Topical Discussion Meeting report

Name of the meeting: TDM10 - Solar Energetic Particle Measurements and Model Validation at High Energies: Challenges and Advances
Convener/s: G. Vasalos, P. Quinn, A. Papaioannou, R. Vainio
Secretary: G. Vasalos
Data – Time – Room: 30 Oct - 13:30-14:30 (Stockholm time) - Idun
# of attendees (approximate): 50-60
Speakers, if any (names and institution):
Prof. Bernd Heber - Christian-Albrechts-Universität zu Kiel, Germany
Dr Phil Quinn - NASA/JSC/SRAG (Leidos), USA
Dr Piers Jiggens - ESA/Human Exploration, Netherlands
Dr Mirko Stumbo - IAPS-IANF, Italy

Form of TDM: Panel Forum

Objective of the TDM

High-energy solar energetic particle (SEP) events pose significant risks to space-borne and ground-based technologies and human spaceflight. Accurate detection and model validation of these events—particularly above ~100 MeV—remain complex tasks, hampered by instrumental limitations, event variability, background variations, and signal contamination. This topical discussion meeting will bring together researchers and stakeholders to discuss the current state of SEP model predictions at high energies, the cross-calibration of instruments, the standardization of event lists, and the integration of new data sources. The latter includes high-resolution satellite measurements and ground-level enhancement (GLE) observations. Emphasis will be placed on recent methodological advances, machine learning applications, and coordinated international efforts to improve consistency across datasets. The goal is to identify gaps, refine validation criteria, and enhance the reliability of high-energy SEP catalogs, paving the way for improved space weather forecasting.

The objectives of the TDM are outlined in the above abstract and are summarized as follows:

- Review the current status of high-energy SEP model predictions.
- Strengthen cross-calibration and standardization of instruments and event lists.
- Integrate new satellite and ground-based data sources.
- Highlight advances in methodology and machine learning applications.
- Foster international collaboration and data consistency.
- Refine validation criteria to improve the reliability of SEP catalogs and space weather forecasting.

Discussion highlights

<u>Presentations</u>

- The dual sources of interplanetary high-energy particles (galactic cosmic rays and solar energetic particles) were outlined emphasizing the unpredictability of the latter. It was noted

that correct energy characterization is crucial for interpreting satellite anomalies and radiation hazards.

- Reliable high-energy observations remain limited between spacecraft and neutron monitor energy ranges. The need for new lightweight instruments capable of covering the 50–500 MeV range relevant to aviation and deep-space exploration radiation exposure was underscored.
- Prof. Heber stressed that SEP forecasting requires distinguishing between flare-related and CME-driven acceleration processes. He emphasized the importance of real-time radio data (e.g., from STEREO) to capture particle release times and improve forecasts beyond purely flare-based approaches.
- A comprehensive NASA validation effort for high-energy SEP models was presented using 37 SPE and 9 ESP events. Validation showed that median model accuracy remains low—only 63% of predictions within one order of magnitude and 7% within a factor of 2—highlighting the need for improvement.
- Current high-energy SEP models are integrated into the SEP Scoreboards. However, high variability, modest correlation, and time-lagged CME-based inputs limit their real-time usefulness for astronaut safety and mission planning.
- Strengths of machine learning like its ability to handle nonlinearities, multi-source data, and probabilistic forecasting, but also its limitations such as bias from rare-event scarcity, absence of causal reasoning, and degradation of performance in real-time operational contexts were outlined.
- Dr. Stumpo cautioned that validation on artificially balanced datasets leads to unrealistically low false-alarm rates. He recommended bias correction using real-world event probabilities, regression-based forecasting of continuous fluxes, and leveraging multi-point data from heliospheric constellations.

<u>Discussion</u>

- Integration of Models and Machine Learning
    - Dr. Jiggens (ESA) emphasized the importance of machine learning for combining and harmonizing outputs from multiple forecasting models to deliver a single, continuously updated forecast—similar to terrestrial weather systems.
    - He noted that users (e.g. mission control) care more about a unified, up-to-date result than about the internal model differences.
- Need for Coordination Framework
    - Prof. Heber suggested establishing a coordination effort under ESA (or E-SWAN) to unite machine learning specialists, instrument developers, and data analysts.
    - Dr. Jiggens agreed this aligns with ESA's long-term exploration goals and hinted that post-ministerial funding might support such a framework.
- Advanced Warning Times
    - A participant raised the issue that model accuracy must be balanced against lead time.
    - Dr. Quinn explained that CME-based models, due to inputs' time lag, tend to provide less timely warning and sometimes even after event onset, while flare-based models give earlier but less reliable alerts.
    - Prof. Heber added that particle transport conditions can change warning times from minutes (impulsive events) to over an hour (gradual events), depending on interplanetary conditions.
- Data Assimilation and Model Updating
    - Questions were raised about whether models perform real-time data assimilation.
    - Dr. Quinn said some models are experimenting with updating predictions as e.g. CMEs are measured, but this currently clutters operational dashboards.

    - It was noted that future developments should integrate continuous assimilation and probabilistic updates—mirroring ensemble approaches in weather forecasting.
- Use of L5 and Multi-Point Observations
    - Dr. Aran discussed how modeling energetic storm particles (ESP) using MHD simulations could benefit from L5 measurements, allowing data assimilation from multiple vantage points.
    - The group agreed that distributed heliospheric observations would enhance both physics-based and ML-based forecasting frameworks.
- Forecasting Philosophy and User Expectations
    - Dr. Jiggens drew parallels with public weather forecasts, saying that even imperfect early predictions are valuable for situational awareness, and that continuous updates, rather than one-off forecasts, are key to maintaining user trust and relevance in space-weather predictions.
- Focus on Extreme Events
    - A question was raised about whether operational research should prioritize extremely rare, high-energy SEP or GLE events.
    - Dr. Quinn and Prof. Heber agreed that despite their rarity, these events are crucial for exploration missions and for understanding radiation exposure in human spaceflight.
    - They underlined the need for higher-energy (>100 MeV) modeling and better spectral characterization, potentially supported by neutron monitor data.
- Machine Learning vs. Physics-Based Models
    - Participants concurred that ML should complement, not replace, physics-based understanding.
    - Combining ML's pattern recognition with physically grounded models was seen as the most promising path forward.

Main conclusion of the meeting

The main conclusion of the meeting was that reliable forecasting of high-energy solar energetic particle events requires closer integration between physics-based modeling, coordinated multi-point measurements, and machine learning approaches. Participants agreed that future efforts should focus on improving model validation, ensuring continuous data assimilation, and prioritizing forecasts of high-energy and extreme events relevant to human spaceflight, supported by a coordinated international framework that bridges modeling, instrumentation, and AI expertise.

Annexes

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