Exploring Flow Fields Using Fractal Analysis of Field Lines

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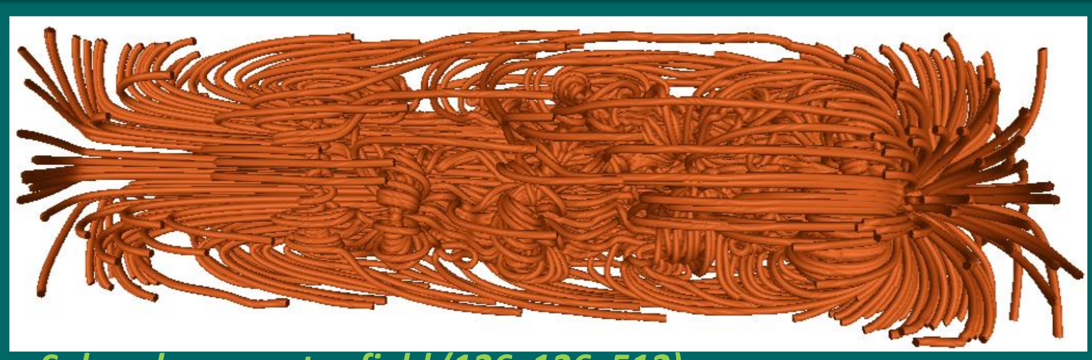
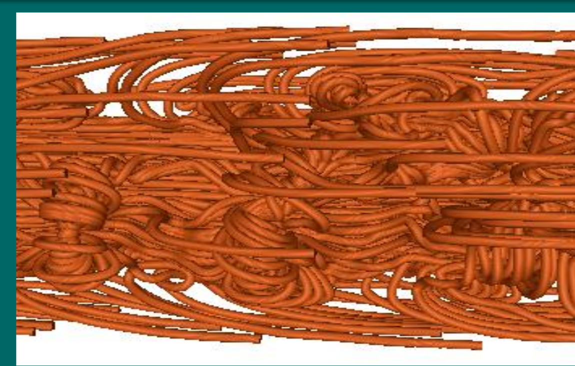
Motivation



Solar plume vector field (126x126x512): A static visualization with 1000 streamlines is barely helpful due to clutter and occlusion

Change of viewpoint is not necessarily useful



However, a close-up view indicates presence of many vortices and other complex features

- Modern simulations produce enormous vector fields
- Extracting information from large flow fields is a challenging problem
- Visualizing all streamlines together is not useful due to clutter
- Our objective is to identify, extract and visually present the streamlines or the streamline segments which represent interesting flow features

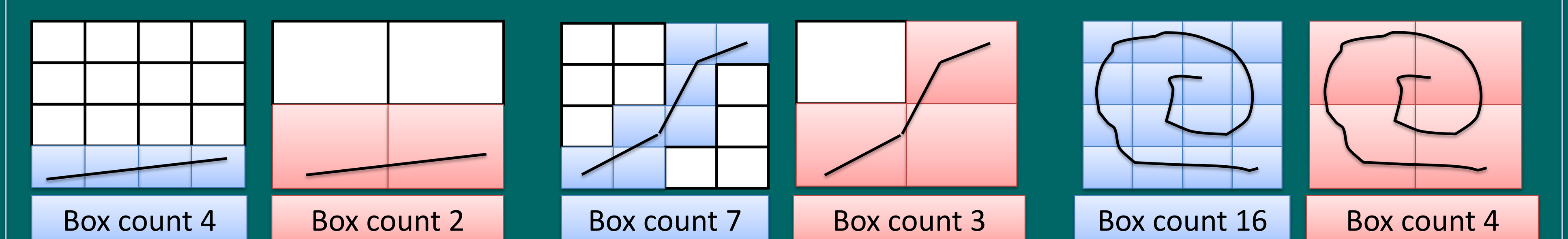
Box Counting Ratio

- ***Observation:*** Different flow features are represented by streamlines of different geometric complexity
- A metric which quantifies geometric complexity can be useful
- ***Proposed solution:*** We adapt a fractal dimension based metric called ***box counting ratio*** [1] which can capture geometric complexity of streamlines
- Streamlines are known to have self-similarity near vortex like points [2]

