Kamodo's Satellite Constellation Mission Planning Tool (AGU 2022)
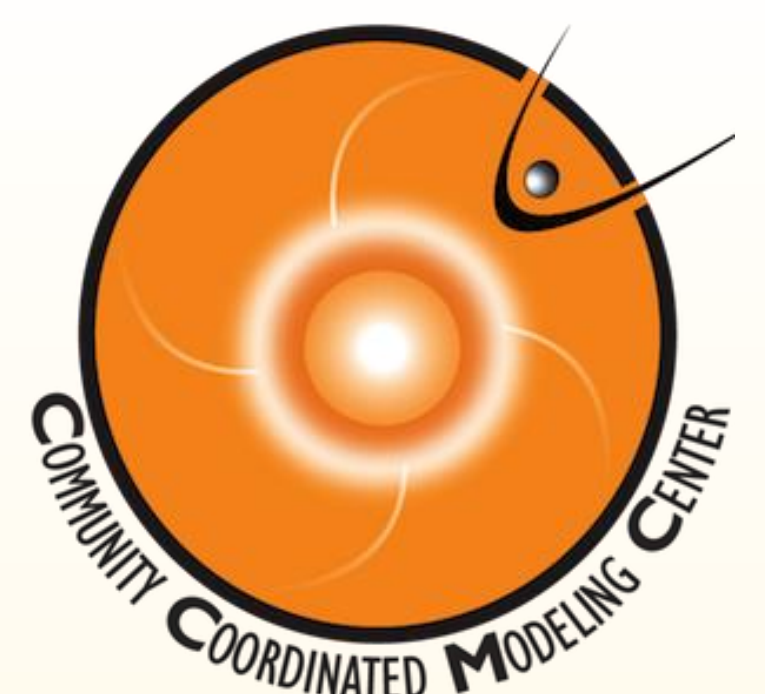
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SM25C-2002: Kamodo's Satellite Constellation Mission Planning Tool

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Abstract:

Kamodo provides a functional model-agnostic interface to a growing collection of Heliophysics model outputs. The CCMC, in collaboration with the Geospace Dynamics Constellation Science Team, has recently developed Kamodo's satellite constellation mission planning tool to perform reconstructions in any pair of dimensions, including time. The 'reconstruction' tool enables users to fly any 4-dimensional grid of satellites through a given model data set, reconstructing what the given constellation would observe during the mission. This capability facilitates determination of what satellite configuration is best for a given science question, even allowing comparison across multiple models. This tool, written in Python, is built upon Kamodo's flythrough tool, which in turn depends on a growing network of model-specific interfaces. Since each model interface is designed with model-agnostic syntax, the flythrough tool and the satellite constellation mission planning tool also feature model-agnostic syntax. In this work, we will describe the basic analysis choices available in the tool and provide a variety of sample workflows. The tool is freely available at https://github.com/nasa/Kamodo for the public. We invite the community to use the reconstruction tool and adapt the provided workflows for their mission planning, and to contribute their own workflows to share with others.

Sample Workflows:

All of the sample workflows are located on the CCMC's Kamodo GitHub repository (see QR code in the center bottom panel) and currently located in the **/docs/notebooks/** directory.

The best starting place to learn how to use the satellite constellation planning tool (AKA the reconstruction tool) is the **ReconstructionTutorial_SphericalCoords** notebook, which demonstrates how to fly a constellation of six satellites equally spaced in longitude through a given model output and compare the results to model predictions.

For cartesian reconstructions, see **ReconstructionTutorial_CartesianCoords** notebook and the notes given there.

ReconstructionTutorial_DifferingGrids_Orbit Slicing is a workflow that demonstrates how to use the orbit slicing analysis method (described later) and how to compare results from executions with different grid resolutions.

