 3-D flow field, and it is often difficult and unnatural to understand these phenomena in an Eulerian reference frame as opposed to the Lagrangian reference frame in which nature operates.



BENEFITS OF EXTENDED REALITY (XR)

- Improved Visualizations
  - Quicker and more **intuitive understanding of complex, spatially related,** problems and situations
  - Improved retention and recall
- Improved Interactions
- Improved Collaboration

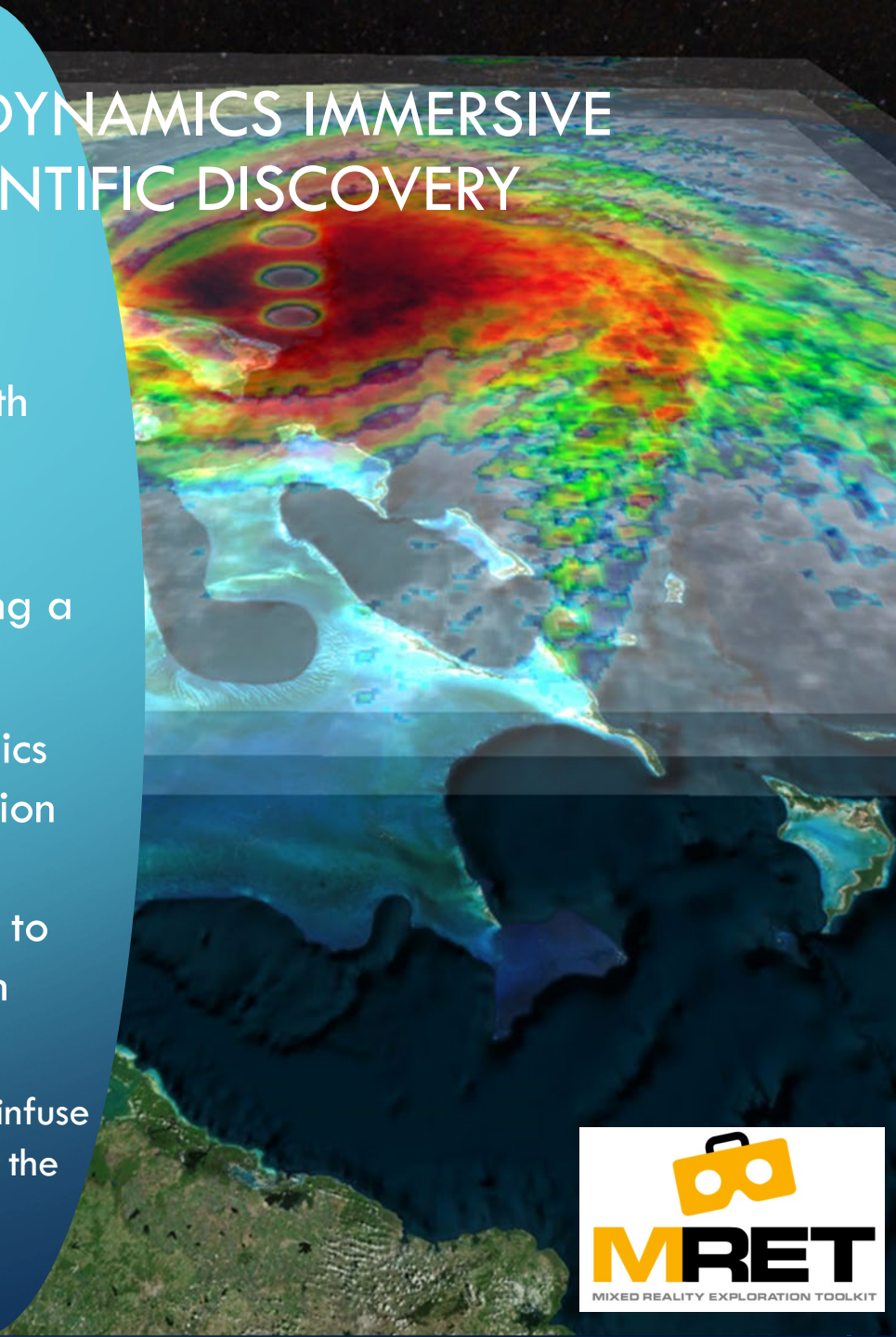
COMBINE XR WITH LAGRANGIAN MODEL OUTPUT

- Get ANIMATED Lagrangian Model Data
- Visualize as animated point clouds, volumetric data and isosurfaces in XR
- Use Interactions in XR to select parcels for subsequent model runs
- Goals for XR
  - Don't graft XR onto a traditional 2D/3D tool
  - Exploit unique user interaction paradigms and visualizations (Human Factors Based Approach)
  - Provide fluid framerates with large datasets

VALIXR

GEOS VISUALIZATION AND LAGRANGIAN DYNAMICS IMMERSIVE EXTENDED REALITY TOOL (VALIXR) FOR SCIENTIFIC DISCOVERY

- Integrate trajectory model into GEOS numerical weather model to calculate Lagrangian trajectories of specific Earth Science phenomena
- Create an open-source point cloud component for visualizing and animating a set of point clouds netCDF files
- Enhance MRET with Lagrangian Dynamics (LD) tools for the initialization, finalization and visualization of trajectories with associated dynamic budget terms, and to output a parameter package for use in GEOS model runs
  - Working closely with two universities to infuse improved human factors paradigms into the visualizations and interactions in XR



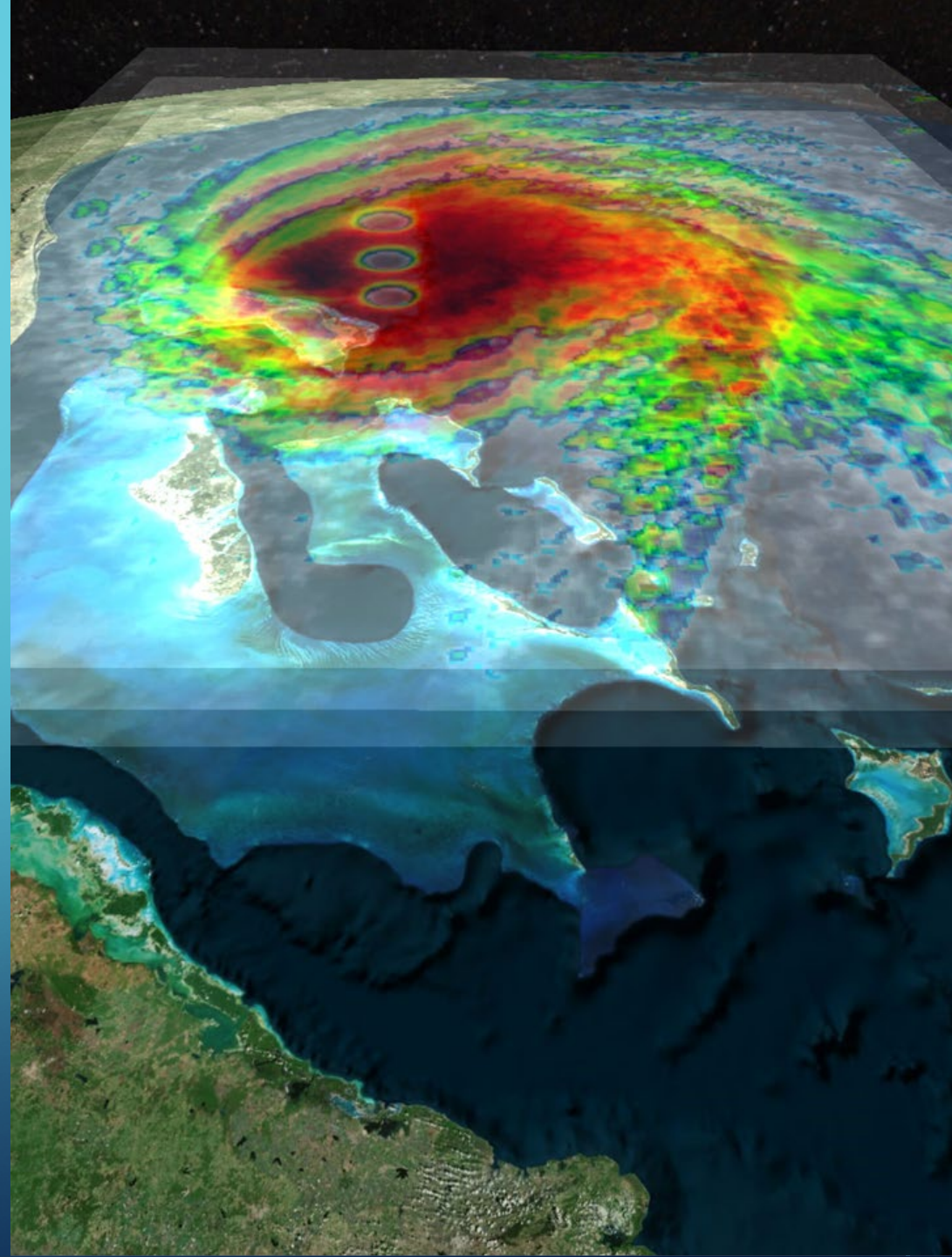
ESTO AIST 2021 Project
(Started Aug 1, 2022)