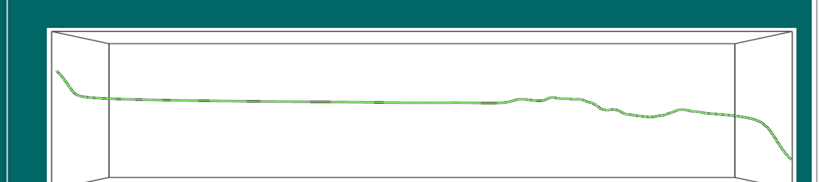
$$\textit{Fractal Dimension} = \lim_{\delta \to 0} \frac{\log(N_\delta(F))}{-\log(\delta)}$$

where F is an object, N is the number of cells covered by F, δ is scale of measurement

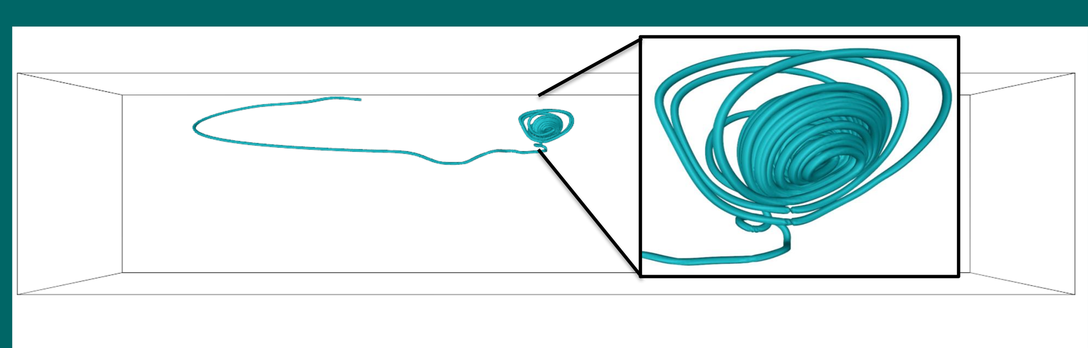
$$\textit{Box Counting Ratio} = \log_2 \frac{\text{box count at finer resolution}}{\text{box count at coarser resolution}}$$



Ratio = 1 | Ratio = 1.22 | Ratio = 2

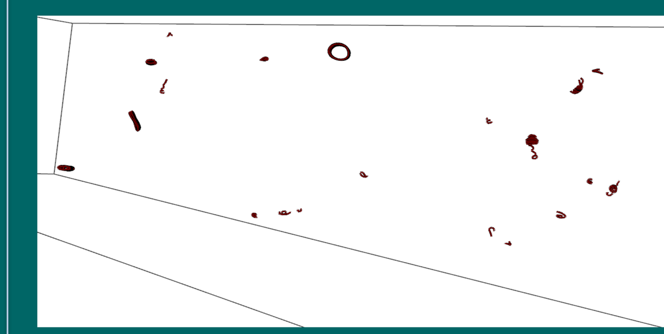


Range of box counting ratio in 3D is 0-3. Fairly straight streamlines have box counting ratio close to 1