ReconstructionTutorial_IrregularConstellations shows how to use the tool with an irregular satellite constellation configuration (e.g. the DMSP constellation).
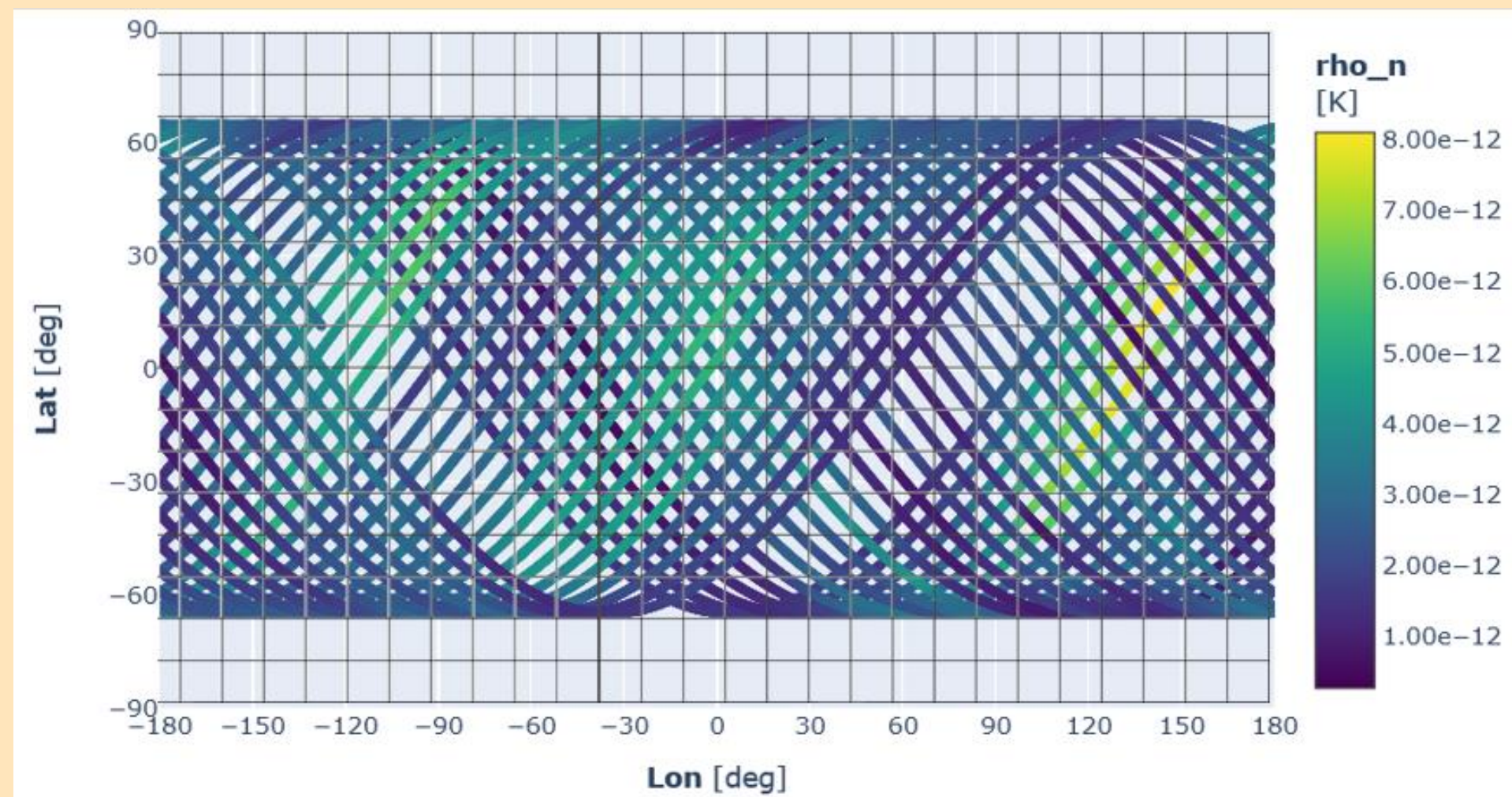
How it works (Part 1):

