RayPC: Interactive Ray Tracing Meets Parallel Coordinates

Jonathan Fritsch* Markus Flatken Simon Schneegans Andreas Gerndt Ana-Catalina Plesa
Christian Hüttig
German Aerospace Center (DLR)

Figure 1: Interactive visualisation and analysis of mantle flow in the Earth’s interior: hot mantle plumes (left image), mantle plumes with associated pathlines and cold downwellings shown in blue color (center image), stagnated cold material (light blue) and pathlines indicating sinking of downwellings in the lower mantle (right image).

ABSTRACT
Large-scale numerical simulations of planetary interiors require dedicated visualization algorithms that are able to efficiently extract a large amount of information in an interactive and user-friendly way. Here we present a software framework for the visualization of mantle convection data. This framework combines real-time volume rendering, pathline visualization, and parallel coordinates to explore the fluid dynamics in an interactive way and to identify correlations between various output variables.

1 MOTIVATION
Over the past decades, with the increase of processing power and available memory, global-scale computational models have become state-of-the-art to investigate the complex physical processes in the interior of the Earth and other rocky planets in the Solar System, e.g., [1,2,4]. Numerical models that employ a high spatial resolution are widely used to link the evolution of mantle flow to the formation and evolution of surface structures, such as volcanoes and tectonic plates. Depending on the research question, the size of each snapshot file, which is typically written during a simulation and contains output quantities such as the temperature field, velocity, thermal conductivity and expansivity etc., can increase considerably. This requires a dedicated visualization software that can handle a large volume of data and present it in a user friendly way. In particular, such a visualization software needs to be able to quickly react to user input, increasing the level of interactivity, and to provide an intuitive option to identify potential correlations between output quantities.

In this study, we present a new plugin for the open-source software CosmoScout VR [3], which can visualize large-scale simulation data of a planet’s interior. In Section 2 we give some implementation details. We used the plugin to fulfill the five given tasks and present the results in Section 3 and conclude with a discussion and plans for future work in Section 4.

*e-mail: jonathan.fritsch@dlr.de

2 APPROACH
The idea of our implementation is to use well-known visualization approaches from different domains in one interactive 3D rendering application. We combine real-time volume rendering and pathline visualization with a parallel coordinates plot which is usually used in the field of information visualization. Figure 2 shows an example of the parallel coordinates. This not only allows users to visually detect correlations between variables, but also enables the specification of upper and lower bounds for each variable. These bounds are then used during rendering to only visualize a subset of the data (brushing and linking). This mechanism enables efficient isolation of structures such as plumes or cold slabs. Additionally, we display pathlines spawned inside the currently selected subset of the data. This provides an idea of where the selected material will move to.

In order to achieve interactive volume visualization we use an asynchronous rendering approach. The frame rate of the OSPRay based ray tracing is decoupled from the main render thread. In order to hide the varying frame rates and latencies an image-warping technique is used. To further increase the performance of our volume rendering, we use a level-of-detail data structure and progressive render passes. All together, this enables explorative data analysis and interactive visualization.

2.1 Data Preprocessing
To reduce the memory and I/O requirements, as well as to enhance the data with derived information, we introduce a preprocessing step. First, we generate an octree-based level-of-detail data structure with two lower resolution levels. Each level only contains $1/8^{th}$ the number of cells as the previous level. Second, we compute additional derived variables (radial velocity and altitude) which help the identification of plumes or slabs at specific heights using the parallel coordinates. Third, we randomly select up to 100000 cells and store their scalar information in a file. This is later used to draw the lines of the parallel coordinates. Lastly, in order to be able to correlate volume structures (plumes or slabs) with the velocity flow field, we generate pathlines seeded at critical points of the temperature anomaly field. The critical points of each time step were identified by using the Topology Toolkit (TTK) [5] and then traced forward for 10 time steps (20 Myrs). This enables the visualization of dynamic behavior in a static image as it depicts where the selected material will move to.
We applied our visualization software to address the five given tasks with OSPRay, too. This results in an easier composition with the volume selection are displayed. Optionally, the visible pathlines can be used also for many other features and can be used also for many other tasks, data sets, or applications (e.g., climate data).

### Task 1:
Here we show stagnated or diverted cold slabs (descending mantle material) at ~600 km (upper and lower mantle boundary) depth. To this end, we use the parallel coordinates and select an altitude range of ±100 km around 660 km depth, a non-positive radial velocity, suggesting stagnated and sinking material, and a negative temperature anomaly, indicative of cold downwellings. We use the radial velocity as transfer function, to color the areas of stagnated slabs (radial velocity ~0). Sinking slabs can also be seen in the volume rendering since we selected a non-positive range for the radial velocity.

### Task 2:
In this task, we visualize stagnated or diverted cold slabs at ~1600 km (mid-mantle) depth. As before, we select a negative temperature anomaly for volume rendering. However, this time we did not restrict the depth in order to see where the cold material comes from and where it moves to. We select the spin transition-induced density anomaly as color. A positive density anomaly indicates sinking downwellings, while a negative one shows stagnating downwellings. By selecting the entire altitude range we can observe the behavior of downwellings over the entire mantle (i.e., stagnated at 660-phase transition, stagnated or diverted in the mid-mantle or sinking to the core-mantle boundary).

### Task 3:
Here we identify stagnated or diverted hot plumes (rising hot mantle material) at ~1600 km depth and their rise to the upper regions of the lower mantle. In the parallel coordinates we select the regions with a positive temperature anomaly and the entire altitude range. This actually allows to observe stagnated and deflected plumes both in the mid-mantle and at 660 km depth. We distinguish between stagnating and rising plumes by using the spin-transition induced density anomaly as color for volume rendering. A negative density anomaly indicates rising plumes, while a positive one indicates stagnating plumes.

