Vortices Identification Based on Projection of Streamlines

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1 Introduction

In this work we present a visualization strategy to support identification of vortices in a vector data set. Usually, two methods may be employed for this task: $lambda_2$[3] or the $Q-criterion$[2]. However, these methods are not necessarily the best options for vortex identification. Rather than using the original attributes and selecting either of those methods for vortex identification, we change the focus of the problem by applying a transform and conquer approach. We first compute various streamlines from the vector data and extract shape information from them by means of the Discrete Fourier Transform (DFT), building a feature space with the (low frequency) Fourier coefficients. In this way, our new problem is how to localize the vortical streamlines, i.e., the streamlines belonging to vortical regions. We do so employing multidimensional projection techniques, which strive to preserve the relationships of the high-dimensional feature space on the 2D projected space. The underlying idea is to locate vortical streamlines by recognizing the peculiar shapes of groups formed from projecting their distinguishing features.

We have compared different projections techniques for the task and the best results were obtained with the Piecewise Least Square Projection (P-LSP) technique [5]. Once the streamline feature space is projected, one can select groups in the 2D visual space and visualize the selected vortical streamlines in the object space.

The views and linking mechanisms were developed in Java and the streamline visualizations were done using The Visualization Toolkit [1].

2 Visual Exploration Process

The data set made available by the Vis Contest 2011 organizers results from a time-varying fluid dynamics simulation of a pump. The simulation includes different attributes: pressure, total pressure, total pressure in stn frame, turbulence kinetic energy, velocity and velocity in stn frame. The simulation dataset consists of 80 time steps, each one comprising 6.7 million nodes and 6.4 million cells. Furthermore, three data sets are available from the same centrifugal pump, by the application of three distinct turbulence models: LES, RANS and the hybrid LES/RANS. We focused our efforts in the LES simulation model.

Each time step is divided in 24 parts. In this work we have focused our analysis in the rotor domain (i.e., all volume elements named with ROTOR_VOL), which consists of 2.24 million nodes.

A major problem in streamline computation regards seed positioning. We compute streamlines with seeds uniformly distributed throughout the whole volume, using the nodes as seeds. We believe that this approach is able to cover all regions of the volume. As the streamlines tend to cover similar regions, we have used only a subset consisting of 22,478 nodes to generate the same number of streamlines.

The streamline feature space is computed by applying a Fourier transform over the 3D points on the streamline path [7]. The 1D Fourier transform is computed for the X, Y and Z coordinate arrays. We then select only coefficients related to low frequencies, 20 coefficients per coordinate, resulting on a feature vector with 60 coordinate values for each streamline.

The streamline vector space is projected onto a 2D plane, using an adapted version of the PLSP technique. The adaptation introduced fixes certain control points across different time stamps to maintain visual coherence accross successive time steps. Users can locate and select in the projection well formed groups of points representing vortical streamlines. As multidimensional projections such as PLSP strive to derive a layout that preserves proximity of highly similar instances (in the multidimensional feature space), vortical streamlines are likely to group in the same projection regions over time. When a neighboring time step is loaded, the object space is updated according to the previous user selection. The nodes corresponding to selected points are then rendered in object space. Linking between the feature and object space representations provides an interaction mechanism that supresses the need of users handling three dimensional spaces or interacting with complex structures in the volume.

Figure 1 illustrates the exploration process enabled by our linked view approach. Initially, in Figure 1(a) the first time step is loaded and visualizations of both the projected feature space and the fluid are shown. Next, in Figure 1(b), the user selects a few groups in the projection (left image) which are then shown in object space (right image), revealing that the selection comprises groups of vortical streamlines. This same user selection is maintained when the next (second) time step is loaded. As illustrated in Figure 1(c), spatial coherence is preserved between the projections, that is, the vortical streamlines belong to the same selected region.

Figure 2 illustrates a vortex, highlighted by the red polygon, appearing in the sequence comprising time steps 5 to 10. The vortex appears from the inside to the outside part of the rotor blade. Projections and selections corresponding to Figure 2 are shown in the attached pictures.

3 Time Consumption

The visualization application was executed on a Intel i7 2.8 GHz computer with 16GB of RAM and an IDE hard disk. Prior to exploration the data set was preprocessed to generate the streamlines for each vertex, with a step of 100. Streamlines were computed employing the vtkStreamTracer class, and computing the 22k streamlines took approximately three hours. We have also preprocessed the projections associated to all (80) time steps, which takes under 18 minutes. The streamlines and the projection relative to one time step (both stored in the hard disk) are loaded during visual exploration in just under a minute. Coordination between projection and object space is done in real time.

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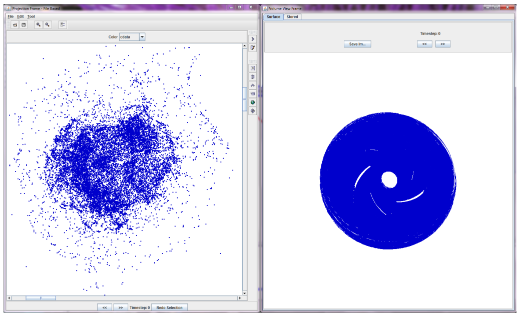
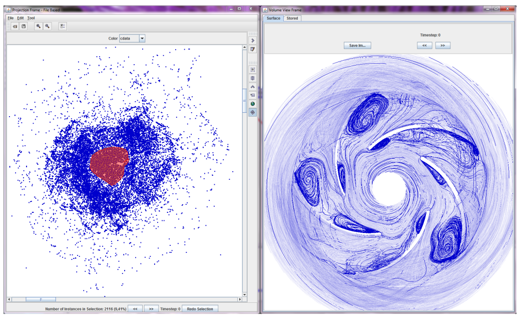
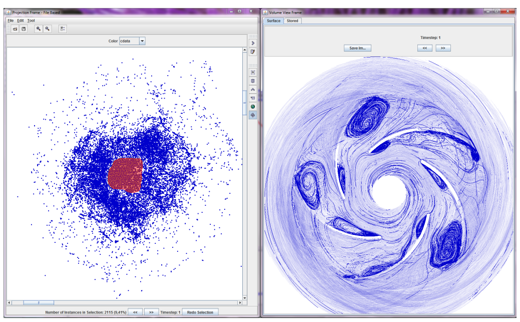


(a) Time step 0.