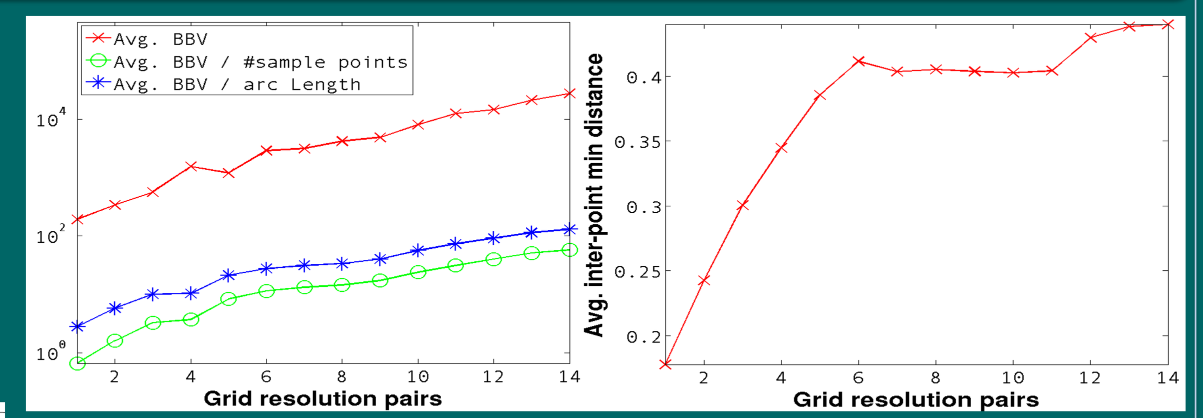


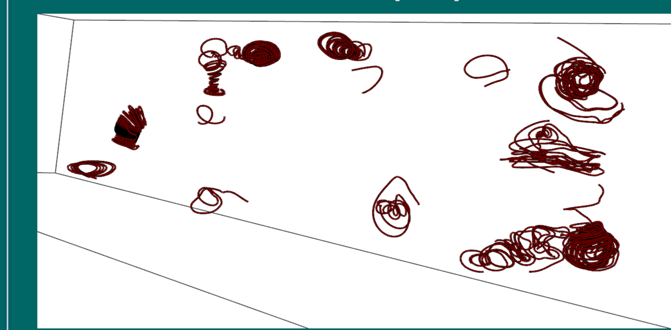
Streamlines with complex part(s) have box counting ratios well above 1. The complex parts alone may have box counting ratio above 2. Basic analysis such as streamline filtering can be done using box counting ratio

Multi-scale Feature Detection



Features extracted at (1,2) from Plume



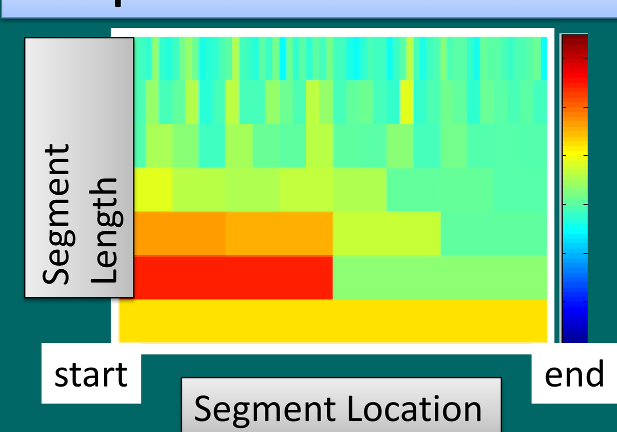


Features extracted at (8,16) from Plume

- Unlike other measures, box counting ratio can detect features at different scales
- Average size and sparseness of the top scoring features show strong correlation with the scale of measurement (box size)

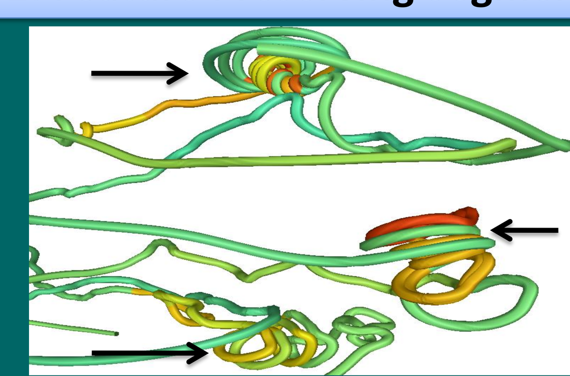
Feature Exploration Framework

Step 1: Feature Localization



Feature Map: A top-down binary subdivision of each streamline followed by box count ratio computation of each segment is done to localize high scoring regions