MRET
MIXED REALITY EXPLORATION TOOLKIT

OBJECTIVES

- VALIXR will provide Earth scientists:
  - Enhanced scientific discovery of key phenomena in the Earth system through the combination of advanced visualization and quantitative LD with NASA models and data
  - An immersive, interactive, and animated visualization of GEOS fields and particle trajectories to allow scientists to intuitively initialize LD for subsequent GEOS model runs
  - **Intuitive initialization, manipulation and interaction with GEOS data and trajectory paths through the use of XR**

To provide the tools to conduct “what-if” investigations that can result in actionable predictions



ADVANCEMENTS

Integrating GigaTraj with the GEOS model will enable a more natural, feature-specific analysis of Earth science phenomena compared to the current Eulerian (fixed grid points in space/time) nature of the GEOS model and its associated output.

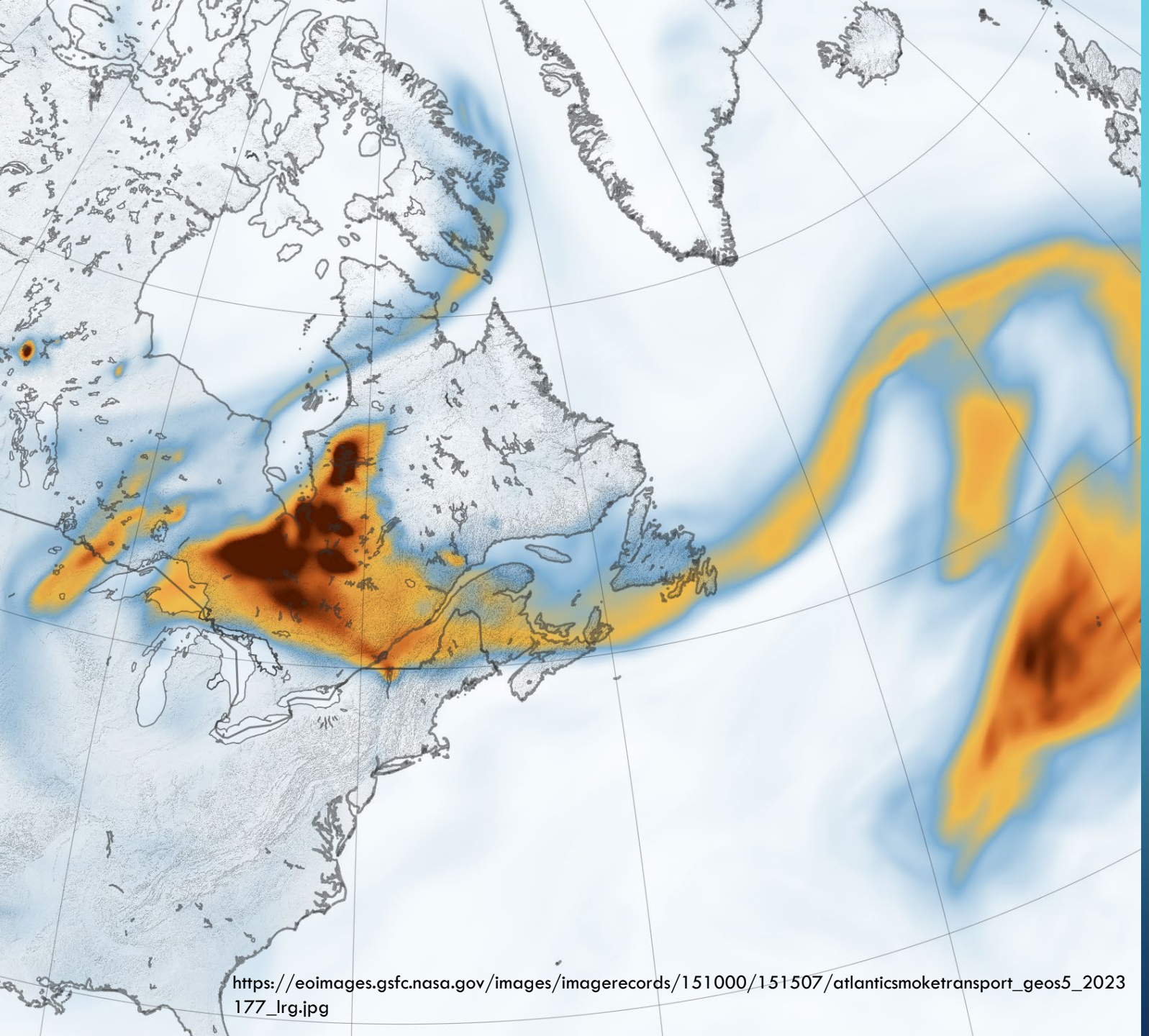
Leveraging the NASA open source MRET tool and integrating it with a generalized open-source point cloud system has huge applicability to any Earth Science domain.

The key challenges lie with ingesting, visualizing, and animating large sets of large point cloud files and displaying and interacting with them in an intuitive way for Earth Scientists.

VALIXR MRET will provide an open source XR foundation for integration with Earth Science Digital Twin architectures and other weather (or really any point cloud generating) numerical models, and will be especially suited for the coming generation of fast turn-around, ML-enhanced numerical models.

An open-source XR software for animating and visualizing large point clouds has applicability for further research projects and applications even outside of NASA domains.