(b) Time step 0 - User selection.



(c) Time Step 1 - Same position of previous user selection.

Figure 1: Identification of vortices: (a) visualizations of the streamline feature space and the object vector space; (b) Selection of well defined groups and visualization of the corresponding streamlines. Selected group corresponds to vortical streamlines; (c) Next time step loaded, maintaining the selection performed in (b), reveals the 2D spatial coherence of the projected streamlines.

4 Comments and Conclusions

We initially tried to analyze the relationship of the nodes by projecting a feature space composed by the raw attributes given in the data set. The rationale was to check wether nodes with similar attributes lead to grouping of vortical regions. Results were not satisfactory, that is, apparently vortices are not well grouped by their raw simulated attributes. That first run took the team nearly 20 days, part time, to complete.

The approach described in this work was the best solution we found to enable user controlled vortex detection in a fluid flow data set. The final solution was achieved by the team in one week, also working part time.

We have also investigated other projection techniques to group the streamlines, e.g., Principal Component Analysis [4], Fastmap [1] and Part Linear Multidimensional Projection [6], but PLSP yielded the best results.

We developed a prototype tool for this linked view approach,

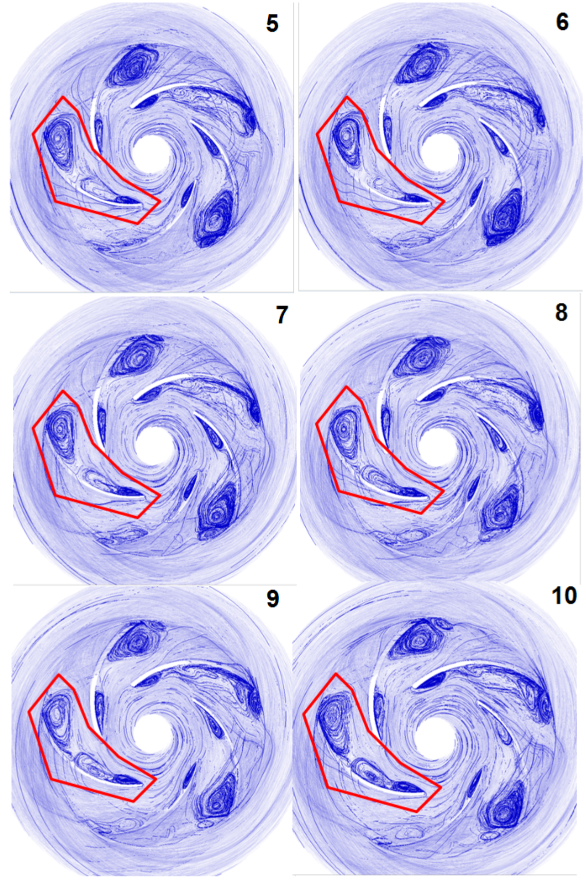


Figure 2: Illustration of a vortex appearing from the center to the border of a blade (highlighted in red).

which provides an effective way to select groups of streamlines in 2D space, aiding in the selection and identification of vortices.

5 Acknowledgements

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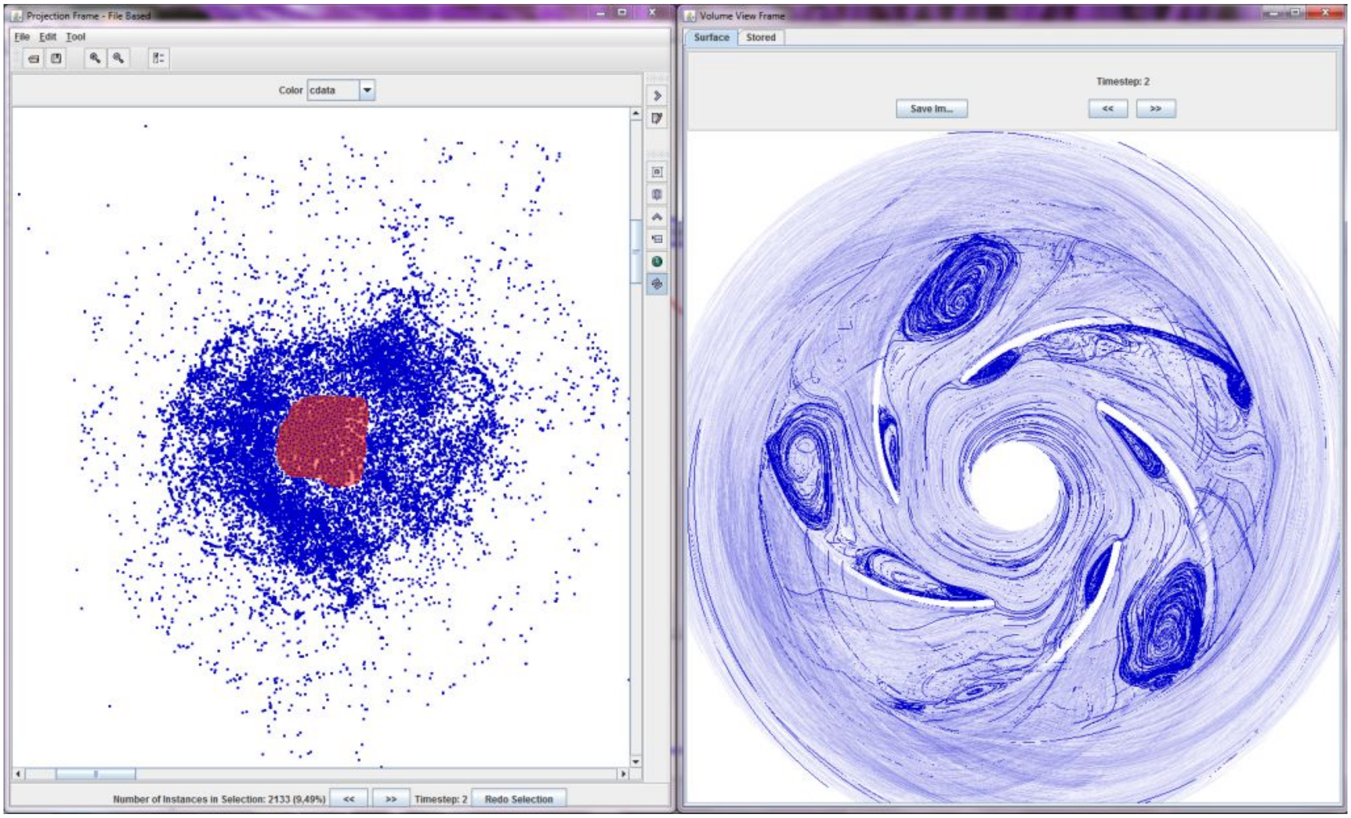

Figure 3: Appendix: visualization of time step 2.