To more easily explain how Kamodo's satellite constellation planning tool works, let's take the simplest case: a single satellite as our constellation. The tool can reconstruct what the 'constellation' will see in any pair of coordinate dimensions, whether spherical or cartesian, but let's again choose one scenario that is easily approachable: a reconstruction in spherical coordinates, specifically longitude and latitude.
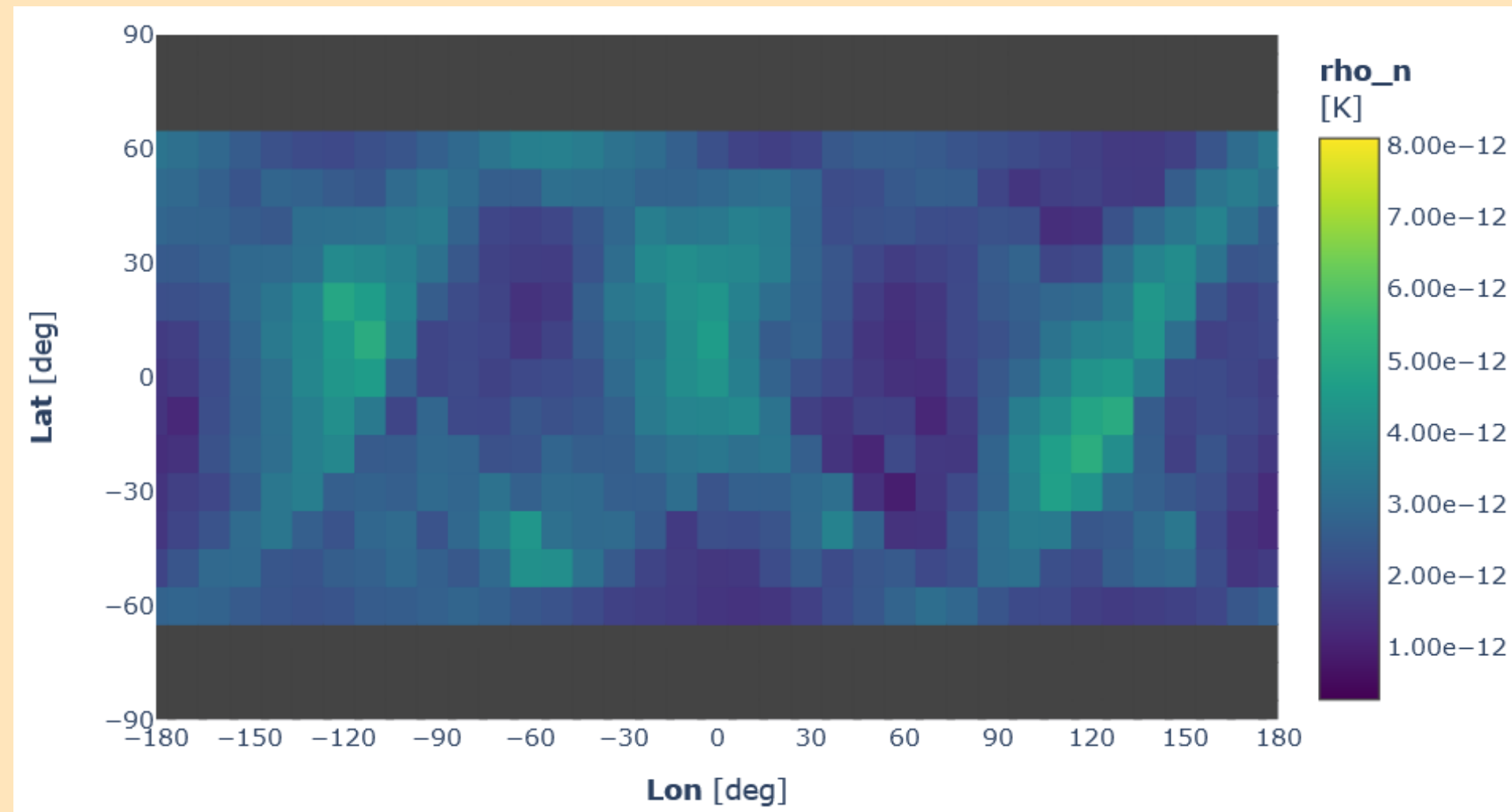
1. Fly the given trajectory through the chosen model data (GITM model data shown here, the 'UnMod' option in table at right).
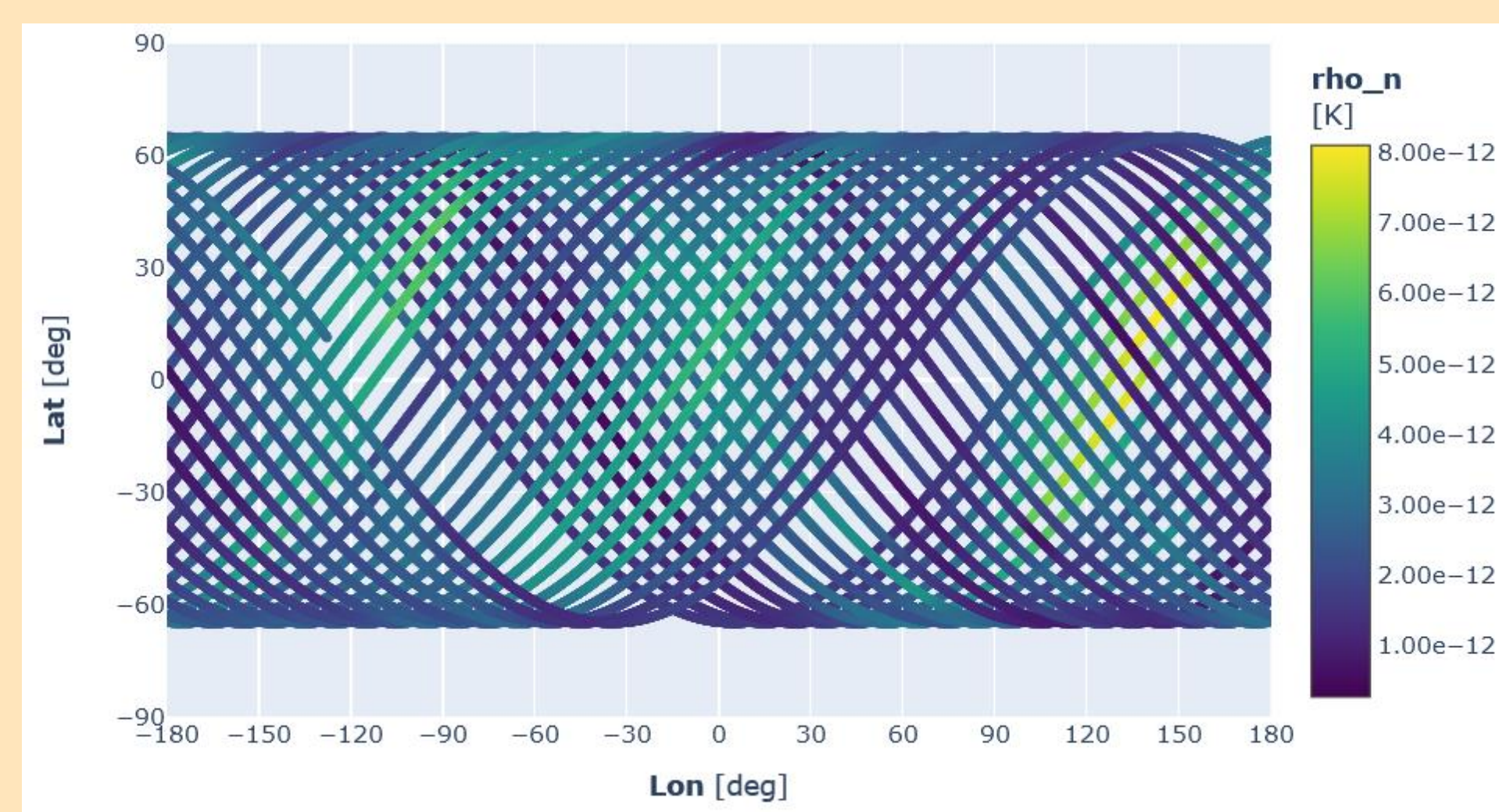
2. Sort the resulting values into a grid of longitude-latitude cells (the resolution of the grid is chosen by the user).
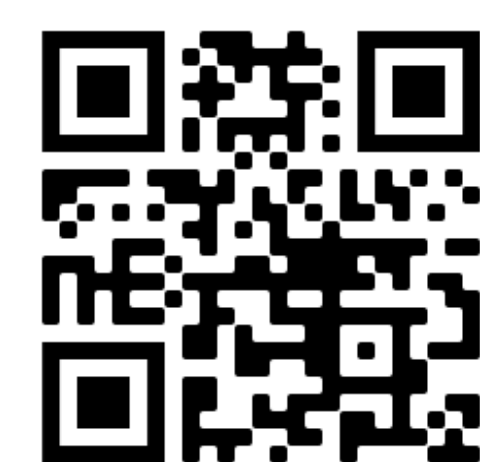

