Vlasov Informed Super Resolution (VISR): A Deep Learning Approach for De-Aliasing Particle Data

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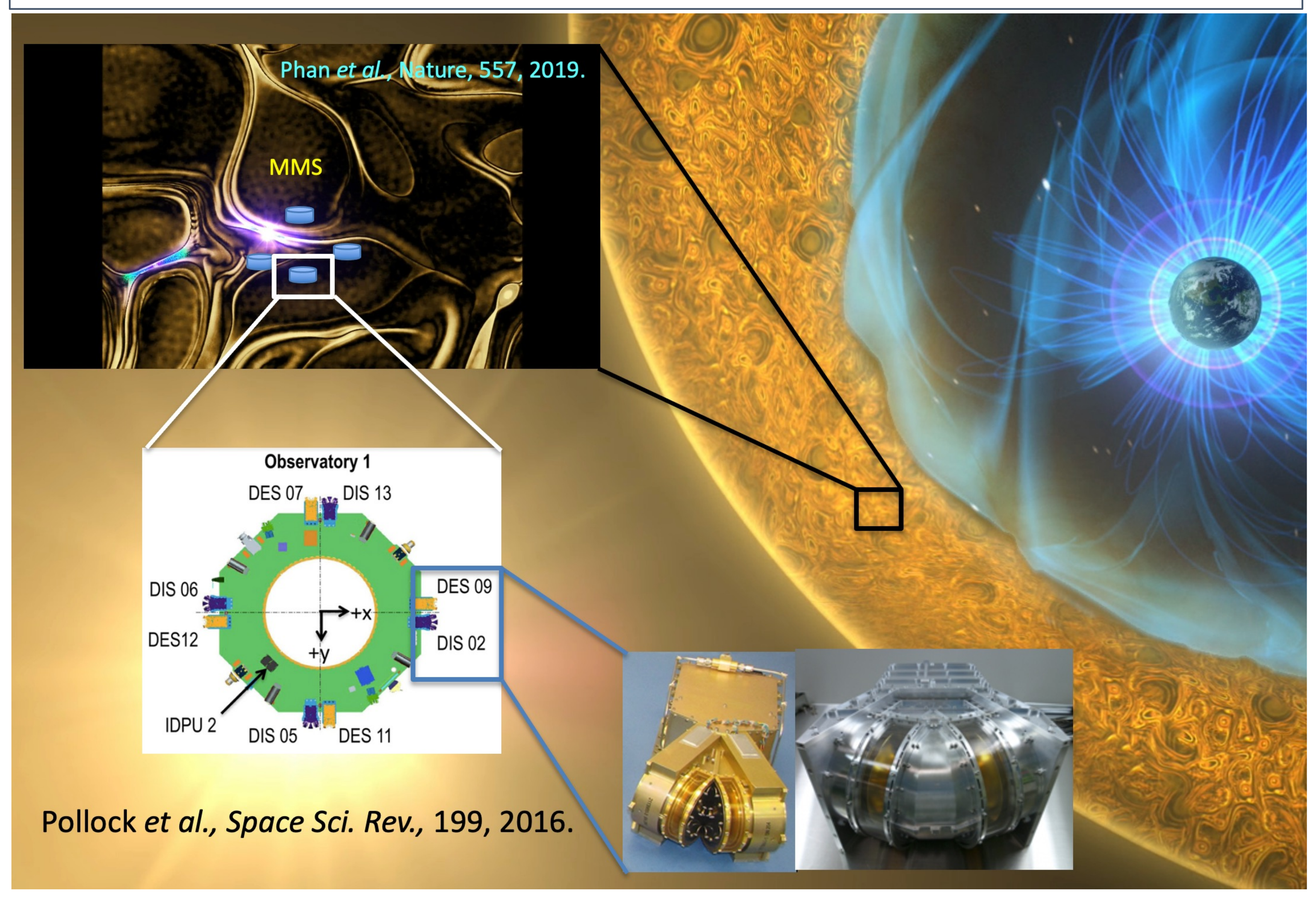
Abstract

NASA science missions must solve the challenging problem of understanding the structure and dynamics of severely under-sampled systems. Missions are designed with a suite of instruments on one or more spacecraft, each instrument making observations along spacecraft world lines sampling a very small volume of space and time. In the case of particle instruments, the sample space is the full seven-dimensional single-particle phase space, and the finite energy sweep limits the temporal resolution. Solving this aliasing problem would enable an order of magnitude increase in the temporal resolution of particle instruments.

