Space Weather of the Heliosphere: Processes and Forecasts
Proceedings IAU Symposium No. 335, 2017
C. Foullon & O.E. Malandraki, eds.

doi:10.1017/S174392131700713X

Prediction of Ground Level Enhancements

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Abstract. This paper summarizes the first tool that is able to predict Ground Level Enhancements (GLE). It makes real-time predictions of the occurrence of GLE events from the analysis of soft X-ray and differential proton flux measured by the GOES satellite network. Before the development of this tool, space weather systems have been warning users about evolving GLE events by processing neutron measurements recorded on ground level. This tool, called HESPERIA UMASEP-500, can predict GLE events before the detection by any neutron monitor (NM) station. The prediction performance measured for the period from 1986 to 2016 is presented for two consecutive periods, because of their notable difference in performance. For the 2000-2016 period, this prediction tool obtained a probability of detection (POD) of 53.8% (7 of 13 GLE events), a false alarm ratio (FAR) of 30.0%, and average warning times (AWT) of 8 min and 15 min with respect to the first NM station's alert and the GLE Alert Plus warning, respectively. This project has received funding from the European Union's Horizon 2020 research and innovation programme under agreement No 637324.

Keywords. Ground Level Enhancements, prediction

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1. Introduction

Strong solar events may accelerate solar particles to near the speed of light reaching the Earth in a few minutes (Reames 2004). These particles may interact with the Earth's atmosphere to produce penetrating neutrons known as Ground Level Enhancements (GLEs) which are detected by neutron monitors (NMs) worldwide (Aschwanden 2012). These particles may irradiate astronauts in space and passengers and flight crews in commercial aircraft flying at polar latitudes (Shea & Smart 2012).

Currently, GLE warning systems can only provide a forewarning for an event that has already started (Souvatzoglou *et al.* 2014). In this work, we present the HESPERIA UMASEP-500 real-time predictor of the occurrence of GLE events constructed under the HESPERIA Horizon 2020 project (Malandraki *et al.* 2015), using the UMASEP scheme (Núñez 2011; Núñez 2015). Solar energetic proton (SEP) event and GLE predictors are of great significance because they offer the unique advantage of valuable added minutes to space weather users. Given a prompt and accurate warning message, pilots can re-route their planes at lower latitudes to be better protected by the Earth's shielding (Beck *et al.* 2005), and launch operators may postpone or re-schedule a launch (Shea & Smart 2012).

The UMASEP scheme makes predictions from the analysis of soft X-ray (SXR) and proton data. This approach has been used to develop other tools. The original UMASEP model was used to develop UMASEP-10, a tool for predicting > 10 MeV SEP events. Since 2010, NASA's integrated Space Weather Analysis system (iSWA) and the European Space Weather Portal redistributes UMASEP-10's forecasts, which have obtained successful results on an operational level (Tsagouri *et al.* 2013). The UMASEP-10 tool was also included as a real-time forecasting module in the European Space Agency's SEPsFLAREs system (García-Rigo *et al.* 2016). The HESPERIA project presented a tool, UMASEP-10mw (Zucca *et al.* 2017), that uses microwave instead of SXR data. In order to predict > 100 MeV SEP event, a High-Energy UMASEP model was proposed (Núñez 2015) to construct the UMASEP-100 tool from 5-min SXR and proton data.

This paper summarizes the HESPERIA UMASEP-500 GLE forecasting model and its results in Sections 2 and 3, respectively. Concluding remarks are presented in Section 4.

2. Model

The UMASEP scheme infers a magnetic connection, along which energetic protons are arriving in the near-Earth environment, by estimating a lag-correlation between SXR with differential proton fluxes at near-Earth. If the correlation is high and the associated solar flare is also strong, then the UMASEP scheme issues a SEP event prediction. To predict GLE events, we use the High-Energy UMASEP model, explained in Núñez (2015) with 1-min input data and a different set of thresholds.