USE CASE #1: WILDFIRES



https://eoimages.gsfc.nasa.gov/images/imagerecords/151000/151507/atlanticsmoketransport_geos5_2023177_lrg.jpg

- Analyze wildfire events and understand their short and long term effects on the atmosphere.
- Use VALIXR to tag the smoke plumes of interest and initialize an ensemble of Lagrangian trajectories that will follow the center of mass of that plume as it moves around the globe. See additional diagnostics along the trajectory of the smoke plumes to understand the physics of their evolution.
  - Trajectories colored by temperature to identify rising and sinking motions of the plume from radiative heating effects
  - Dry and wet deposition budget terms interpolated to the trajectory locations that describe the removal of smoke
  - Sub-grid scale processes interpolated to the trajectory locations that describe the effect of mixing and transport not explicitly simulated on the model grid

https://eoimages.gsfc.nasa.gov/images/imagerecords/8000/8542/ISS016-E-27426_lrg.jpg

USE CASE #2: DEEP MOIST CONVECTION

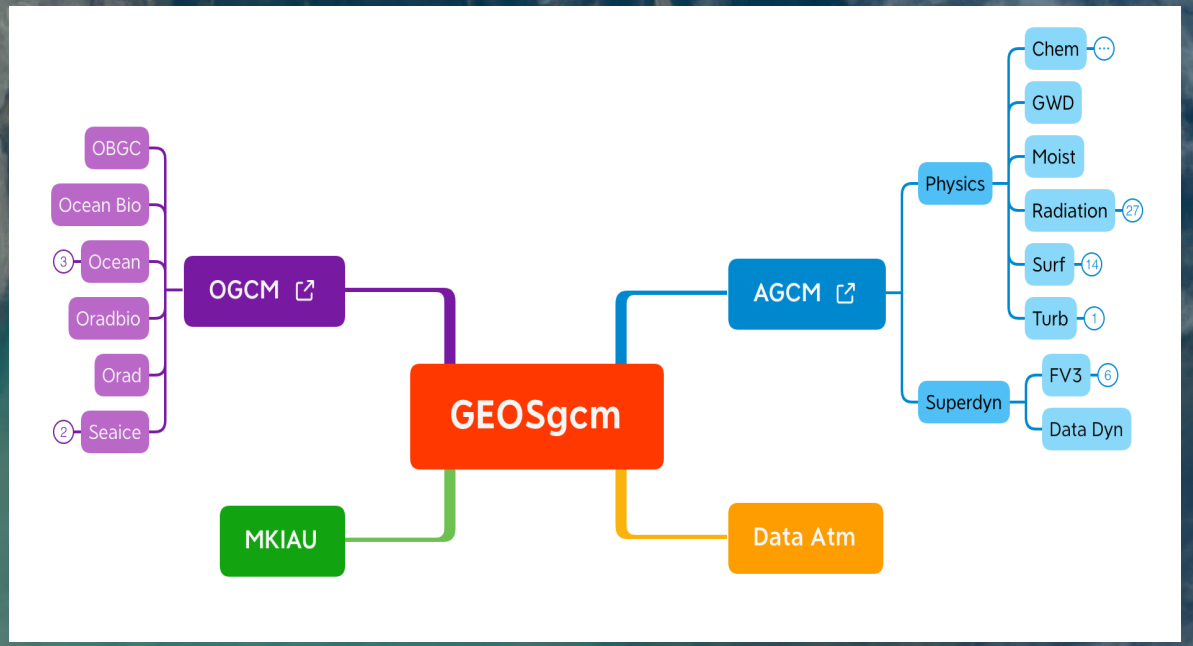
- Examine the fate of overshooting thunderstorm tops, to determine the long-term effects of polluted air injected into the lower stratosphere by severe thunderstorms.
- Use VALIXR to identify overshooting thunderstorms and trace the paths of injected air over the course of the next few days.
  - Generate air particle initial locations over storm locations in the lowermost stratosphere, using radar and satellite imagery as well as GEOS tropopause data. Use these particle locations and times to initialize the trajectory model.
  - Receive the trajectory model output back into VALIXR for visualization and analysis.
  - Tag air particles by attributes such as potential temperature, tropopause-relative altitude, time spent in the stratosphere, etc. Use these attributes to understand the air particle dynamical and chemical histories after injection.

DEVELOPMENT

2 YEAR PHASED DEVELOPMENT

- Foundation Phase
  - Requirements, Design
  - Scientists and Programmers talked past each other – lot to learn, misunderstandings, and subsequent requirements creep as we understood the scientists better
  - Human Factors group very helpful in codifying how the scientists work
- Development Phase
  - GEOS and GigaTraj Development
  - XR Development
    - Point Cloud Development
    - XR Development
    - Neural Network Optimization Development
- Refinement (On-going)

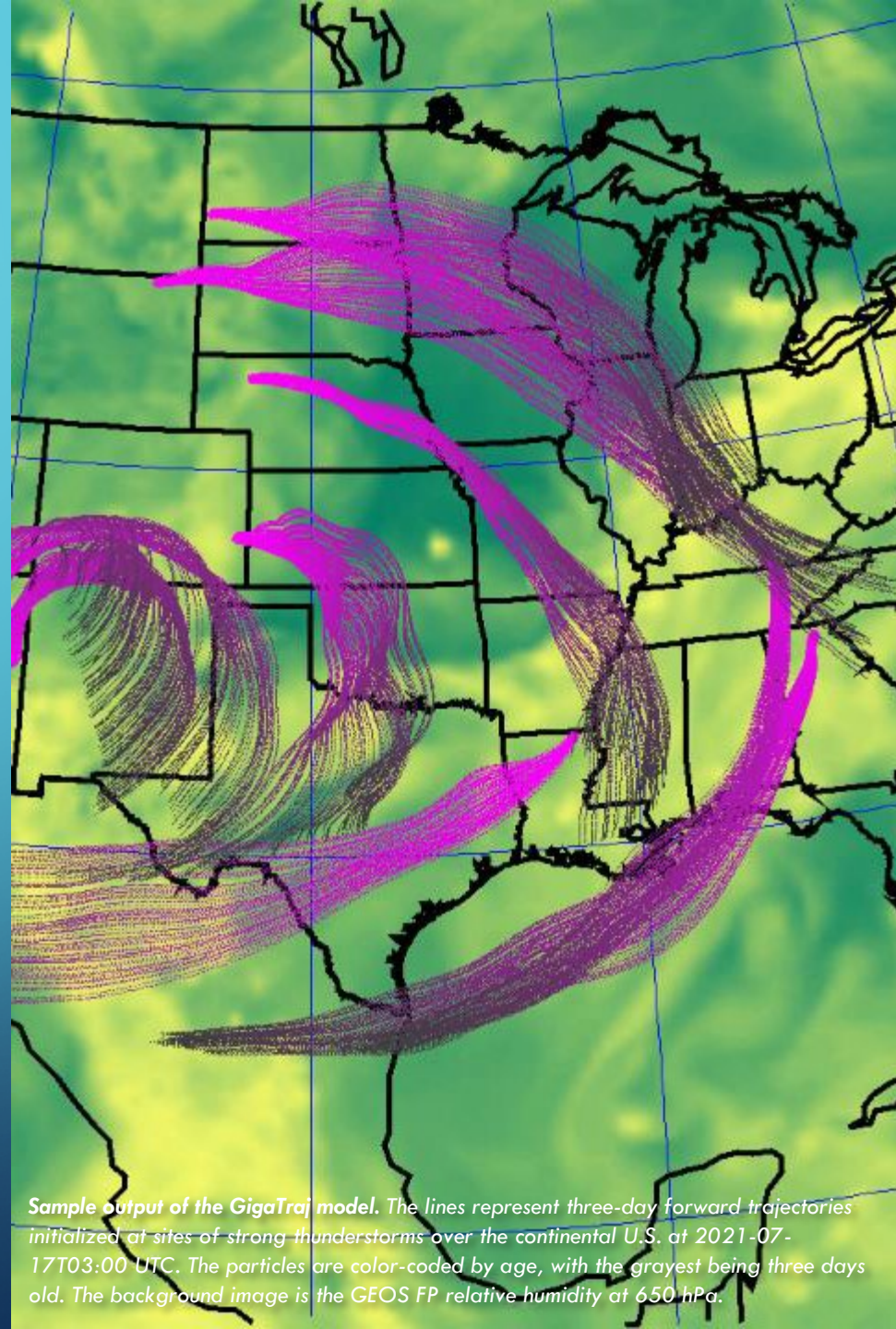
WHAT IS GEOS



- GEOS is a highly modular Earth modeling system based upon the Earth System Modeling Framework (ESTO funded)
  - Data assimilation
  - Weather forecasting
  - Chemistry transport, etc.
- Additional modules that model physical processes can be readily incorporated with a thin component wrapper that conforms to GEOS conventions.