Deep Learning has shown great promise in recovering structure from sparse observations. Specifically, Physics Informed Neural Networks (PINN) [Raissi et al., 2019] build partial differential equation (PDE) constraints into the loss function, greatly reducing the number of observations required to build an accurate and predictively powerful model. We apply a newly developed PINN technique – Vlasov Informed Super Resolution (VISR) – to "de-alias" particle data and recover dynamics on time scales faster than the energy sweep. We demonstrate the feasibility of the VISR approach using an analytic solution of the Vlasov equation to generate synthetic data from NASA's Magnetospheric Multiscale (MMS) mission.

Introduction

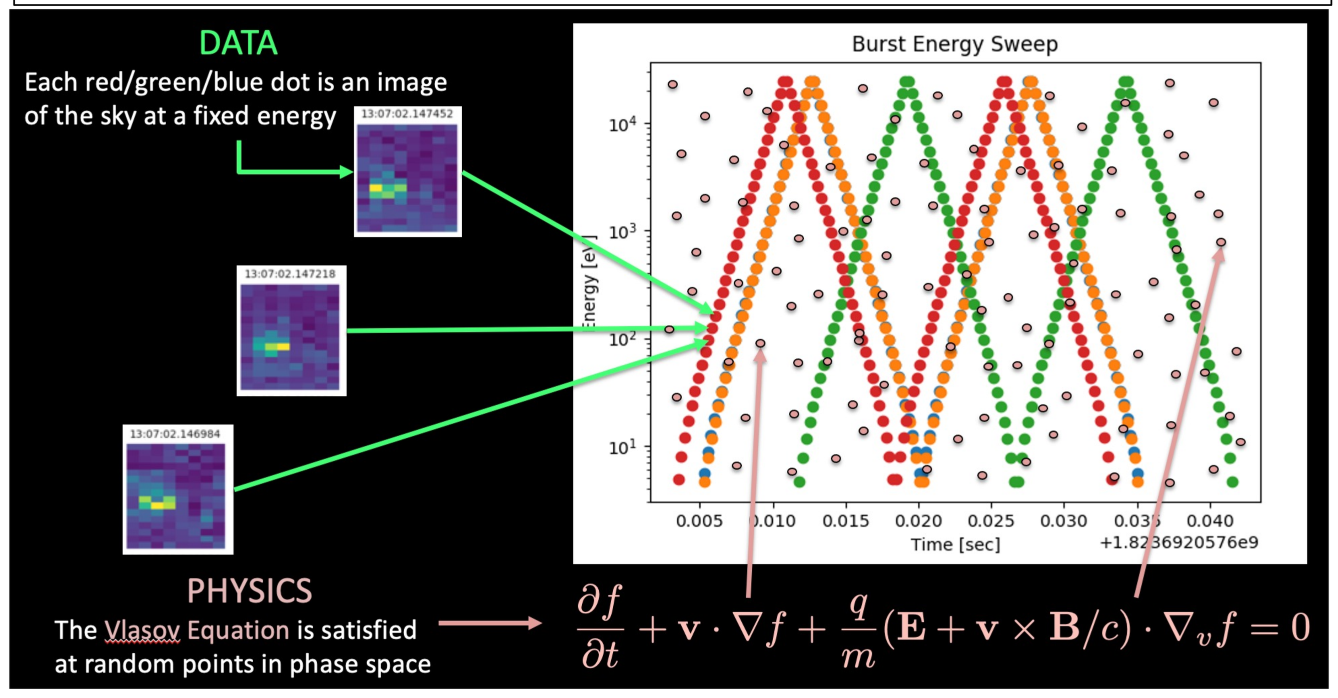
The Fast Plasma Investigation (FPI) on NASA's Magnetospheric Multiscale (MMS) mission.