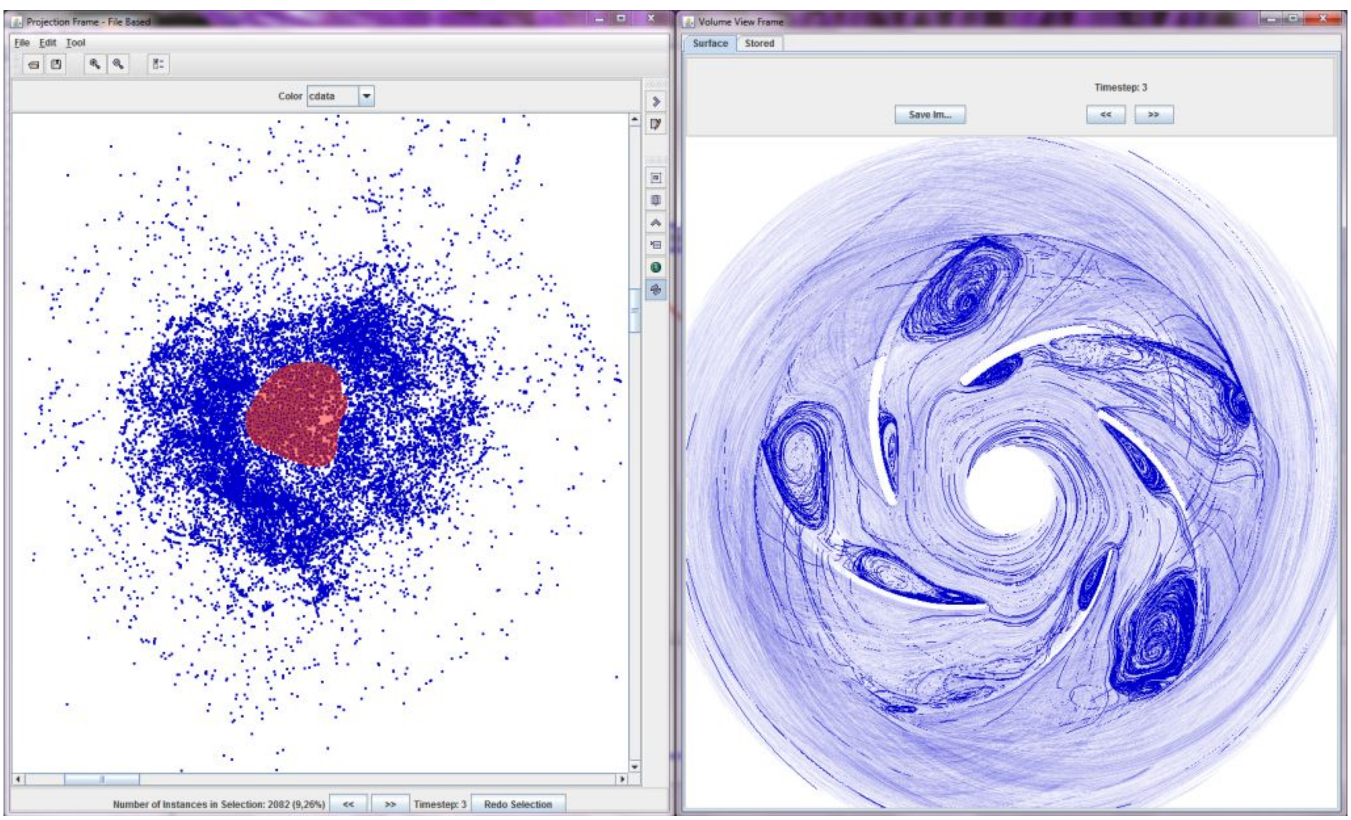

Figure 4: Appendix: visualization of time step 3.