GIGATRAJ

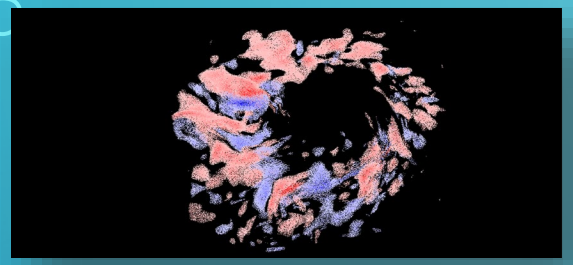
- Lagrangian trajectory model previously developed at Goddard Space Flight Center for use in atmospheric research
- Traces particle motions as they are carried by the wind fields obtained from any of several meteorological sources (selectable at run-time) and in any of several coordinate systems, reflecting different physical approximations. For example, particles may be traced
  - Kinematically (i.e., using vertical wind fields)
  - Isentropically (along surfaces of potential temperature)
  - Diabatically (approximately along isentropic surfaces, while using diabatic heating fields to move the particles vertically)
- GigaTraj has been wrapped as an Earth System Modeling Framework (ESMF) component in GEOS



Sample output of the GigaTraj model. *The lines represent three-day forward trajectories initialized at sites of strong thunderstorms over the continental U.S. at 2021-07-17T03:00 UTC. The particles are color-coded by age, with the grayest being three days old. The background image is the GEOS FP relative humidity at 650 hPa.*

POINT CLOUDS DEVELOPMENT

Point Clouds Implementation has been a major effort. VALIXR point cloud requirements (animatable, selectable) versus more general point cloud requirements have required pursuing multiple solutions



ComputeRasterizer

Porting ComputeRasterizer (open source c++ GLSL implementation) components and logic to Unity

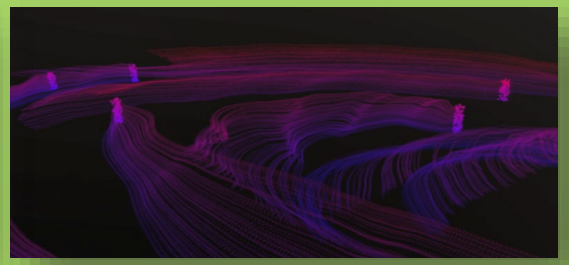
- BILLIONS of points
- Animatable with minor modifications
- Integration of ComputeRasterizer as DLL failed (UMBC)
- Unity Shader Language (HLSL) limited compared to GLSL
- Two previous attempts to translate GLSL to HLSL have failed (UMD and UCLA)
- Third attempt on-going

Remote Rendering

Render PC frames on remote computer and transfer to VALIXR computer (UMCP)

- BILLIONS of points
- Animatable with minor modifications
- Too slow (1 frame/second)
- Distorted graphics

UMBC upgraded the Potree Unity implementation to support Potree v2: https://github.com/SFraissTU/BA_PointCloud/commit/674a172c1f7ff88ba0ca19a330fbb4470e9fcdff



Unity VFX

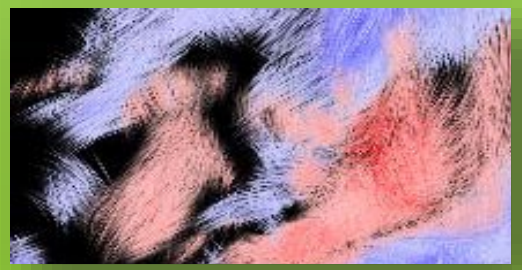
Native Unity solution that relies on Unity VFX Graph for visualizing point clouds

- Limited by GPU (10M-40M points)
- Animatable
- Selectable

Potree

Integration of open source point cloud solution for visualizing point clouds

- BILLIONS of points
- Requires preprocessing
- Static (not animatable)
- No transparency



Neural Net

Using NN to enhance point cloud visualization with FX (UMCP)

- Mitigates issues with visualizing limited size point clouds
- Post processing step in pipeline
- Limitations:
  - Approximation
  - Needs training for domain
  - Not interactable
  - Does not optimize the point cloud
- Still to be integrated

VALIXR

Holes and Gaps

Aliasing Artifacts

ENHANCE POINT-CLOUD RENDERING THROUGH NEURAL NETWORK TECHNIQUES

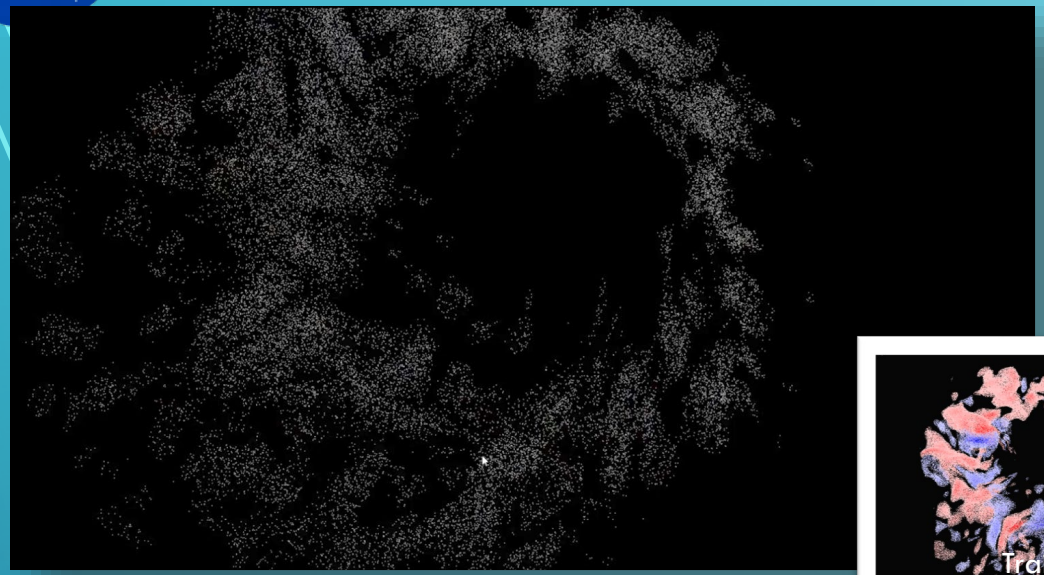
Deferred rendering with 2D neural networks can enhance high-quality and real-time rendering of point clouds

- Mitigate image artifacts in point-cloud rendering through neural network techniques