- MMS was designed to resolve microscopic (~10 km) structures in Earth's magnetosphere.
- FPI solves this problem by arranging 64 electrostatic analyzers around each of four spacecraft, allowing full coverage of the sky without relying on spacecraft spin.
- Nevertheless, there are sill many processes (e.g., turbulence in the magnetosheath) that cannot be fully resolved by FPI due to dynamics occurring on the time scale of the energy sweep.

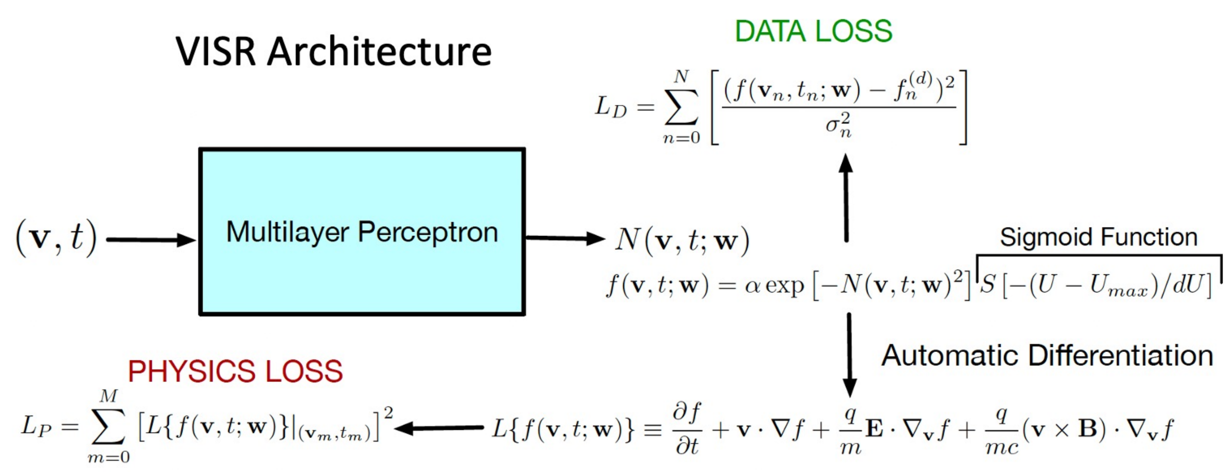
Methodology

Using the Vlasov Equation to increase the temporal resolution of the FPI instrument.