The High-Energy UMASEP model generates a bit-based time series from the SXR time-derivatives and three bit-based time series from the time-derivatives of each of the P9-P11 channels of the GOES6-GOES15 satellites. The "1s" in each bit-based time series are set when an extreme rise is detected; more specifically, when a positive time derivative surpasses a percentage p of the maximum value of the time derivative in the present sequence of size L (beyond which no influence is assumed in the SEP event to be predicted); otherwise, the flux level is transformed into a "0". This forecasting approach creates a list of cause-consequence pairs as follows: it takes the first "1" of the SXR-based time series, and the first "1" of the proton-based time series, to create a pair; it then takes the second pair of "1s" in each time series, and thus successively, until all the "1s" of the SXR-based time series are inspected. For more information about this model consult Núñez *et al.* 2017).

The original purpose of the HESPERIA UMASEP-500 tool was to correlate SXR with neutron and proton data; however, we found that the use of neutron data provoked the generation of many false alarms due to some quality data problems caused by technical issues in the NMs (Souvatzoglou *et al.* 2014), such as problems in the sensor tubes and power supplies, temperature conditioning of the sensors, software disruptions, and bad communication links with the Neutron Monitor Data Base (NMDB). For this reason we decided not to use neutron data for making GLE predictions.

3. Results

The overall prediction performance of event occurrences for the analyzed period (1986-2016) was calculated in terms of probability of detection (POD), false alarm ratio (FAR) and average warning time (AWT). The forecasting results for the most recent half of the evaluation period (i.e. 2000-2016) may be summarized as follows: the POD was 53.8% (7 of 13 GLE events); the FAR was 30.0% (3/10); the AWT to the first NM's alert was 8 min; and, the AWT to the GLE Alert Plus's warning was 15 min. The GLE Alert Plus system (Souvatzoglou *et al.* 2014) is probably the cutting edge in operational GLE warning systems.

For the first half of the evaluation period (i.e. 1986-1999) the POD was 31.6% (6 of 19 GLE events), the FAR was 33.3% (3/9); and, the AWT to the first NM's alert was 13.3 min. For the whole evaluation period, the POD was 40.6% (13 of 32); the FAR was 31.6% (6 of 19); and, the AWT to the first NM's alert was 10.5 min. We do not know the reason for the better POD performance in the most recent period; nevertheless, we think that the use of a more recent and refined instrument technology and/or more experienced calibration procedures yields better forecasting performance.

We validated the HESPERIA UMASEP-500 GLE forecasting model by replacing the GOES/HEPAD proton data with SOHO/EPHIN proton data, and the results were similar in terms of POD, FAR and AWT (Núñez *et al.* 2017); this study shows that the predictions were issued at similar times using both EPHIN and HEPAD data. Previously, Kühl et at. (2016) had found that there is a possible > 10 MeV electron contamination of the EPHIN high energy proton measurements. Given the coincidence in prediction times using EPHIN and HEPAD data, we plausibly speculate that the HESPERIA UMASEP-500-based GLE predictions have possibly benefited from the early electron contamination in high-energy proton detectors.

4. Concluding remarks

The HESPERIA UMASEP-500 SEP forecasting tool makes real-time predictions of the occurrence of GLE events from the analysis of SXR and differential proton flux measured by the GOES satellite network. We assume that a prediction is successful when it is reported before the first GLE alert is issued by any NM station. Regarding the prediction of GLE events for the period 2000-2016, this tool had a POD of 53.8%, and a FAR of 30.0%. For this period, the tool obtained an AWT of 8 min and 15 min with respect to the first NM station's alert and the GLE Alert Plus warning, respectively.

The current GLE warning systems provide only a forewarning for an evolving GLE event. The main innovation is that the HESPERIA UMASEP-500 tool utilizes in-situ proton data measured in space to perform GLE predictions compared to existing tools based on ground-based neutron monitor measurements. Núñez *et al.* (2017) speculate that GLE predictions can possibly benefit from the early electron contamination in high-energy proton detectors.

This tool has been developed to improve the mitigation of adverse effects both in space and in the air from a significant solar radiation storm, providing valuable added minutes of forewarning to space weather users.

Real-time predictions are available via the HESPERIA web site (http://www.hesperia.astro.noa.gr/index.php/results/real-time-prediction-tools/umasep).

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https://doi.org/10.1017/S174392131700713X Published online by Cambridge University Press