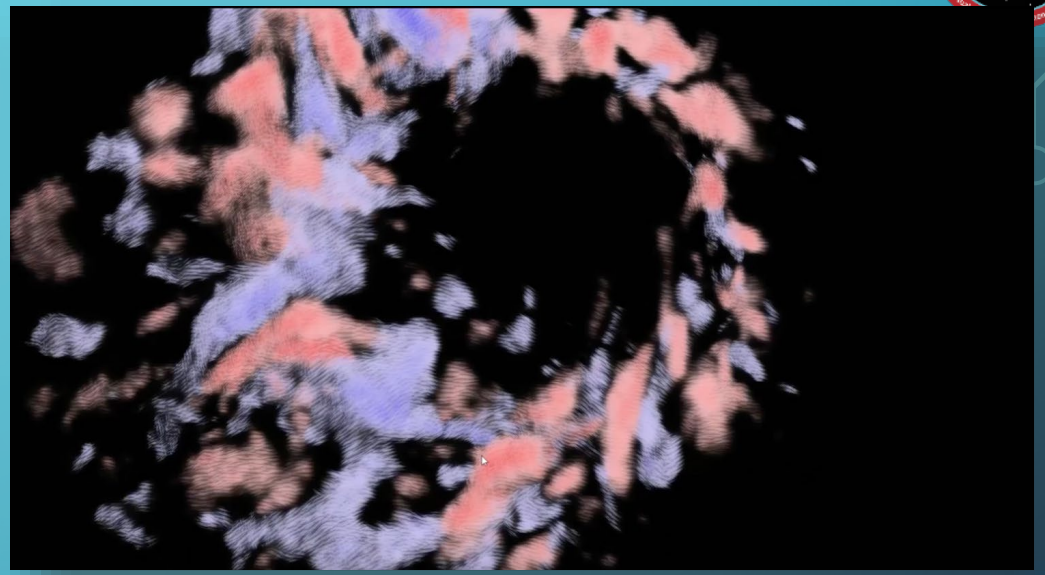
Leverage same concept for efficient, high-quality visualization of point clouds in VALIXR

Schütz, Markus, Bernhard Kerbl, and Michael Wimmer. "Rendering point clouds with compute shaders and vertex order optimization." *Computer Graphics Forum*. Vol. 40. No. 4. 2021.

NEURAL NETWORK SUPER-RESOLUTION



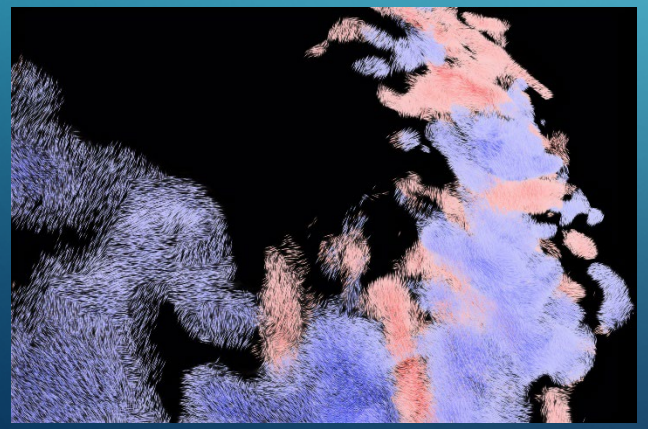
Sparse Point Cloud 2D Image



Neural Super-resolution of same image

Rendering Performance

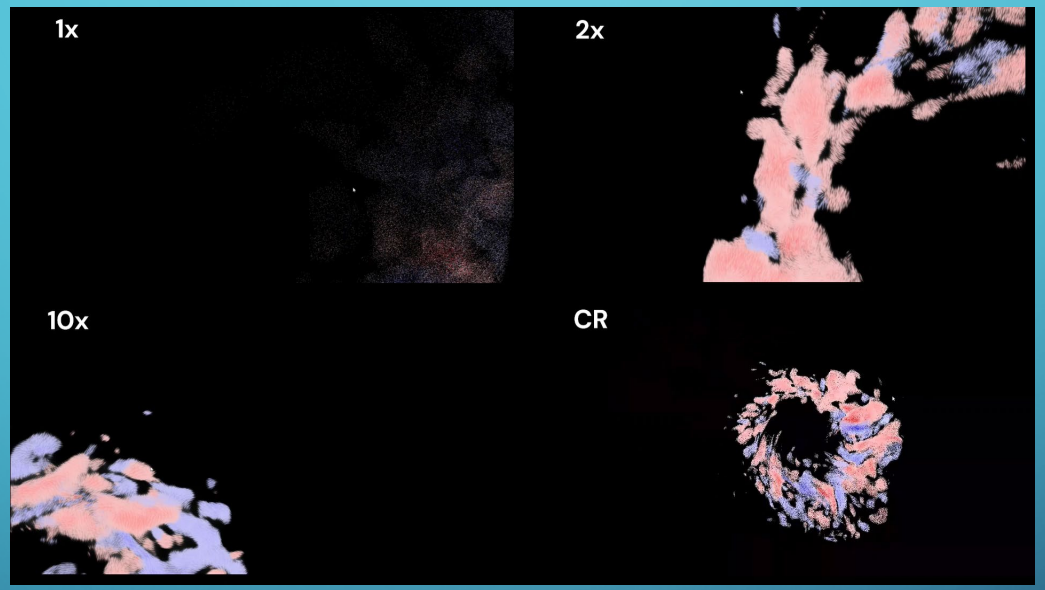
(on GeForce RTX 2080Ti GPU at 2000 × 1328)