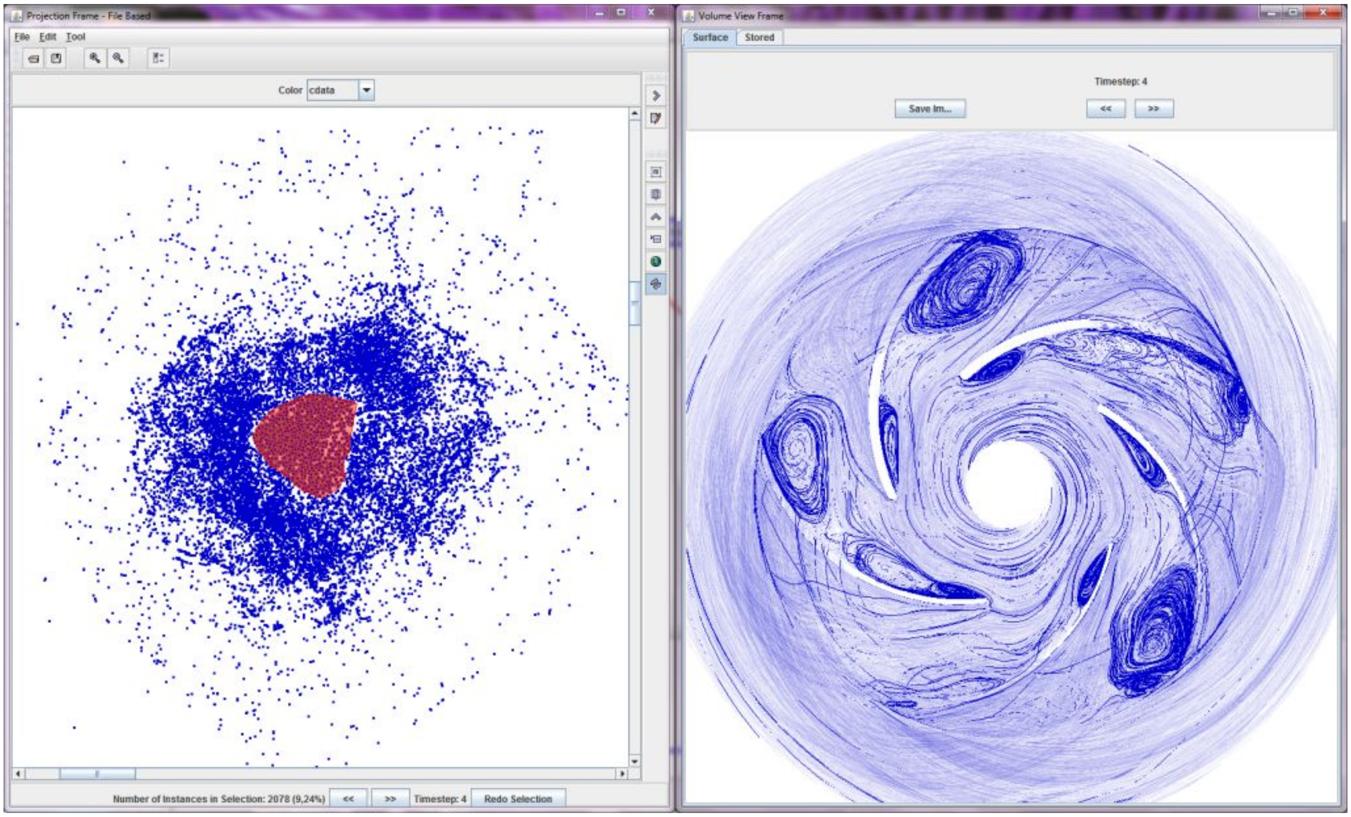

Figure 5: Appendix: visualization of time step 4.

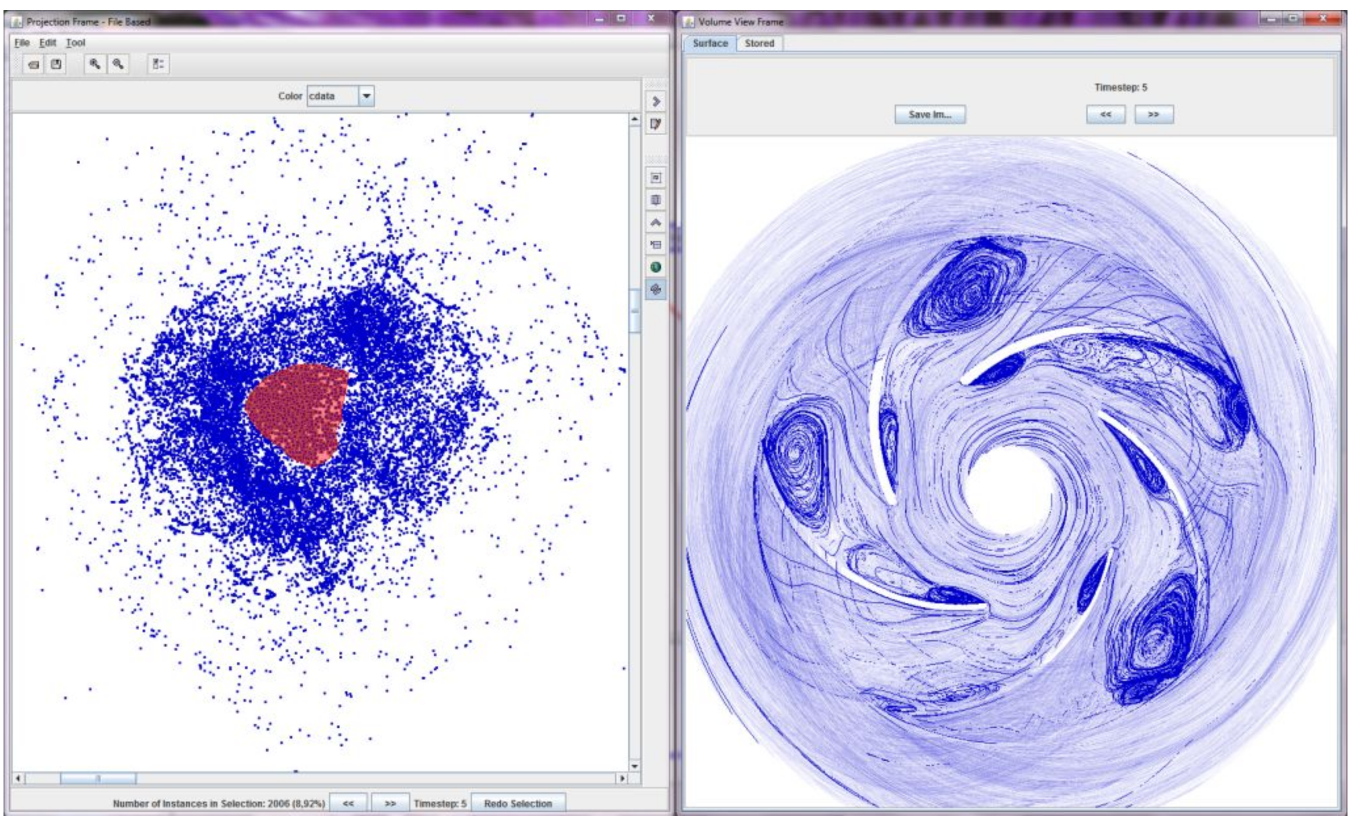

Figure 6: Appendix: visualization of time step 5.