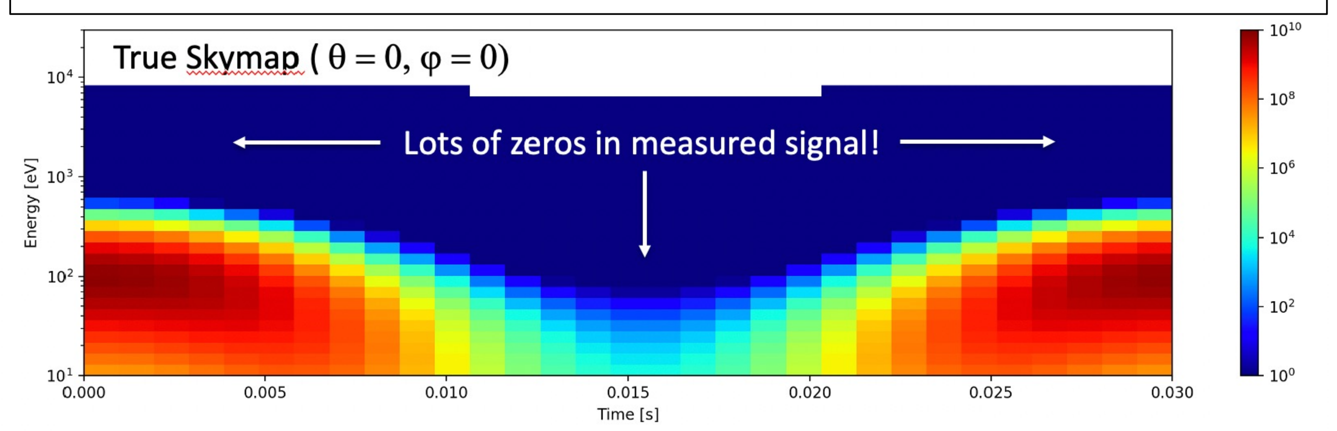


- The FPI high voltage power supplies sweep the full energy range in ~7.5 ms.
- At each energy step, 32 spectrometers arranged around a single spacecraft build up a 32x16 image of phase space density f for each plasma species (electrons and ions).
- We have electric and magnetic field observations, **E** and **B**, respectively, at < 1 ms resolution.
- If f satisfies the Vlasov equation with measured **E** and **B**, then in principle we can find f that satisfies both the Vlasov equation and the data in some optimal sense.
- Physics Informed Neural Networks [Raissi *et al.*, 2019] suggest a natural way to formulate this as a regression problem.

Vlasov Informed Super Resolution (VISR) architecture



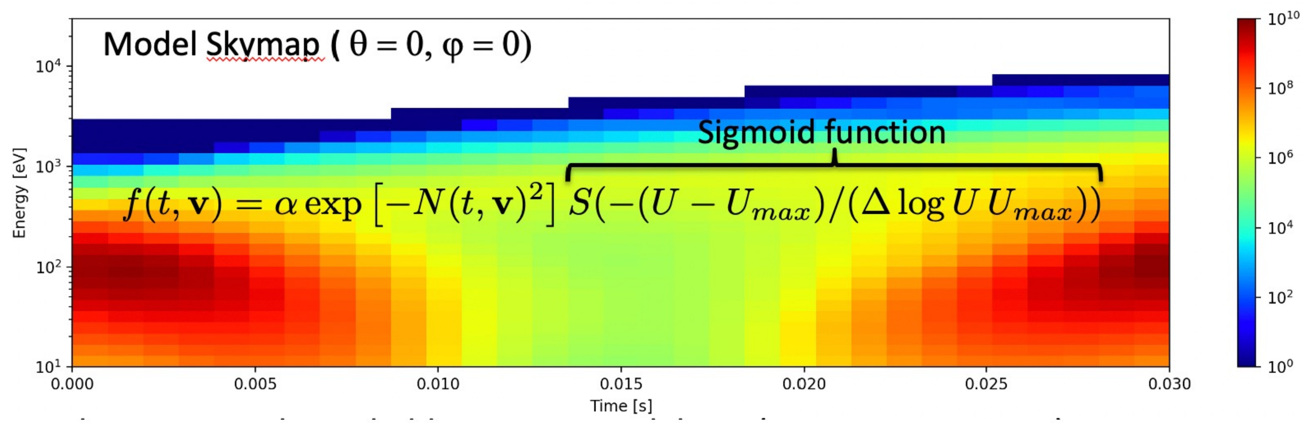
Synthetic FPI data generated from oscillating electric field analytic solution of the Vlasov equation