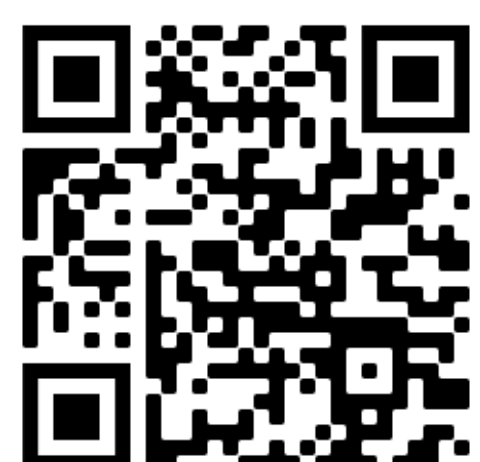**3. Take the average of the values in each grid cell.**


How it works (Part 2):

Now the tool has reconstructed what the satellite constellation will see. Next, we need to know what the model prediction looks like to determine if there are enough satellites in the constellation or if the satellites are arranged appropriately to detect the structures we are looking for.

The next portion of the analysis takes the coordinate grid of the reconstruction and interpolates what the model predicts at those locations. However, we must remember that the data has four dimensions, not just the two represented by the grid. There are several options on how to deal with the remaining two coordinate dimensions, but again we take the simplest case for this demonstration: **an interpolation at the average time and height for each longitude and latitude pair** (the AvgSlice option in the table at right).