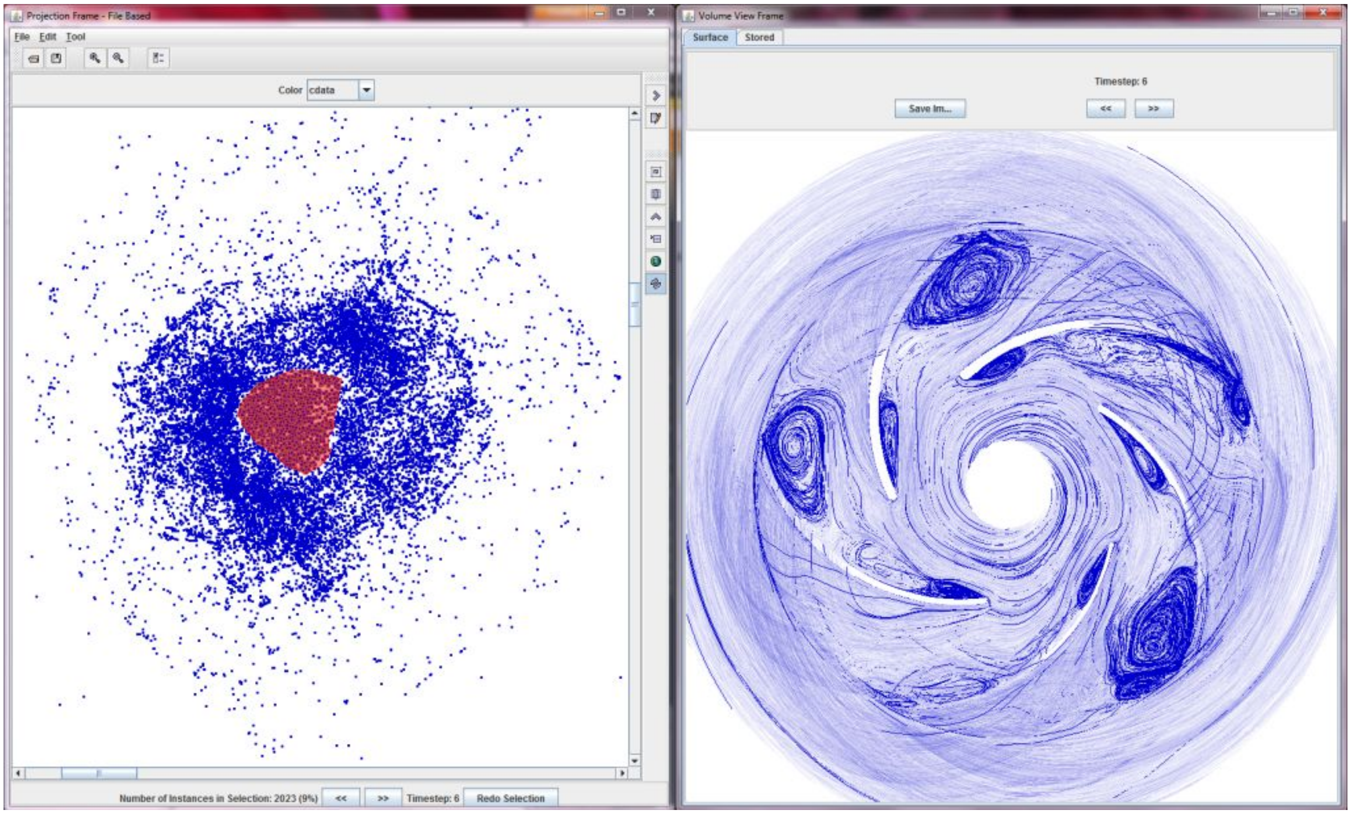

Figure 7: Appendix: visualization of time step 6.

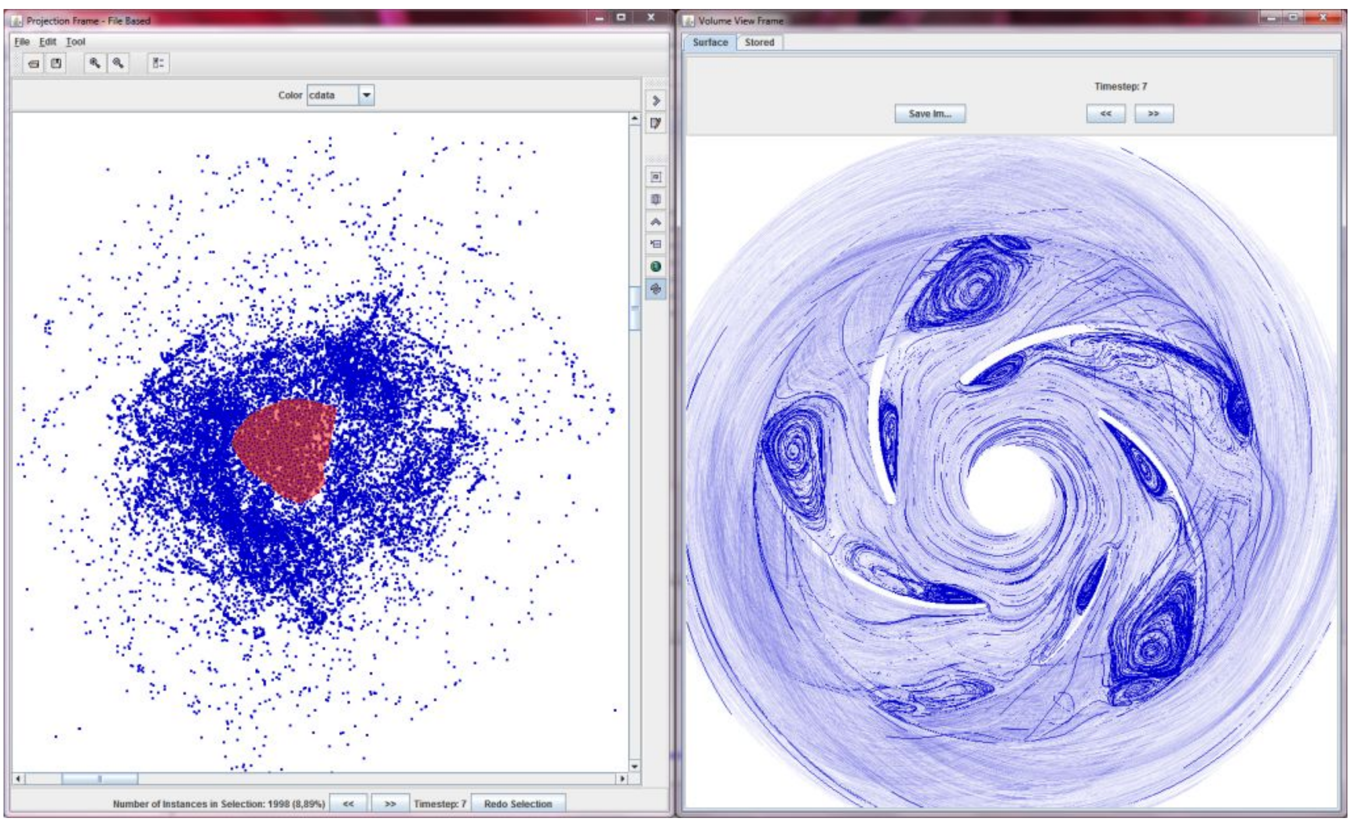

Figure 8: Appendix: visualization of time step 7.