Step 2: Feature Preserving Segmentation



For each streamline, the high-scoring segments from different levels of hierarchy are accumulated to form a single segment from an entire complex region

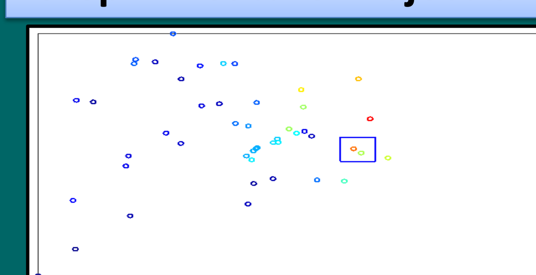
Figure above: a streamline with three high-scoring segments corresponding to three features

Step 3: Feature Vector Construction

Feature location	Feature Size	Box counting Ratio
… …		
… …		
Feature location	Feature Size	Box counting Ratio

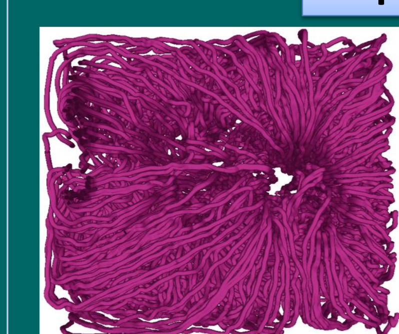
All the high-scoring segments are extracted from all streamlines using some threshold. A pool of feature vectors is created from these feature segments, along with their size and location information

Step 4: Feature Projection

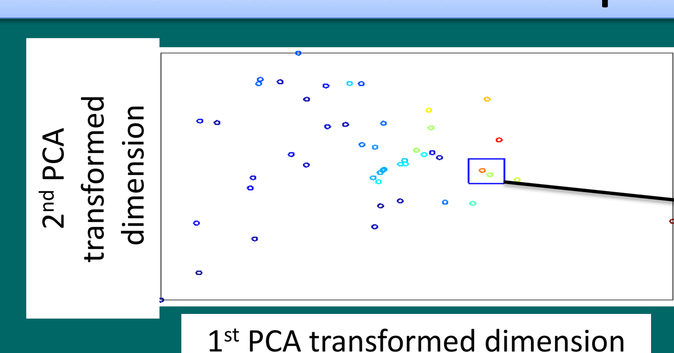


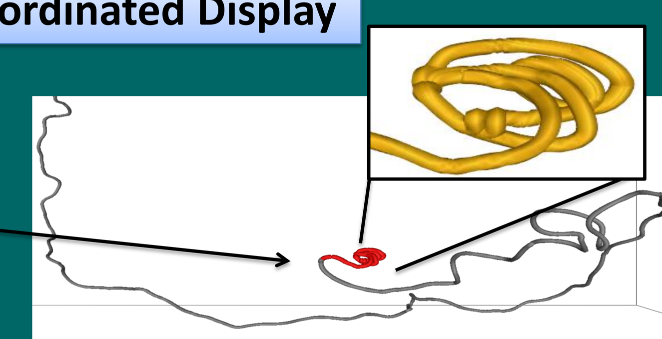
The feature vectors are projected on an occlusion-free and interaction-friendly 2D space using PCA or MDS. Feature selection from this space is much easier than exploring the 3D spatial domain