The averages of the entire array of times and heights for the constellation trajectory are first calculated. Then, the set of longitude-latitude pairs from the reconstructed grid are 'flown' through the model data at the average time and height (result shown below). This recontructs what the model predicts.
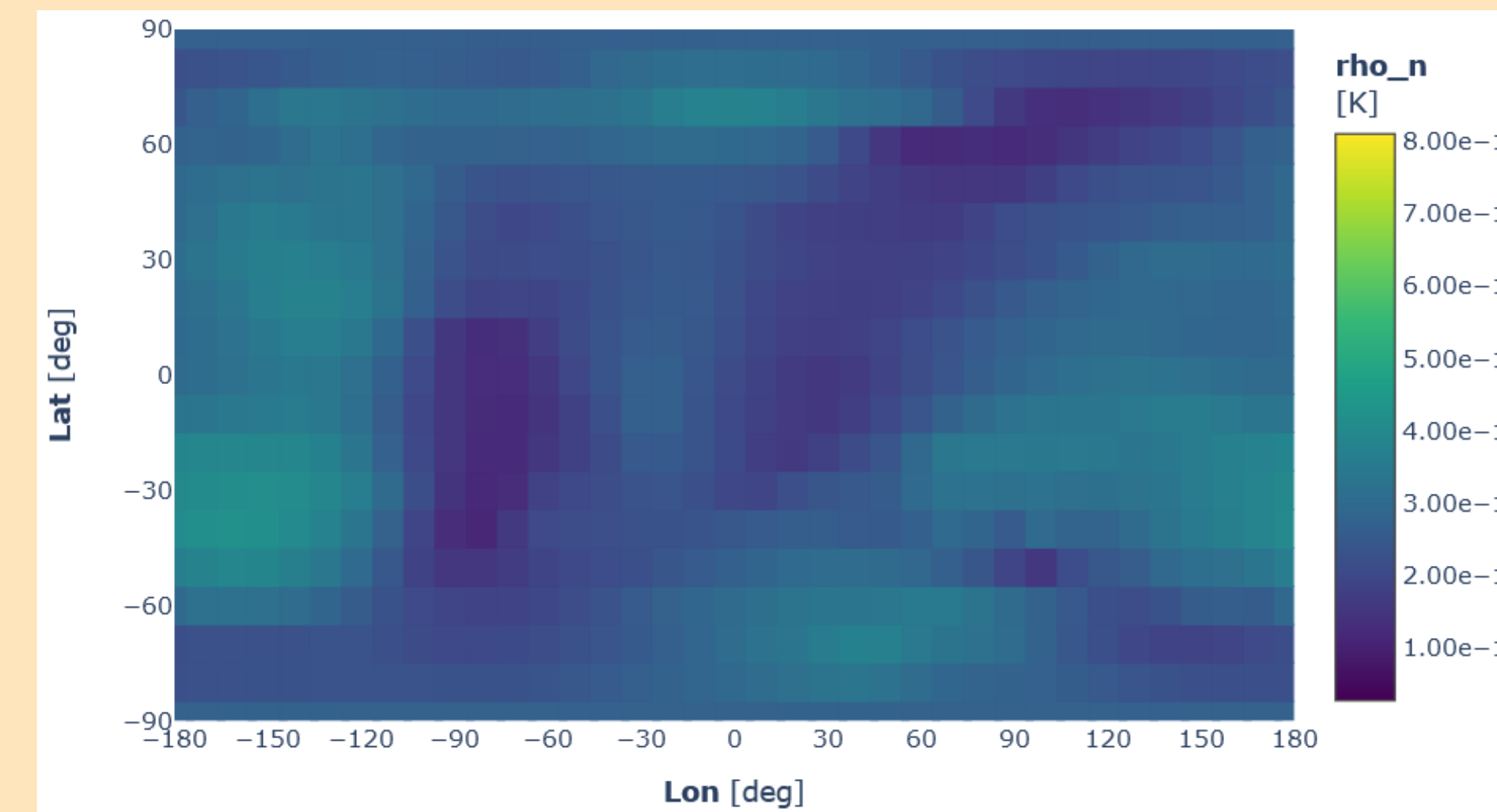
Since the reconstruction of the satellite 'observation' and the model prediction are on the same coordinate grid and with the same resolution, they can be easily compared, such as with a percent difference calculation (shown below).
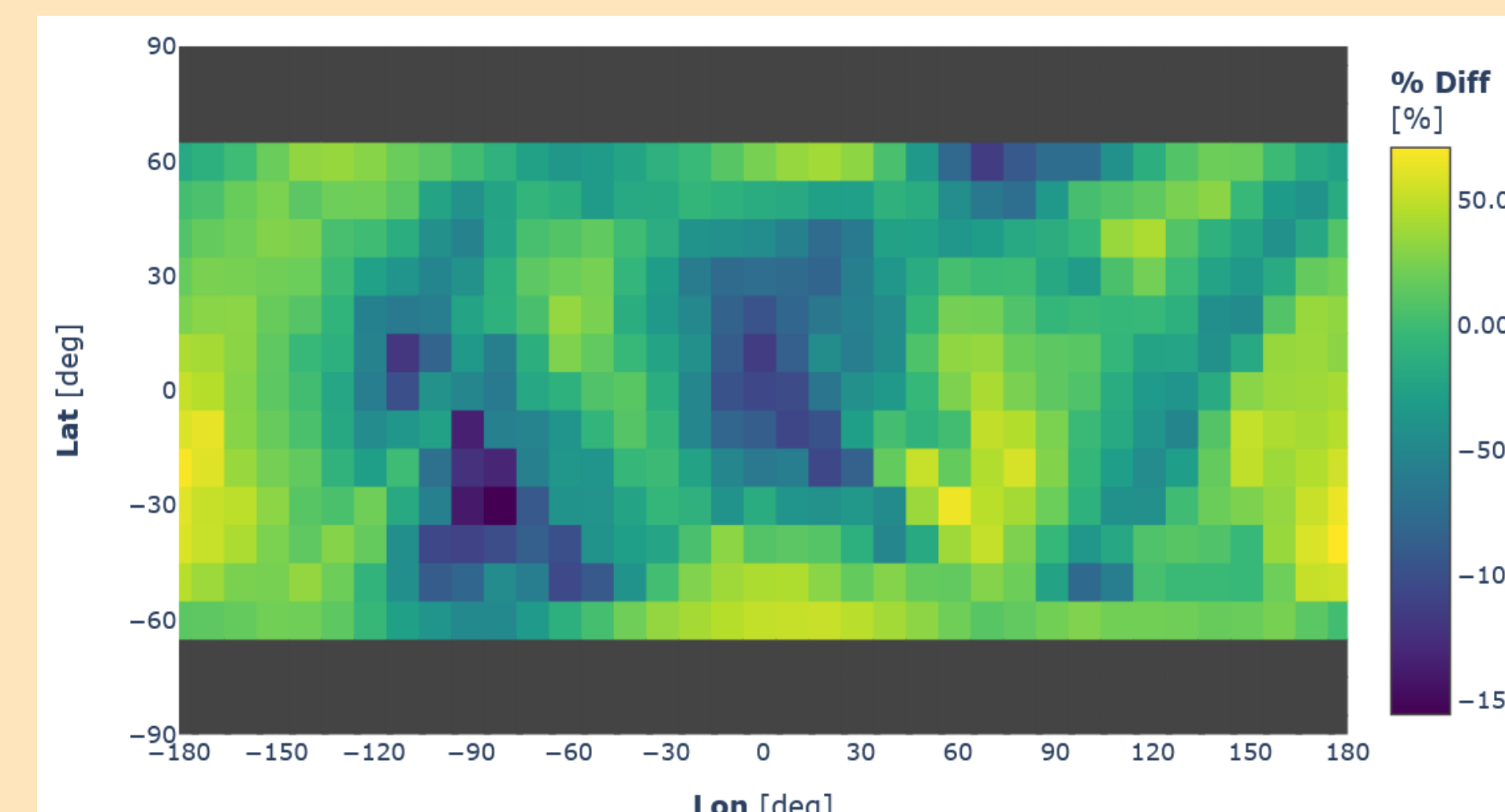