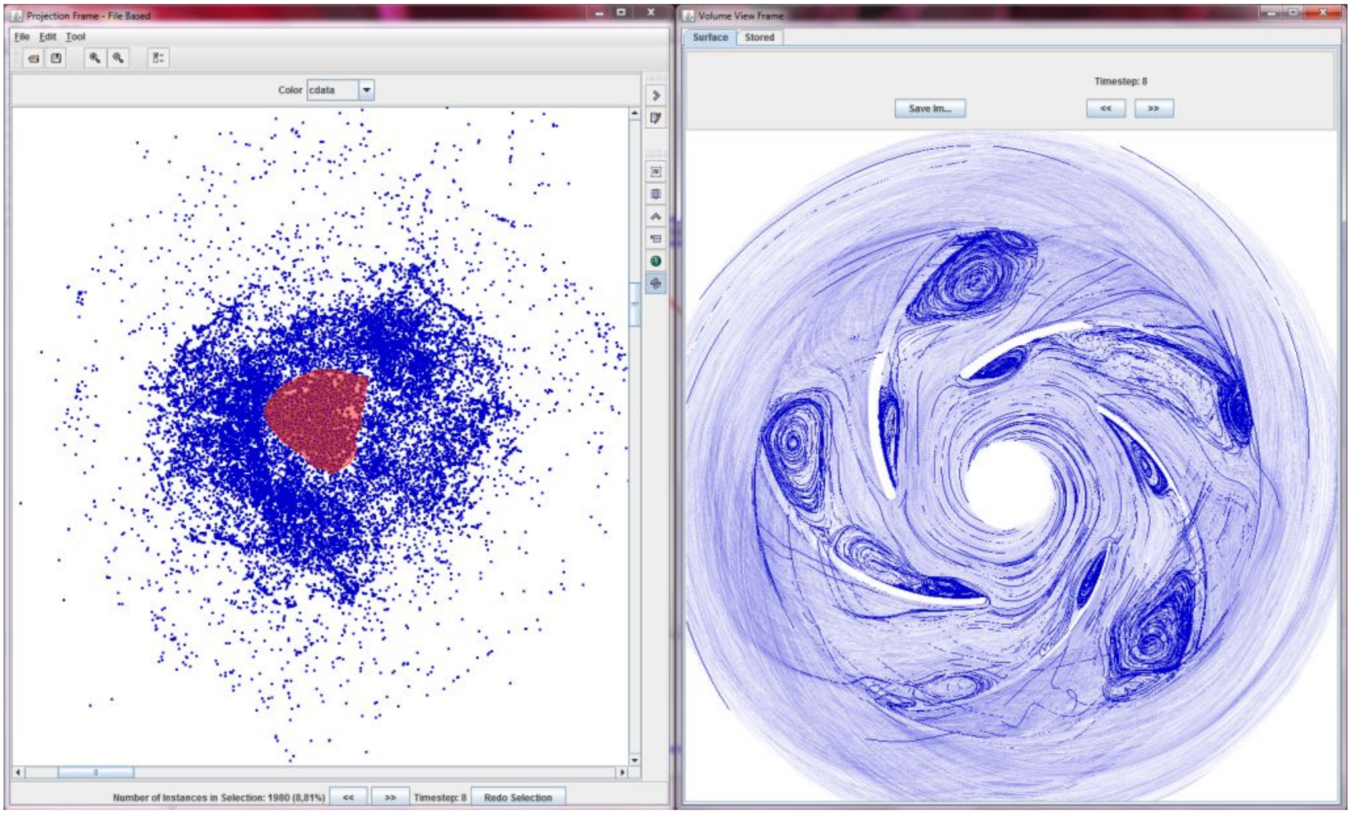

Figure 9: Appendix: visualization of time step 8.