Hurricane (400K pts) 145 fps

Storms (45M pts) 147 fps

Morro Bay Terrain (350M pts) 139 fps

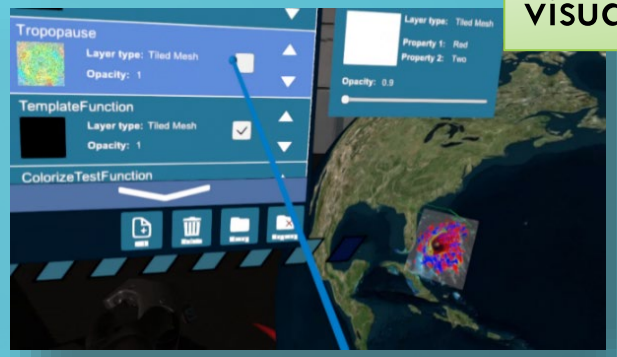

1x
2x
10x
CR

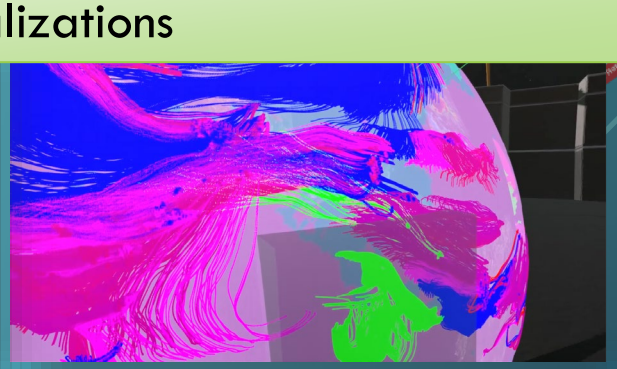
MRET

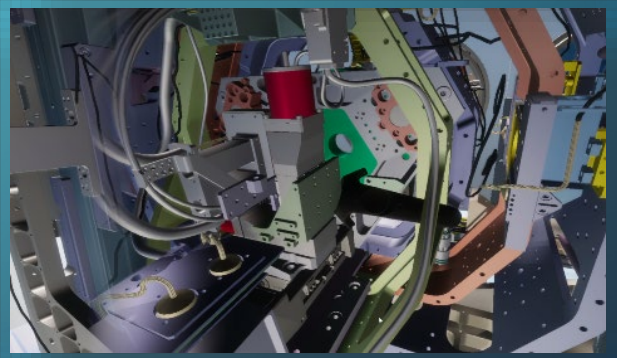
MIXED REALITY EXPLORATION TOOLKIT

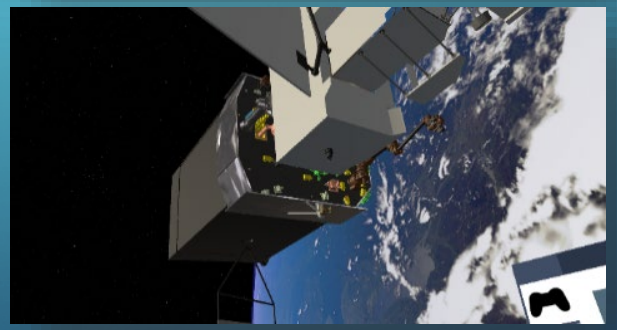
- Cross-domain, mission lifecycle support tool in Science and Engineering for rapidly building XR environments for NASA domain problems, e.g., pulling in CAD models of thermal vac chamber and Roman Space Telescope to do fit checks
  - NASA Open Source
  - Integration with NASA data
  - Secure Collaboration
- VR/Desktop/AR (Hololens 2)
- Developed in Unity/C#

