ELaborate Particle Analysis from Satellite Observations - EL PASO

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Abstract

We propose a new Python package for processing satellite data of particle measurements in Earth's magnetosphere. While most particle measurements of the radiation belts are openly available, they still must be processed (which may include time binning, calculation of equatorial pitch angles and invariants, converting flux to phase space density, etc) to be used in publications. Currently, each research group processes data individually without a standard procedure, making published data challenging to reproduce. An open, easy-to-use package would help new students handle the data and reproduce previous results.

I. *Introduction*

Charged particles are trapped in Earth's magnetic field, forming a hazardous environment for spacecraft due to surface and internal charging effects. Different populations of charged particles coexist, which are studied through satellite observations, which measure particle flux and direction relative to the magnetic field (pitch angle).

Although publicly available, these measurements require extensive processing—such as time binning, quality filtering, mapping along field lines, and calculating phase space density (PSD) and adiabatic invariants (Northrop, 1963). Some physical phenomena are only visible in invariant space, making calculating these invariants indispensable for research (e.g., Shprits et al., 2008; Drozdov et al., 2022). Machine learning models and data assimilation also depend on the pre-processing of satellite data (Drozdov et al., 2023). Correctly processed data is also crucial for inter-calibrating the different instruments, which often hold biases.

While a standard library exists for magnetic field calculations (https://zenodo.org/records/6867768), no equivalent library exists for processing satellite data. **This lack complicates data processing for new researchers and limits reproducibility in publications, as processing codes are rarely shared, leading to inconsistencies in results (e.g., Zheng et al., 2024).**

In this incubator project, we propose to adapt and make our processing code available to the scientific community. The repository will include read-the-docs-like documentation and tutorials of the most used satellite missions, such as VAP and POES. Our group at GFZ Potsdam has two decades of experience dealing with particle measurements of satellites and processing them for publication (e.g., Shprits et al., 2006). It is currently establishing data standards for the radiation belts through the Metadata for Ionospheric and Space Weather Observations (MISO) project funded by the Helmholtz Metadata Foundation, which this repository will follow.

During my Ph.D., I worked with satellite particle measurements for three years during my PhD, developing a processing package for radiation belts, ring current, and plasmasphere data (Haas et al., 2022, 2023, 2024a, 2024b; Bianco et al., 2023). **This project will generalize the package for broader use, making it accessible to new researchers with comprehensive documentation and tutorials.**

II. *Incubator Project description*

1. **Collection of data standards (1 week)**
   We will collect the most recent results concerning data standards for radiation belt measurements and particle measurements in the inner magnetosphere. This includes recent results from the MISO project and COSPAR PRBEM (https://prbem.github.io/) panel outcomes. These standards will be incorporated into a database within the package, ensuring that all processed data adheres to these established standards.

2. **Adopting the existing package to the data standards and streamlining its usage and adaptability (7 weeks)**
   Our current package processes particle measurements by downloading raw satellite data, filtering, time-binning, mapping to the magnetic equator, and calculating equatorial pitch angles, magnetic fields, phase space density, and adiabatic invariants. However, the package lacks a cohesive structure, making it difficult to use and adapt. We will refactor it by removing outdated features, implementing an object-oriented class hierarchy, and enabling users to select from multiple file formats (.mat, .npy). The new package will reproduce results from previous publications (e.g., Bianco et al., 2023; Haas et al., 2024) and include unit tests for complex logic. Developed in Python, the package will be cross-platform, lightweight, and compliant with FAIR principles.

   The existing package for processing particle measurements currently facilitates the download of raw satellite data, file reading, filtering using quality flags, time-binning of measurements, and mapping to the magnetic equator. It also enables the calculation of equatorial pitch angles, local and equatorial magnetic fields, phase space density, and adiabatic invariants, with results saved in .mat files. These computations can be done using different internal magnetic field models, such as the centered Dipole, IGRF (Alken et al., 2021), or the T89 magnetic field (Tsyganenko, 1989) driven by the Kp index (Matzka et al., 2021).

3. **Extending the package to include arbitrary magnetic fields (4 weeks)**
   After implementing basic functionalities, which include the T89 magnetic field (Tsyganenko, 1989) driven by the Kp index (Matzka et al., 2021), we will add support for

more complex magnetic field models, such as those driven by solar wind parameters (e.g., TS04 (Tsyganenko and Sitnov, 2005)), which provide more accurate calculations but are computationally intensive.

4. **Writing documentation and tutorials (2 weeks)**
   Comprehensive documentation is a key component of the package. We will use Sphinx to create standardized documentation hosted on readthedocs.io. Each equation and its corresponding reference will be clearly presented, making the package particularly beneficial for students, postdocs, and early-career researchers.

   The package will be easy to install and use and will include Jupyter notebooks containing examples and tutorials for our field's most often used data sets (e.g., Van Allen Probes, POES). Sample data for these datasets will also be available to help users quickly get started.

5. **Releasing of package and writing of JOSS paper and final report (2 weeks)**
   The package will be released on PyPI following pyOpenSci guidelines. To ensure community approval and recognition, we will also submit a paper to the Journal of Open Source Software (JOSS).

III. *InRelevance for the NFDI4Earth*

The expected users are space physicists in Germany and abroad. Students and early career scientists can use the package as an entry point for their studies. The package will also be used as part of an operational service at ESA to predict the effects of space weather.

The package will use the NFDI4Earth repository 'Indices of Global Geomagnetic Activity (kp-index)' as input for magnetic field calculations.

IV. *Deliverables*

- Open-source code repository on GitLab or GitHub
- Documentation published to readthedocs.io
- Jupyter notebooks containing examples and tutorials for the most used data sets
- Draft of a paper for JOSS
- Final Report

V. *Finance plan*

The funding includes the post-doctoral salary for Bernhard Haas for four months, according to the DFG salary regulations.

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