Detection of Environment Transitions in Time Series Data for Responsive Science

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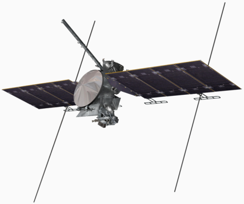
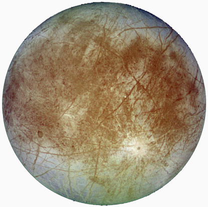
Problem Context





The Plasma Instrument for Magnetic Sounding (PIMS) on the Europa Clipper Mission (scheduled for 2024 launch) aims to study the properties of the plasma around Europa and Jupiter.

PIMS

- Counts the number of particles within ranges of energies.
- Operates in 4 different modes, with different sampling rates and energy ranges. Each mode is optimized for the anticipated plasma conditions in its region.
- Current mode-switching logic is pre-scripted, based on estimates of where regions lie!

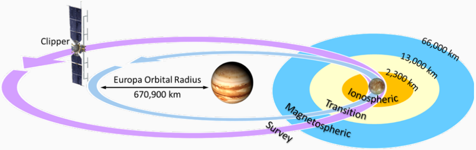


Figure 1: PIMS modes as a pre-defined function of distance from Europa.

Key Question: Can we detect transitions between magnetic field regions to enable onboard real-time instrument adaptation?

Problem Context

- At each time step, PIMS records the number of particles collected in the energy 'bins', each representing a subrange of energies.
- Data can be thought of as a multidimensional time-series!

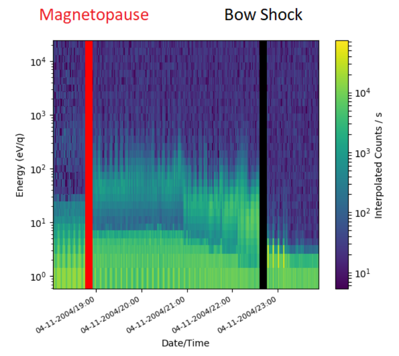
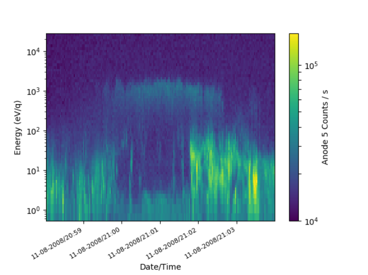


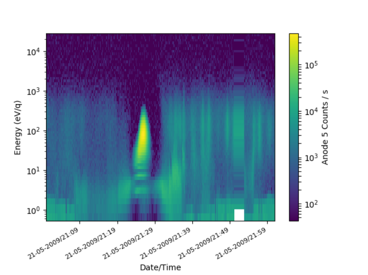
Figure 2: Example 6-hour CAPS-ELS observation, from the Cassini mission to Saturn.

Advantages of Responsive Science

- In the case of Europa, the magnetic environment regions themselves are poorly understood. These methods can help pinpoint boundaries.
- Capture a greater number of electromagnetic phenomena of scientific interest, at the best range of observing energies.



(a) High-energy electrons near Enceladus



(b) Negative ions near Titan

Figure 3: Examples of scientifically important electromagnetic phenomena, as seen in CAPS ELS data.

Why is this hard?

- Severe restriction on computational resources on spacecraft: 130 MHz processor! This restricts us to simple methods.
- The boundaries between magnetic regions are not sharp (especially for magnetopause in CAPS ELS).
- Within a region too, there are many local variations: some of these are due to legitimate electromagnetic phenomena.
- Spacecraft trajectory variation leads to different angles of interaction with the boundaries.

Algorithms Investigated

This problem can be cast in many ways: state transition detection, change-point detection or 'discord' detection.
With an eye on simplicity, we selected:

- Baseline, based on the l^2-difference between vectors at timesteps.
- Hidden Markov Models (both non-Bayesian [Baum, et al, 1966] and Bayesian variants [Fox, et al, 2008]).
- RuLSIF: Relative Unconstrained Least-Squares Information Fitting [Liu, et al, 2013].
- HOT SAX: Heuristically Ordered Time series using Symbolic Aggregate ApproXimation [Keogh, et al, 2005].
- Matrix Profile [Yeh, et al, 2016].