Step 5: Feature Presentation on Multiple Coordinated Display



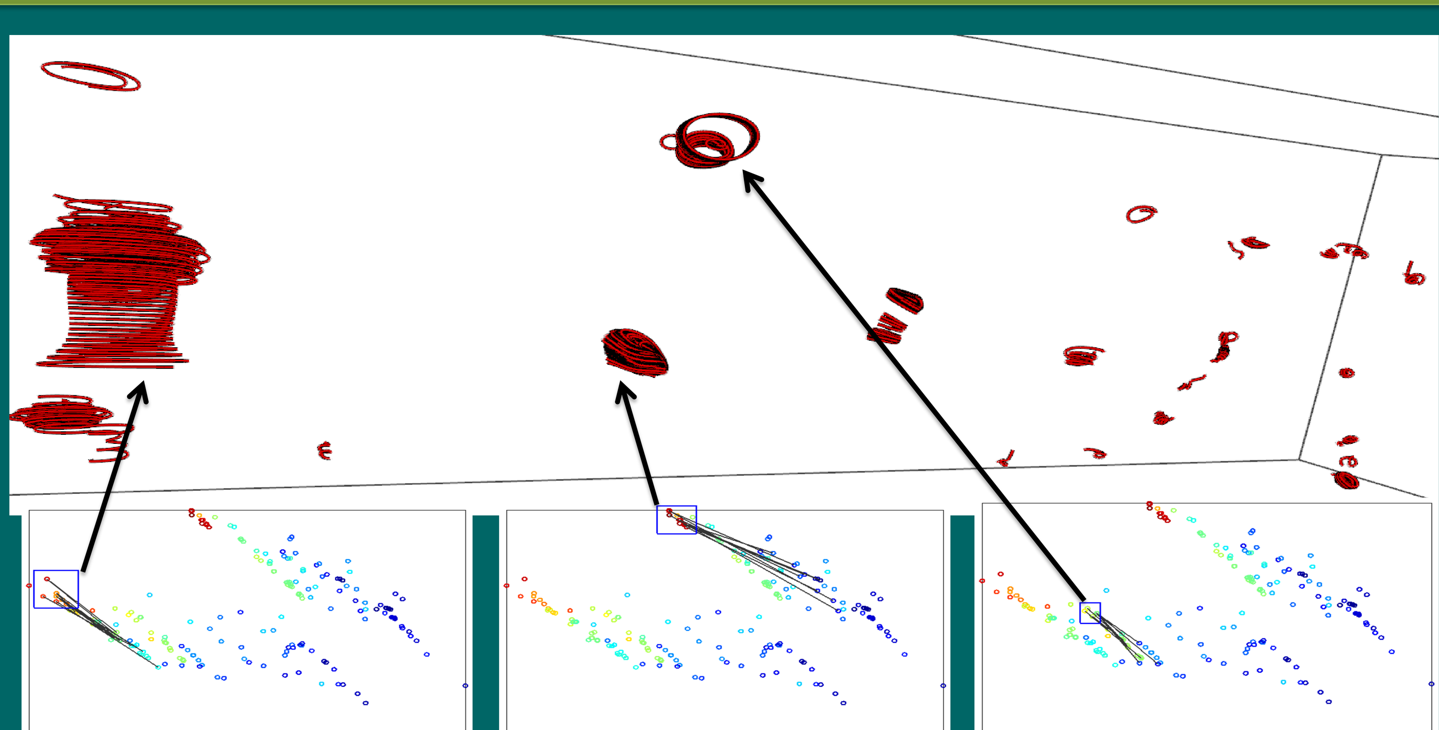
NEK5000 vector field: streamlines causing high degree of occlusion





User interaction: Points on the 2D feature space (left) correspond to complex streamline segments in the 3D spatial domain (right). The features are colored based On size, allowing size-based feature selection and exploration.