VALIXR leverages MRET for XR visualizations

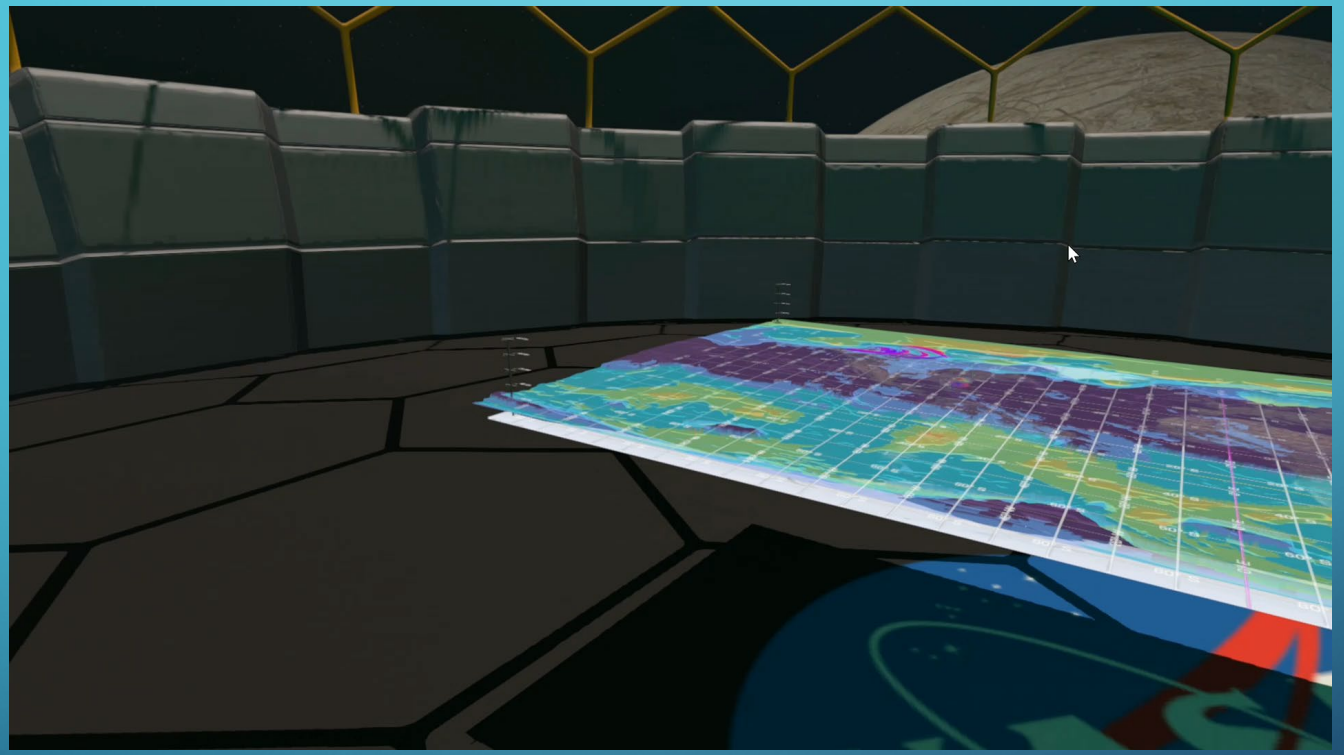






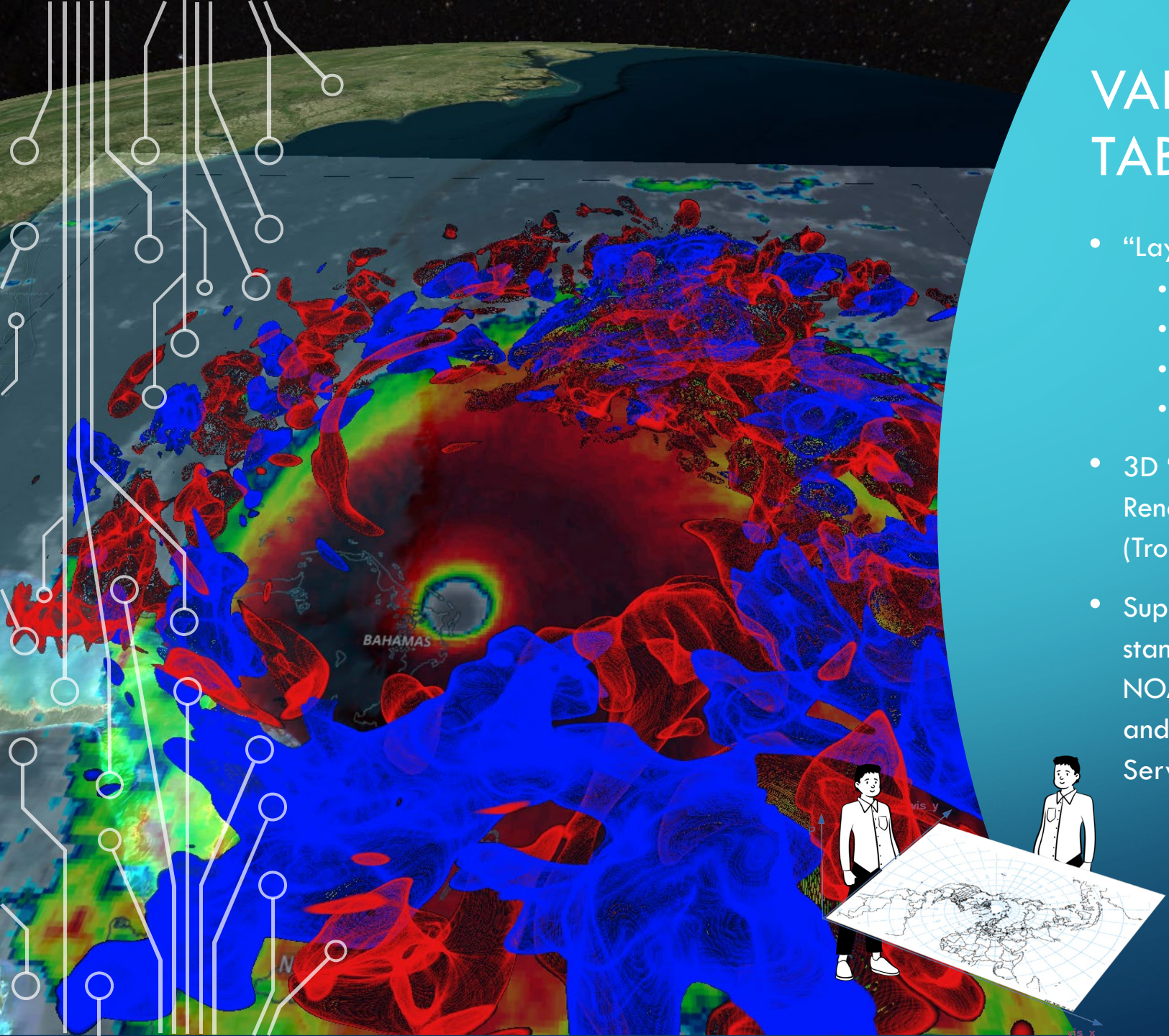


MRET is NASA Open Source and available at https://github.com/nasa/Mixed-Reality-Exploration-Toolkit

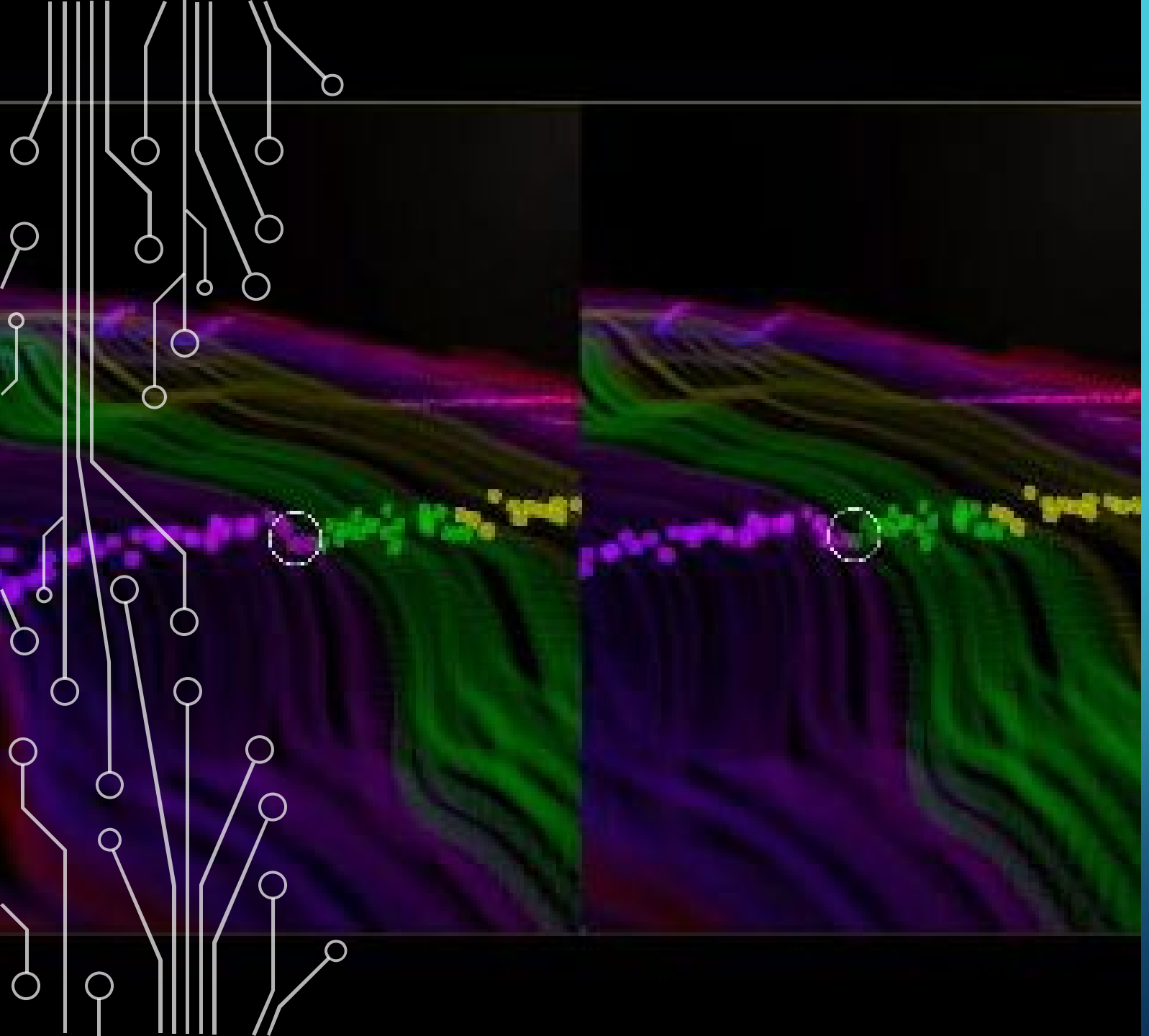


VALIXR "HOLOGRAPHIC TABLE"

- "Layering" of 2D and 3D data with on-demand tiling
  - Elevation Data
  - Geographical/Political Maps
  - GOES Cloud Maps
  - Image overlay layers
- 3D "Layers" using Animated Point Clouds, Volumetric Rendering, Isosurfaces, and Procedural Mesh (Tropopause)
- Supports Open Geospatial Consortium (OGC) standard services* (i.e., WMS, WFS, WCS, etc.), NOAA Open Data Dissemination (NODD) Program, and Grid Analysis and Display System (GrADS) Data Server (OPeNDAP protocol)