The Multidimensional Matrix Profile

- The original Matrix Profile was developed for unidimensional time-series.
- Multidimensional variants have been developed, but these mask discords.
- We instead propose an anomaly-sensitive variant that uses the individual Matrix Profiles $MP^{(d)}$ over each dimension d:

$$MMP_i = \sum_d MP_i^{(d)}.$$

- Can be restricted to the k-th largest Matrix Profile values for each time step, as well.

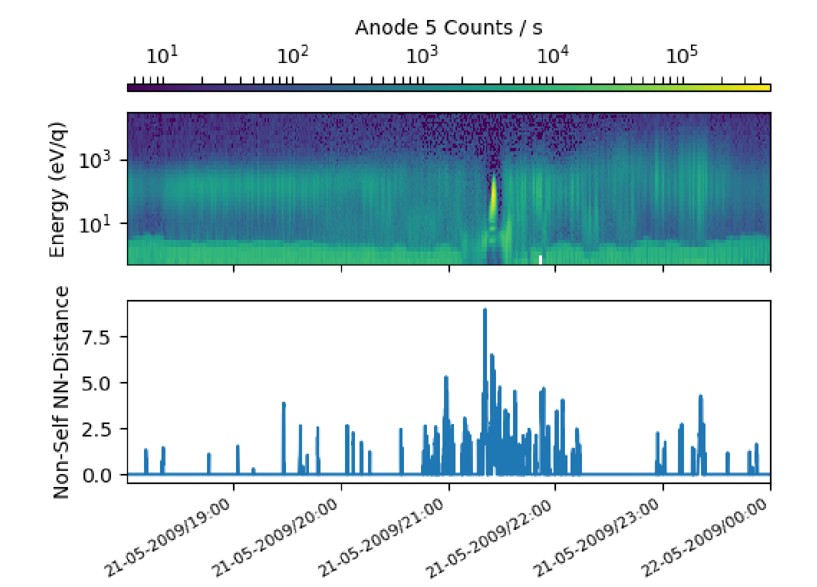
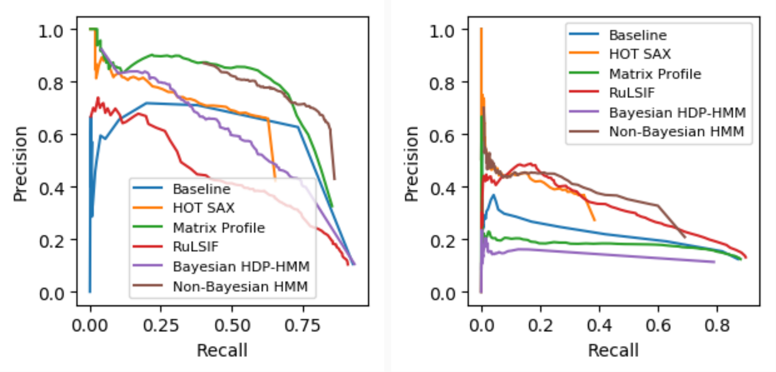


Figure 4: The Multidimensional Matrix Profile scores on the CAPS ELS observation of negative ions near Titan.

Results



(a) Bow shock

(b) Magnetopause

Figure 5: Test performance (recall-precision) on data from 2005 to 2012. Parameters were chosen via validation on data from 2004.

Contributions

- Proposed an extension of the Matrix Profile for discord detection in multivariate data.
- Defined a new, challenging time-series analysis task.

Future Work

- Investigate supervised learning methods: we would be able to use data from the first few flybys of Europa.
- Investigate online change-detection methods, handling observations in a streaming fashion.
- Benchmark run-time in a flight system setting, on an equivalent processor.
- Assess radiation sensitivity of algorithms: important for mission.

Acknowledgements

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Questions?
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