The differences between the predicted satellite constellation observation and the model prediction vary with the number of satellites, the constellation arrangement, and the analysis method chosen. The constellation arrangement can be in any number of dimensions and with any spacing (with some limitations), and the number of satellites in the constellation is only limited by computer memory. The analysis method can also be chosen at run time by simply changing the inputs to the command. Several notebooks on CCMC's Kamodo GitHub repository demonstrate the usage of this tool in several scenarios, including how to compare reconstructions on grids of differing resolutions and how to deal with irregular satellite constellations (e.g. the DMSP constellation).

Links to our GitHub Repositories:

CCMC's Kamodo

Kamodo-core

Analysis Options Explained:

Aside from the various constellation arrangement options, there are eight analysis options to better address a wide variety of science questions. These options are the intersection of two options applied to the input satellite trajectory and four options on the reconstruction of the model prediction shown in the table below. (Note that the last column shows two options.)

Analysis Options	AvgSlice: The reconstructed model is a slice through the model data at the average dimensions not reconstructed. Average values can be chosen.	AvgDSlice: The reconstructed model data is an average of all the slices in the range of trajectory values for the dimensions not reconstructed. Slice intervals must also be given (d1, d2).	OrbitSliceD/N: What an infinite number of satellites would see if positioned along the trajectory with time offsets only. The 'D' and 'N' variations are for retrieving only the day or night portions of the orbit. Time resolution must be given (dt).
UnMod: Input trajectory unmodified.	**Unmod_AvgSlice**	**Unmod_AvgDSlice**	**Unmod_OrbitSliceD/N**
AvgMod: Input trajectory averaged along two dimensions not reconstructed.	**AvgMod_AvgSlice**	**AvgMod_AvgDSlice**	**AvgMod_OrbitSliceD/N**