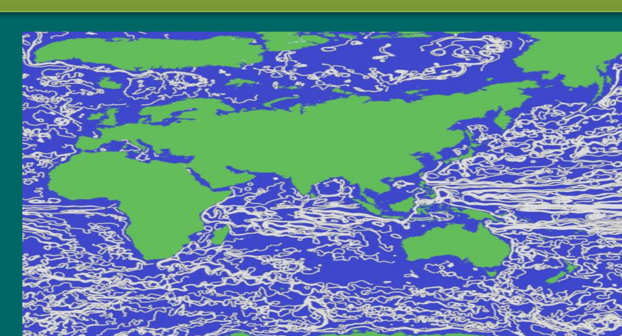
Case Study: Solar Plume



Solar Plume (126x126x512) data set: Triage of complex segments extracted based on box counting ratio. *Top:* Extracted feature segments; *Bottom:* Three different selections on the feature space. Clusters correspond to various clustered streamline segments for this dataset.

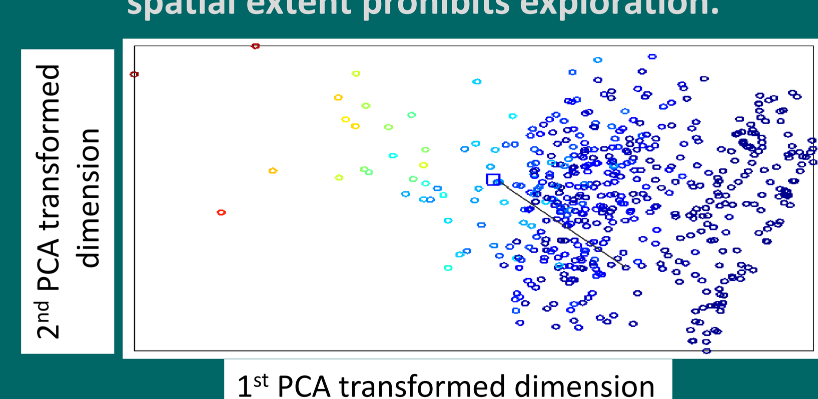
Feature linking: Segments coming from the same streamline are shown as linked.

Case Study: Ocean

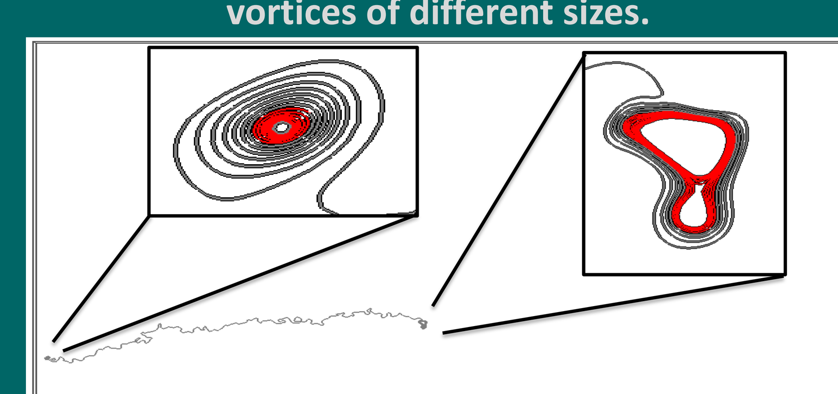


OCEAN (3600x2400x40) data set: Large spatial extent prohibits exploration.

Feature linking reveals connected vortices of different sizes.



Feature linking: Additional visual cue which helps reveal remotely located, yet connected flow features.



Our framework identifies remote vortices connected by very long streamlines. Such connections cannot be easily identified from cluttered streamline based visualization

Future Work

- Plan to generalize the feature exploration framework by including other geometric measures such as curvature
- Extension to time-varying field lines such as pathlines
- Extension to stream surfaces

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2. J. C. Vassilicos and J. C. R. Hunt, “Fractal dimensions and spectra of interfaces with application to turbulence,” Proceedings of the Royal Society of London. Series A: Mathematical and Physical Sciences, 435(1895), 1991.
3. Abon Chaudhuri, Teng-Yok Lee, Han-Wei Shen, Marc Khoury, and Rephael Wenger. “Exploring flow fields using fractal analysis of field lines.” Technical Report OSU-CISRC-4/11-TR15, Dept. of CSE, Ohio State University, Columbus, OH, April 2011.