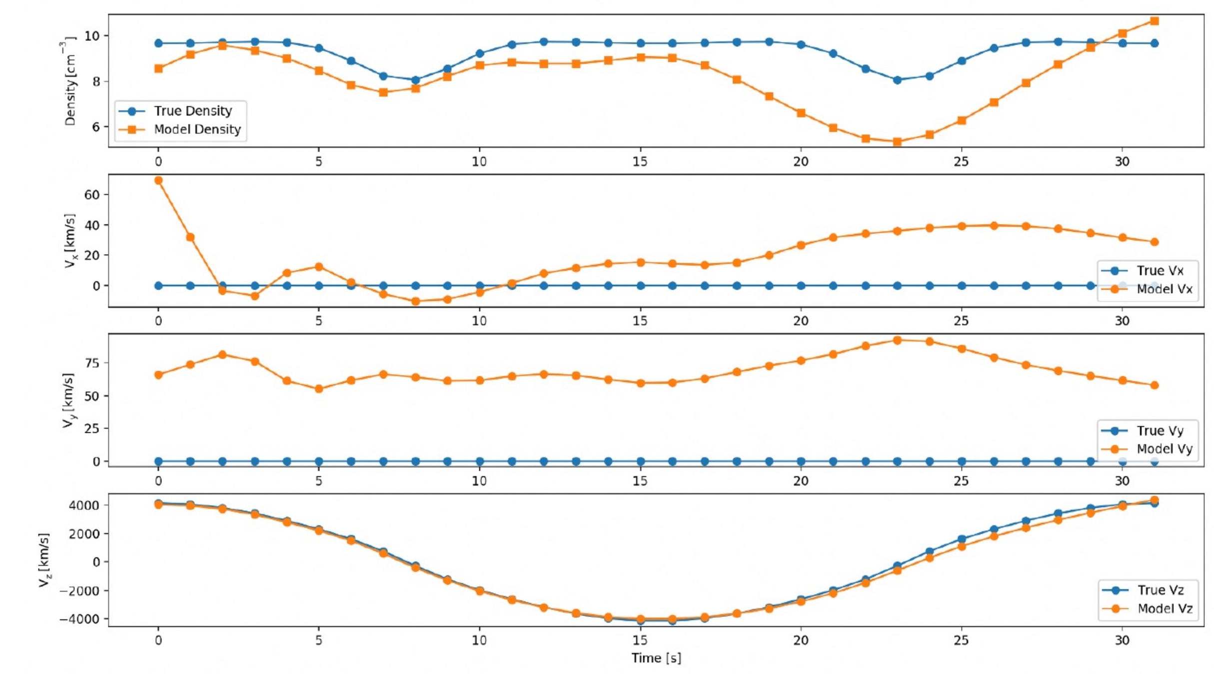
- Synthetic data is generated using an analytic solution of the Vlasov equation, f.
- The FPI instrument response is used to generate counts from f, sampled at the FPI look directions and energies.
- A Poisson random number generator is used to add counting error to the samples.

Results

VISR is able to recover phase space density and plasma moments to within the Poisson error.



- VISR is able to de-alias an oscillating parallel electron bulk velocity signal at a temporal resolution 30x faster than the 0.03 s DES burst time.
- Agreement between the model and analytic solution is very good in regions above the 1-count level



- VISR can reconstruct reasonably accurate DES plasma moments for our test case with density = 10 cm-3, temperature 10 eV and bulk velocity ranging from 0 km/s to 4000 km/s (subsonic to supersonic).
- Systematic errors in the reconstruction are comparable to the expected Poisson error for this case.

Summary

- We have developed a simple Physics Informed Neural Network (PINN) – VISR (Vlasov Informed Neural Network) to de-alias particle spectrometer data.
- Our approach uses a simple MLP architecture with a physics loss consisting of the sum of the squares of the Vlasov equation residual at randomly sampled collocation points.
- Our model is able to recover time variation well below (~ 1 ms) the DES energy sweep time scale (~7.5 ms).
- Systematic errors produced by the model are comparable to the expected Poisson error for the case presented here.
- Future work will:
    - Explore hyperparameter space to determine optimal model architecture and training parameters.
    - Perform Monte-Carlo analysis (randomly varying the sampled phase space density according to Poisson statistics) to propagate errors to model output
    - Deploy VISR on NASA high end computing resources and train it using MMS L2 data

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References

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