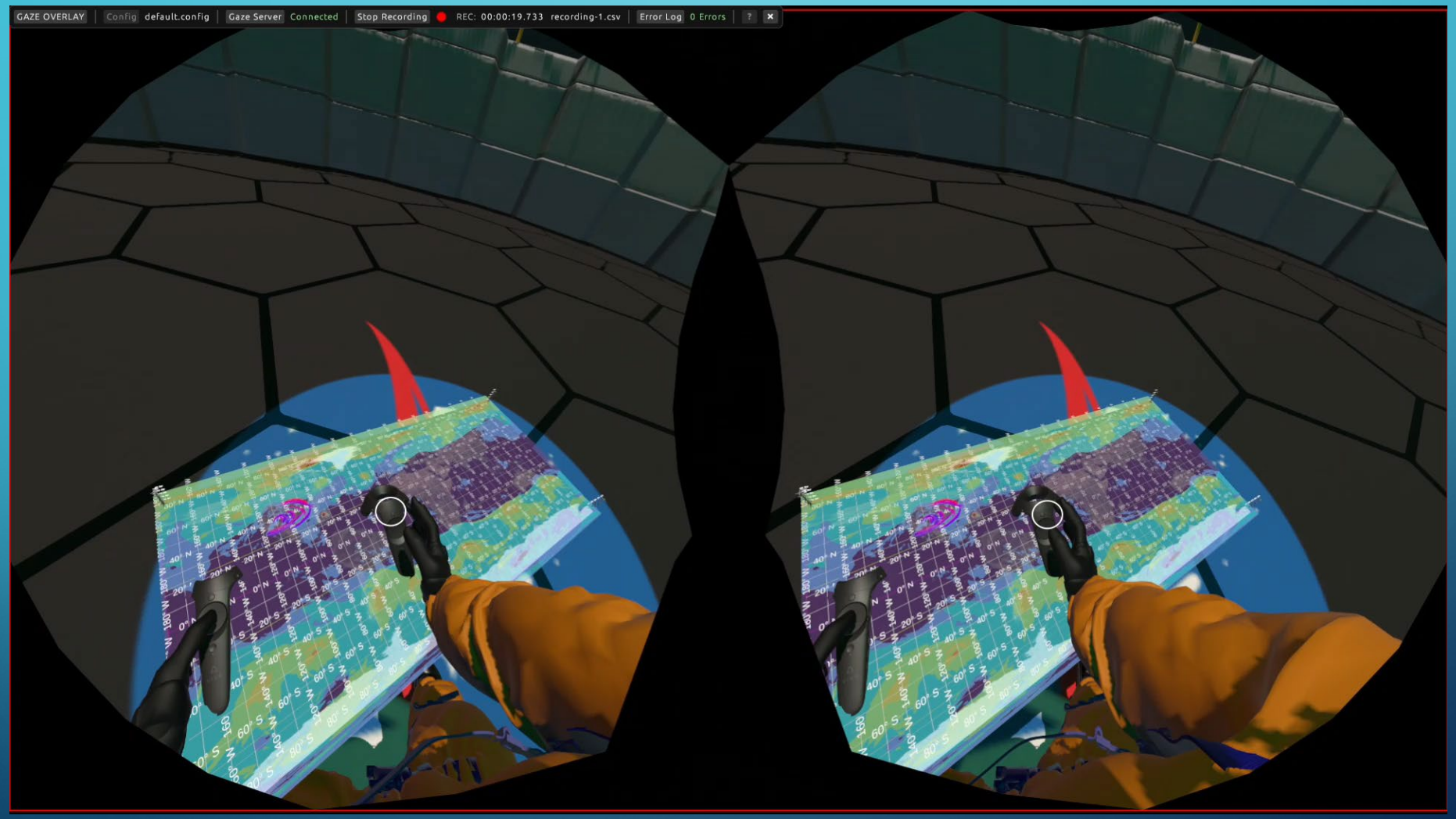


* Support is limited to the data needed right now, but will expand in the future



HUMAN FACTORS

- Developed end-user application agnostic standalone application for capturing and displaying single user eye tracking data for VR.
- Works with any application, without need for access to source code.
- Captures user gaze point location during workflow and individual tasks or sub-tasks in VALIXR
  - Gaze location, duration, and path data to be used in VALIXR human factors evaluation to inform new/modified features and GUI
- Developed UX recommendations for analytic workflow based on cognitive task analysis and workflow diagrams


GAZE OVERLAY
Config default.config
Gaze Server Connected
Stop Recording
REC: 00:00:19.733 recording-1.csv
Error Log 0 Errors

CONCLUSION

- Atmospheric phenomena move with the 3-D flow field, and it is often difficult and unnatural to understand these phenomena in an Eulerian reference frame as opposed to the Lagrangian reference frame in which nature operates
- **Integrating GigaTraj with the GEOS model** will enable a more natural, feature-specific analysis of Earth science phenomena compared to the current Eulerian (fixed grid points in space/time) nature of the GEOS model and its associated output, and has numerous applications for Earth Scientists just on its own
- XR provides an **immersive, intuitive environment for visualizing and interacting with Earth System model output, though it requires a highly iterative, human factors approach to become a true tool for scientists**
- **Leveraging the NASA open source MRET software** and integrating it with a generalized open-source point cloud system has huge applicability to any Earth Science domain
    - Optional Neural Network Super-Resolution post-processing can provide a dramatic visual improvement at low memory and frame rate cost
- By loosely coupling the VALIXR XR front-end to GEOS, VALIXR can be **easily adapted to other models, Earth Science Digital Twins, or even other domains such as the moon**

BACKUP SLIDES

EARTH SYSTEM DIGITAL TWINS COMPONENTS

Digital Replica . . . What now?

An integrated picture of the past and current states of Earth systems.

Forecasting . . . What next?

An integrated picture of how Earth systems will evolve in the future from the current state.

Impact Assessment . . . What if?

An integrated picture of how Earth systems could evolve under different hypothetical what-if scenarios.

- **Continuous observations** of interacting Earth systems and human systems
- From many **disparate sources**
- Driving **inter-connected models**
- At many **physical and temporal scales**
- With fast, powerful and integrated **prediction, analysis** and **visualization** capabilities
- Using **Machine Learning, causality and uncertainty quantification**
- Running at **scale** in order to improve our **science** understanding of those systems, their **interactions and** their **applications**

ESTO Earth Science Technology Office

AIST ESDT Definition from ESTO AIST

VALIXR AND EARTH SCIENCE DIGITAL TWIN

- VALIXR is NOT an ESDT
- Well-constrained development project that fits within broader ESTO ESDT push

- *VALIXR MRET will provide an open source XR foundation for integration with Earth Science Digital Twin architectures and other weather (or really any point cloud generating) numerical models, and will be especially suited for the coming generation of fast turn-around, ML-enhanced numerical models*

ACRONYMS

AAS	American Astronomical Society
ACM	Association for Computing Machinery
ADAPT	Advanced Data Analytics Platform
AGCM	Atmospheric General Circulation Model
AIAA	American Institute of Aeronautics and Astronautics
AIST	Advanced Information Systems Technology
API	Application Programming Interface
AR	Augmented Reality
CAD	Computer-Aided Design
CCRS	Capture, Containment and Retrieval System
CIF	Center Innovation Fund
COTS	Commercial Off-the-shelf
CTA	Cognitive Task Analysis
DCOTSS	Dynamics and Chemistry Of The Summer Stratosphere
DEM	Digital Elevation Map
ESMF	Earth System Modeling Framework
ESTO	Earth Science Technology Office
ESTO	Earth Science Technology Office
ExIS	Exploration & In-space Services
GEOS	Goddard Earth Observing System
GeoTIFF	Georeferenced Tag Image File Format
GIS	Geographic Information System
GMAO	Global Modeling and Assimilation Office
GMAT	General Mission Analysis Tool
GMSEC	Goddard Mission Services Evolution Center
GSFC	Goddard Space Flight Center
GUI	Graphical User Interface
HUD	Heads Up Display
I/O	Input/Output
IEEE	Institute of Electrical and Electronics Engineers
IRAD	Internal Research & Development
IS&T	Information Science and Technology

JPEG	Joint Photographic Experts Group
JPL	Jet Propulsion Laboratory
LD	Lagrangian Dynamics
LIDAR	Light Detection and Ranging
MRET	Mixed Reality Exploration Toolkit
NASA	National Aeronautics and Space Administration
NCAR	National Center for Atmospheric Research
NCCS	NASA Center for Climate Simulation
netCDF	network Common Data Form
NSPIRES	NASA Solicitation and Proposal Integrated Review and Evaluation System
OSAM-1	On-orbit Servicing, Assembly, and Manufacturing 1
PCD	Point Cloud Data
PDL	Product Development Lead
PNG	Portable Network Graphic
PY	Program Year
ROSES	Research Opportunities in Space and Earth Sciences
SED	Software Engineering Division
SOTY	Software of the Year
TRL	Technology Readiness Level
UMBC	University of Maryland Baltimore County
UMD	University of Maryland (College Park)
UMIACS	University of Maryland Institute for Advanced Computer Studies
UNT	University of North Texas
VALIXR	Visualization And Lagrangian dynamics Immersive eXtended Reality Tool (VALIXR)
VR	Virtual Reality
XR	Extended Reality (AR/VR/MR)