The input trajectory can either be taken as is (**UnMod**) or averaged in the two dimensions *not* reconstructed (**AvgMod**). The model prediction options are much more varied. The **AvgSlice** option flies the coordinate pairs of the reconstructed grid through the model data at the average value for the two dimensions not reconstructed (e.g. average time and height for a longitude and latitude reconstruction in spherical coordinates). In comparison, the **AvgDSlice** analysis option flies the same coordinate pairs through the model data at a range of values for the two dimensions not reconstructed (resolution determined by the user at runtime), and then takes the average of the results for the two ranges as the final result. The **AvgSlice** and **AvgDSlice** options are compared visually in the diagram below for an example longitude-latitude reconstruction using GITM data (light blue columns in the table above).
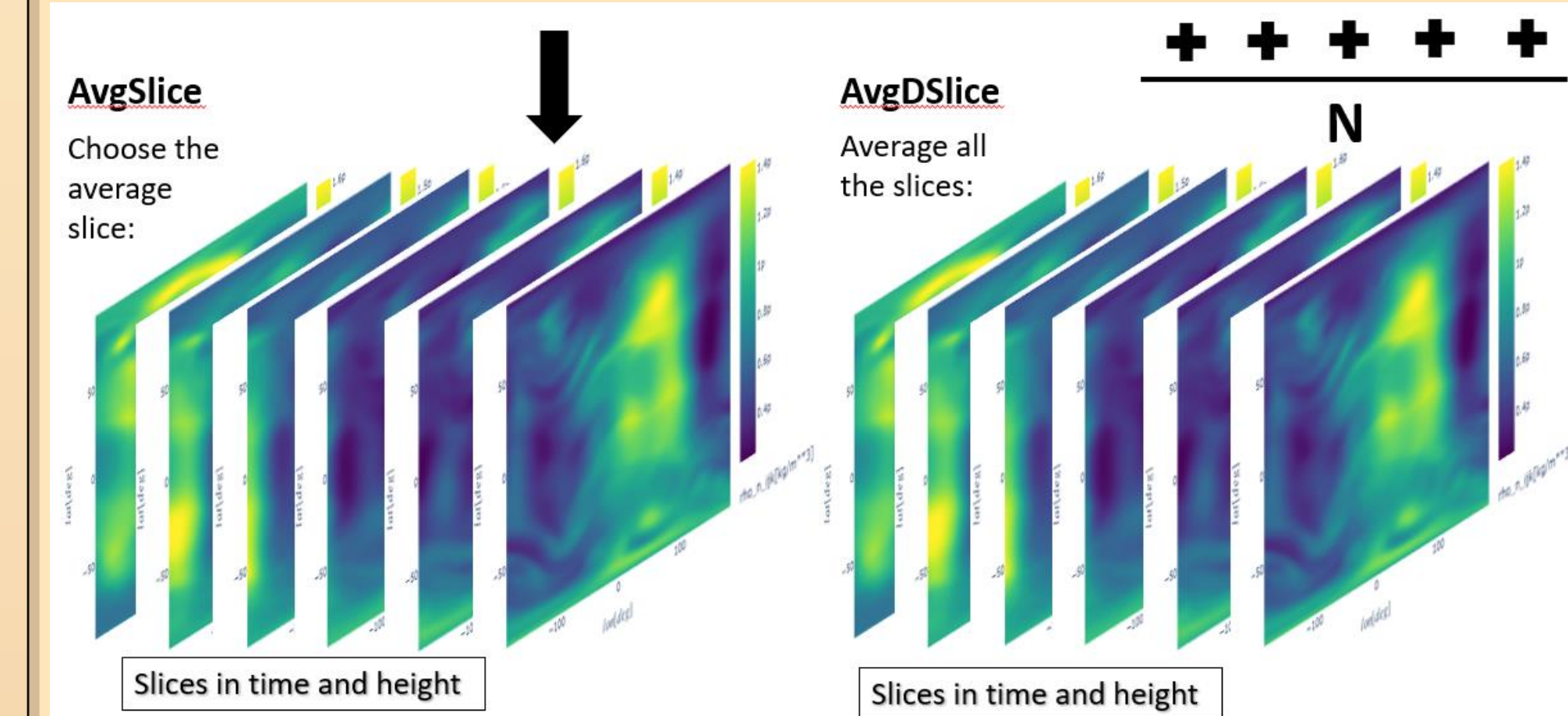
The two **orbit slicing** analysis options are quite similar, only differing in the portions of the orbit used (see medium blue column in table above). Instead of slicing through the model data at specific coordinates, the two analysis methods slice along the satellite trajectory.

Consider a two-satellite constellation where the individual satellites are separated in time (left hand diagram). As the constellation flies around the earth, the position of each satellite changes from the orange dots (t1) to the red dots (t2). In the reconstruction of the model prediction, the software approximates what an infinitely large constellation of the same trajectory would see by using a 60-second separation (dt in the diagram at right) between the individual satellites at each time value in the original trajectory. The left picture in the right diagram shows an example of such as arrangement at t1, and right picture shows the subsequent arrangement at a later time t2.