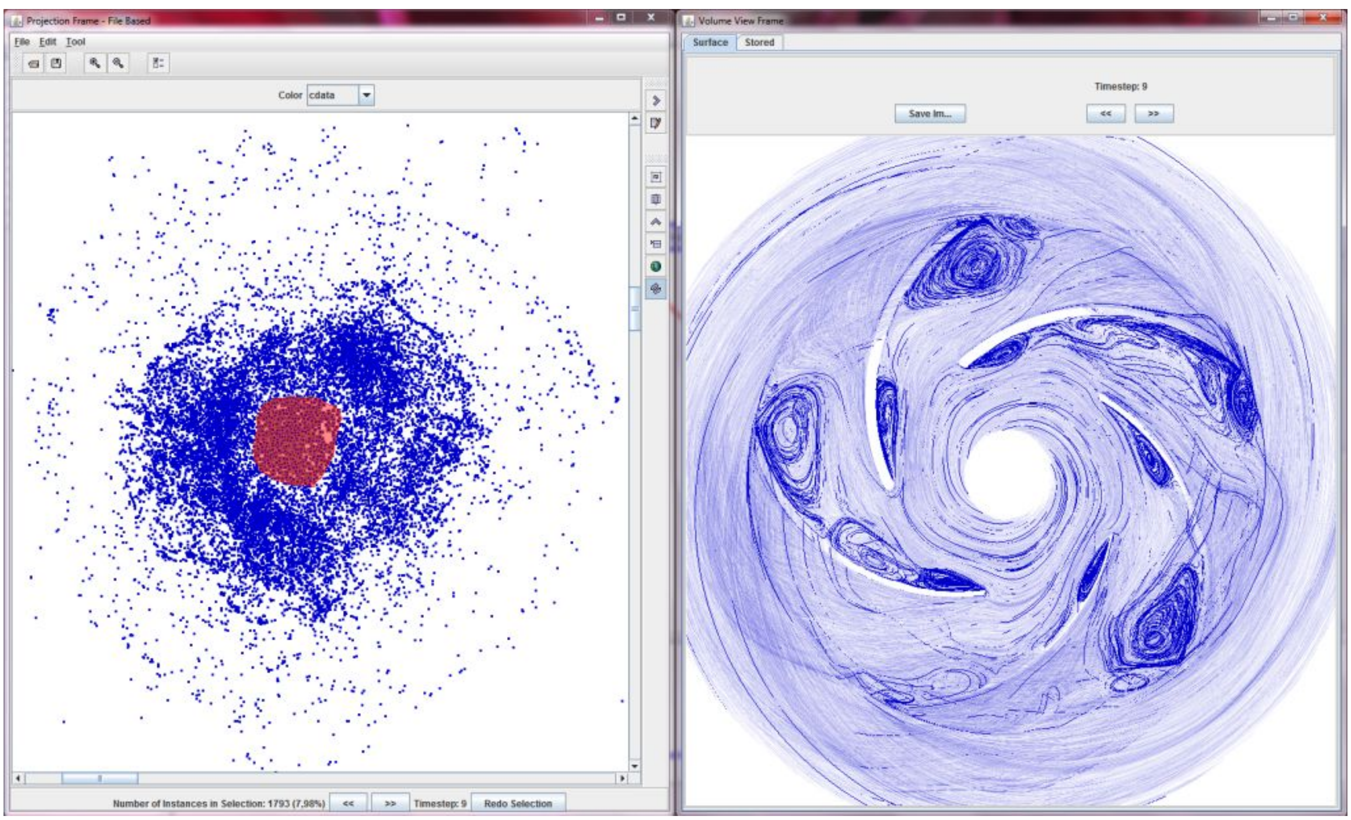

Figure 10: Appendix: visualization of time step 9.

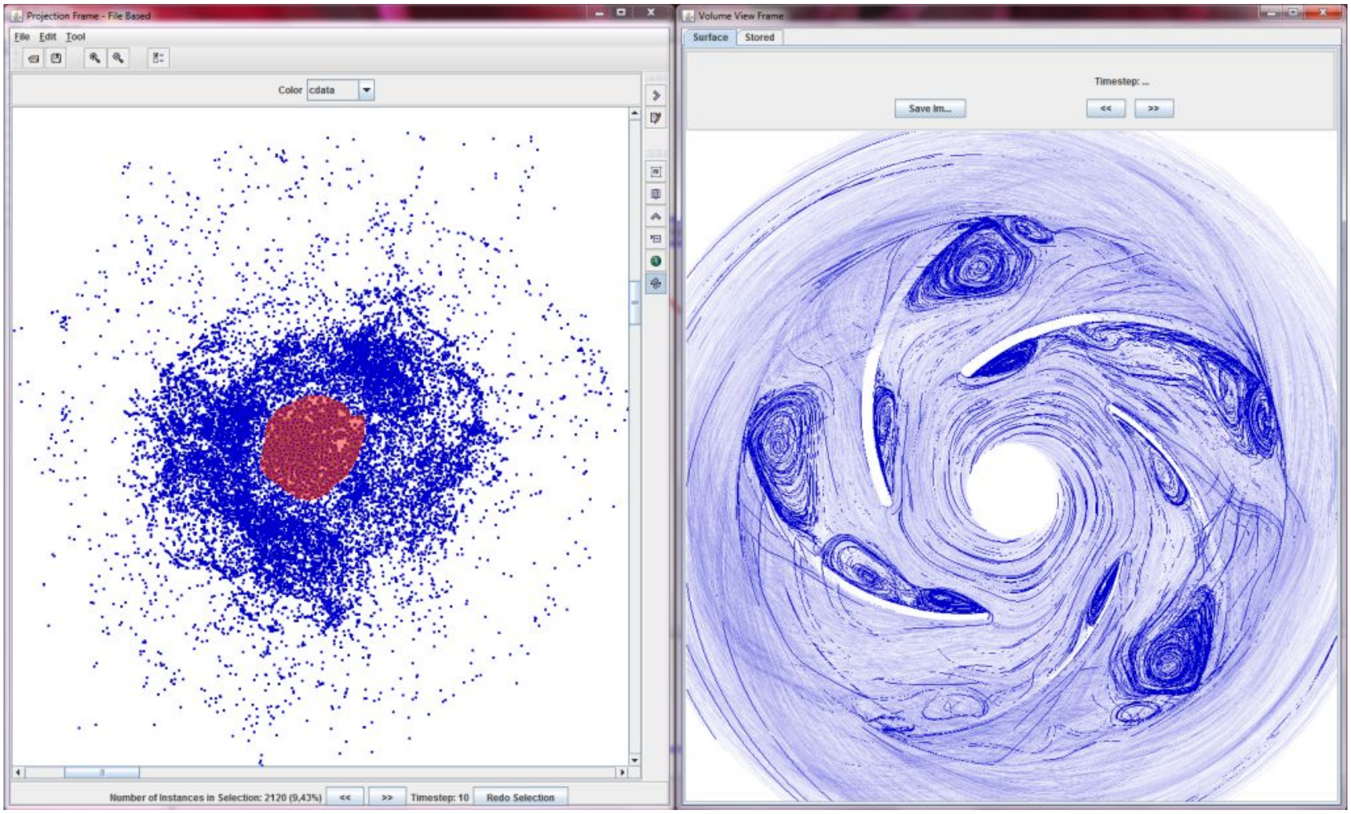

Figure 11: Appendix: visualization of time step 10.