### Task 4:
Stagnated or diverted hot plumes at ~660 km depth have been already seen in the previous task. An additional way to identify these features is to select a positive temperature anomaly, choose an altitude around ~660 km, and use the radial velocity for the coloring. This shows stagnating and rising slabs at ~660 km in a similar fashion as the downwellings in Task 1.

### Task 5:
Correlations between the variables and the flow patterns can be easily identified in our framework through the parallel coordinates. The user can choose various value ranges for simulation variables and selected flow patterns. For instance, a positive thermal expansivity and temperature anomaly can be used to select plumes in the lower mantle. Cold material in the upper mantle can be selected by a negative expansivity and temperature anomaly. More complex correlations can be derived by including additional variables (e.g., spin transition). Additionally, pathlines can help visualize the mantle flow (i.e., if material rises/sinks or glides along boundaries).

## 4 Discussion and Future Work

In this study, we presented an open-source software framework that offers volume rendering, pathlines and parallel coordinates to analyze large-scale data from geodynamic models. It provides a high level of interactivity and the ability to easily identify correlations between various output variables. By fulfilling the tasks of the contest, we demonstrated that our framework is suitable for the visualization of mantle plumes and downwellings. However, our approach is not limited to these features and can be used also for many other tasks. For example, tasks which involve the tracking of material flow rather than stagnating regions can benefit especially from the pathline feature. In the future, we plan to apply our framework to various tasks, data sets, or applications (e.g., climate data).

## References

[1] F. Crameri and P. J. Tackley. Spontaneous development of arcuate single-sided subduction in global 3-d mantle convection models with a free surface. *JGR: Solid Earth*, 119(7):5921–5942, 2014.

[2] A.-C. Plesa, S. Padovan, N. Tosi, D. Breuer, M. Grott, M. Wieczorek, T. Spohn, S. Smrekar, and W. Banerdt. The thermal state and interior structure of mars. *GRL*, 45(22):12–198, 2018.

[3] S. Schneegans, M. Flaten, and A. Gerndt. *CosmoScout* VR 1.4.0, Mar. 2021. doi: 10.5281/zenodo.4646924.

[4] M. Shahnas, D. Yuen, and R. Pysklywec. Mid-mantle heterogeneities and iron spin transition in the lower mantle: Implications for mid-mantle slab stagnation. *EPSL*, 458:293–304, 2017.

[5] J. Tierny, G. Favelier, J. A. Levine, C. Gueunet, and M. Michaux. The topology toolkit. *IEEE Transactions on Visualization and Computer Graphics*, 24(1):832–842, Jan 2018. doi: 10.1109/tvcg.2017.2743938
Figure 3: Using the system on a stereoscopic output device with head-tracking significantly improves the understanding of the complex plume geometry.

Figure 4: Here we used the transfer function editor to highlight regions of a high (orange) and low (blue) temperature anomaly.
Figure 5: Here we used the parallel coordinates to select regions with a high absolute temperature. The pathlines show where the selected material will move in the future. Convection cells are clearly visible.

Figure 6: We can use the parallel coordinates not only to limit the volume based on scalars but also based on Cartesian coordinates. This can be used to create cuts through the volume.
Figure 7: For Task 1, we selected a non-positive radial velocity, a negative temperature anomaly, and a depth range around 660 km. While the cold slabs are well visible in this image, their behavior is much more apparent while playing the animation. The transfer function uses the radial velocity: Stagnating slabs are shown in white while sinking slabs are colored blue.

Figure 8: For Task 2, we select a negative temperature anomaly and colorize the downwellings according to the spin transition-induced density anomaly. A negative density anomaly (blue color) causes the downwellings to stagnate and move laterally at mid-mantle depth (~1600 km). A positive density anomaly (red color) indicates a downward acceleration of the downwellings. Especially in the upper left area of this time step, we can clearly see how cold material flows downward until it slows down and spreads out as it approaches the iron-spin transition at about 1600 km depth.
Figure 9: We used a positive temperature anomaly for Task 3. The transfer function is based on the spin transition-induced density anomaly. A negative density anomaly (blue color) indicates rising plumes. A positive density anomaly (red color) causes the plumes to stagnate and move laterally at mid-mantle depth ($\sim 1600$ km). We also show density anomaly values close to zero (purple regions) that are attained at depths shallower than 1500 km. Here, the endothermic phase transition at 660-km depth is clearly visible, being indicated by the thickening and thinning of plumes in the upper mantle. Some plumes are deflected at around 1600 km depth and additionally at the 660-phase boundary (see structure at about three o’clock).

Figure 10: Pathlines and their color can be used to visualize the flow of material (blue pathline color: starting point of a fluid parcel, red pathline color: its location after 20 Myrs).
Figure 11: For Task 4, we selected a depth around 660 km and a positive temperature anomaly. The transfer function uses the radial velocity. This causes rising material to be shown in red color while stagnating material is shown in white. In this time step there are several good examples of rising plumes with stagnated material at 660-phase boundary (at about two, four, five, and six o’clock).
Figure 12: As an example for **Task 5**, we select a negative thermal expansivity. The lines of the parallel coordinates plot clearly show a separation of the data into two distinct regions. We can use further selections in the parallel coordinates to choose the individual regions. The transfer function uses the temperature anomaly.

Figure 13: The relatively cold region at high altitudes.

Figure 14: The relatively hot region at low altitudes.
Figure 15: If we select a positive thermal expansivity, the data is also separated into two distinct regions. We can use further selections in the parallel coordinates to choose the individual regions. The transfer function again uses the temperature anomaly.

Figure 16: The relatively cold region at low altitudes.

Figure 17: The relatively hot region at high altitudes.