Our Team:
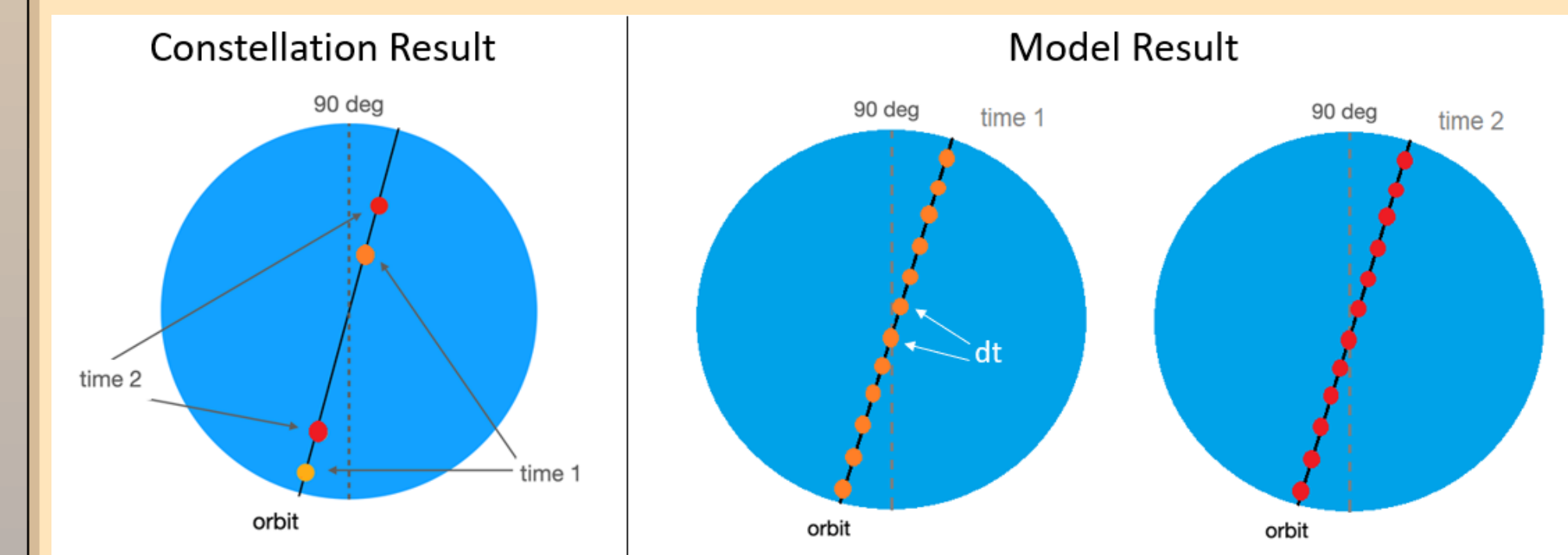
CCMC Staff:
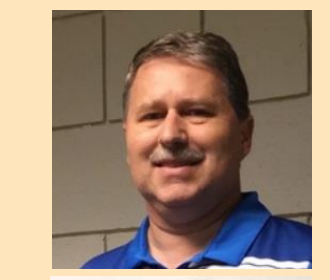https://ccmc.gsfc.nasa.gov/staff/

Rebecca Ringuette: Model interfaces, metadata, flythrough and other CCMC capabilities.

Lutz Rastaetter: Internal cross-language interfaces, specialized interpolators, CCMC-Vis, team management.

Darren De Zeeuw: GitHub management, visualization, metadata.

Katherine Garcia-Sage: Orbit propagation and satellite reconstruction studies, external affairs, GDC support

GDC Science Team Member:

Robert Robinson: Guidance on software development, validation, and analysis options.

Ensemble Government Services partners:
https://www.ensembleconsultancy.com/government-services

Oliver Gerland and company: Core Kamodo capabilities, expert bug squashers.

Related Materials:

Related Posters and Papers:
- SH42E-2338: Magnetic Mapping in the Inner Magnetosphere using Kamodo
- SA32D-1694: Enhanced Visualization using Kamodo for CCMC ITM Instant Runs SH42E-2337: Science Workflows using Kamodo
- Developing an Executable Paper With the Python in Heliophysics Community. Preprint DOI: 10.1002/essoar.10510006.1 Accepted by *Frontiers in Astronomy and Space Science: Space Physics*.

Reference DOIs:
- Kamodo (core): 10.21105/joss.04053
- CCMC's Kamodo Flythrough: 10.3389/fspas.2022.1005977
- CCMC's Kamodo Model Readers: under review by ASR.
- GITM: 10.1002/2016SW001465
- DMSP: 10.1029/JC083iC10p05019

Note:
If you find an issue with the software, please report it on our GitHub. For collaboration, please email **Rebecca.ringuette@nasa.gov**.