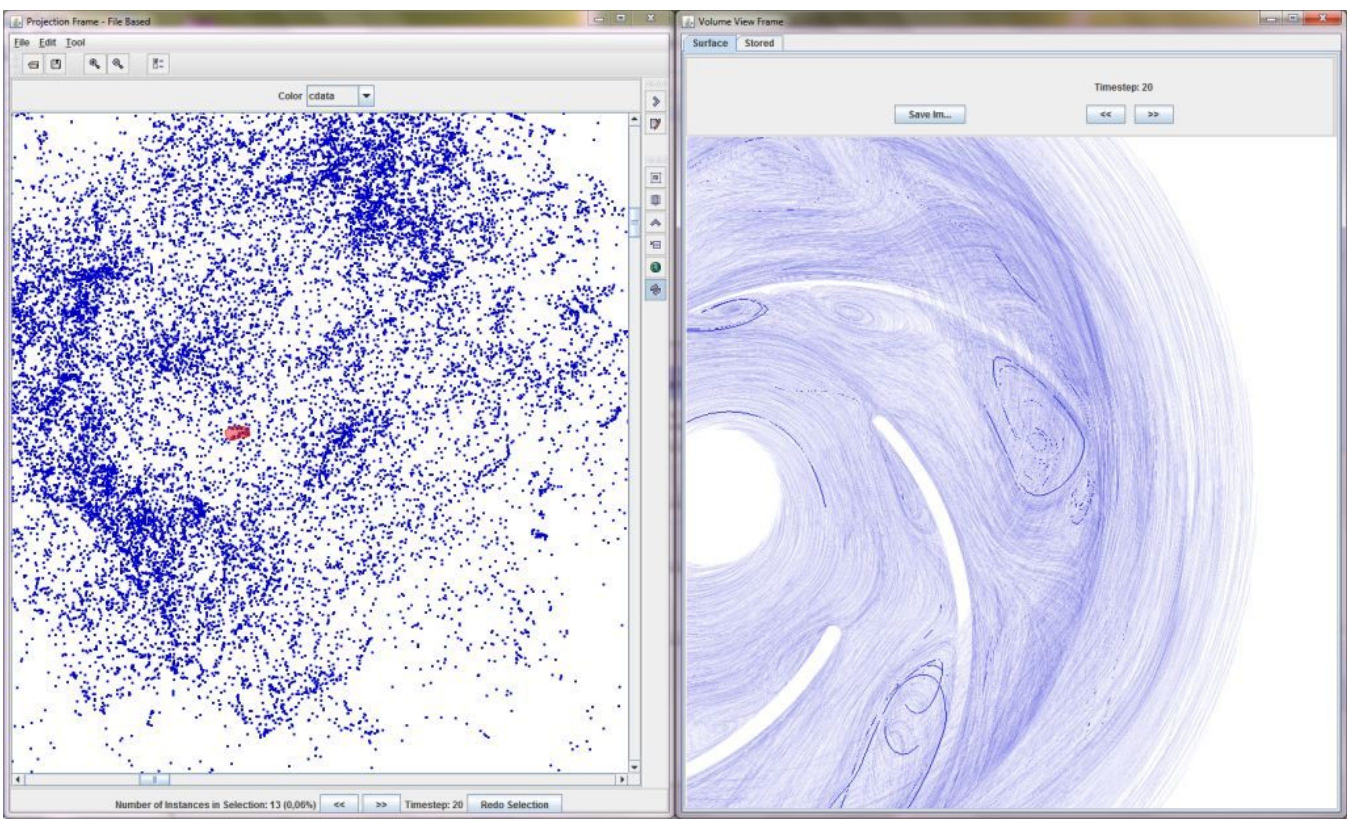

Figure 12: Appendix: detail of the selection of a group in the projection of the streamlines computed for time step 20.

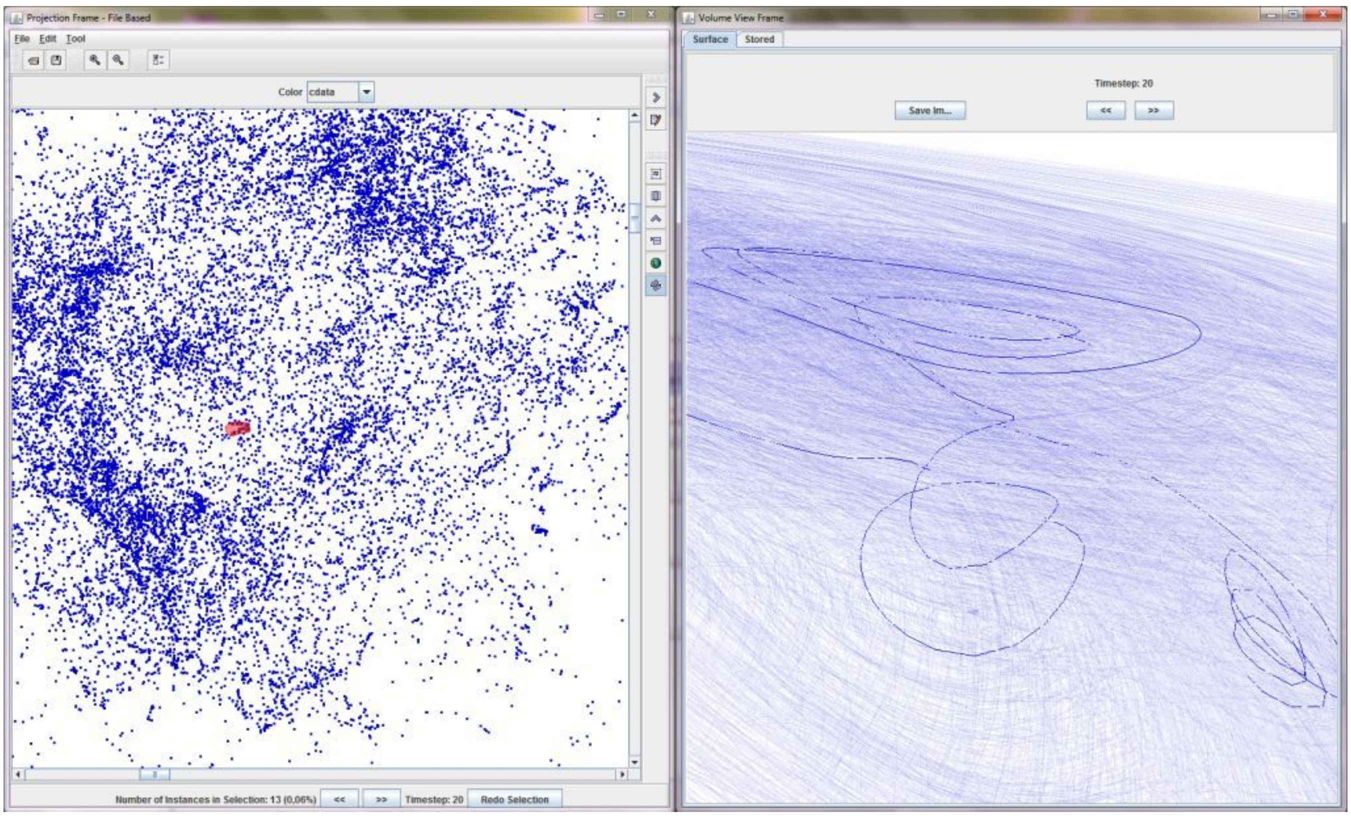

Figure 13: Appendix: zooming in the vortical region shown in Figure 12.