A Novel Forecasting System for Solar Particle Events and Flares (FORSPEF)

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Abstract. Solar Energetic Particles (SEPs) result from intense solar eruptive events such as solar flares and coronal mass ejections (CMEs) and pose a significant threat for both personnel and infrastructure in space conditions. In this work, we present FORSPEF (Forecasting Solar Particle Events and Flares), a novel dual system, designed to perform forecasting of SEPs based on forecasting of solar flares, as well as independent SEP nowcasting. An overview of flare and SEP forecasting methods of choice is presented. Concerning SEP events, we make use for the first time of the newly re-calibrated GOES proton data within the energy range 6.0–243 MeV and we build our statistics on an extensive time interval that includes roughly 3 solar cycles (1984–2013). A new comprehensive catalogue of SEP events based on these data has been compiled including solar associations in terms of flare (magnitude, location) and CME (width, velocity) characteristics.

1. Introduction

Solar Energetic Particle (SEP) radiation storms occur when solar eruptive events (solar flares and/or CMEs) accelerate particles, turning them into a significant risk for satellites, communication and power systems and human life [1, 2]. Due to the sporadic nature of SEP events and the far from complete understanding of the mechanisms (i.e. acceleration and propagation) involved in their generation, their forecasting and/or nowcasting is no trivial task. Adding to the problem are the complex nature of the underlying physical processes and the lack of detailed, spatially distributed in–situ observations. Moreover, successful solar flare prediction consists of identifying the host active region (AR) and projecting of the onset time and size of the flare(s) to be triggered in that region. Credible forecasting of solar flares is a major step forward, as high-energy flare photons entail risk, or even danger, for sensitive space-borne electronics and humans engaging in extravehicular activities with only nominal space-suit protection. As there is no early-warning window for flare photons, flares need to be ideally predicted in advance of their actual occurrence. Over the course of time, the scientific community managed to overcome certain past obstacles and developed forecasting tools to issue notifications on both solar flare and SEP events and thus provide forewarning. It is important to note, however, that from the modeling point of view solar flares, fast CMEs, and SEPs are closely related to each other, with fast CMEs causing SEP events more often than not, associating to a flare and a host AR.

1.1. Solar Flare Forecasting

The nature of the flare prediction problem has resulted in a relatively limited number of researchers applying to this purpose a diverse array of techniques. The interested user should refer to [3]. Several studies focus on the multiscale behavior (fractality and multifractality), and the turbulence in photospheric active–region magnetic fields, indicating that flaring active regions exhibit distinct, distinguishable complexity. Therefore, such information holds significant flare–predictive capability or, at least, it can be utilized to identify flaring active regions before they actually flare [4]. Moreover, morphological flare–prediction methods tend to exploit features of eruptive solar active regions. These methods rely on parameters stemming from these regions' morphological and topological characteristics such as the photospheric magnetic–polarity inversion lines (PILs) or photospheric properties in general [5, 6, 7, 8, 9]. Another morphological parameter is the effective connected magnetic field strength (B_{eff}), originally proposed by [7]. B_{eff} is inferred by means of a magnetic connectivity map in ARs that, by construction, favours and emphasizes connections alongside PILs. Another approach is the use of statistical methods relying on historical data, based on the argument that flare occurrence globally in the Sun is a time-dependent Poisson process [10]. Furthermore, machine–learning, computer–based exploitation of active–region properties shows a predictive ability that is based on either a single or a combination of active-region properties. A notable effort in this respect is the Automated Solar Activity Prediction (ASAP) tool, operating at the University of Bradford [11]. Other machine learning and supervised techniques include methods of logistic regression [12], and multi-resolution predictor terms [13] that may hold more promise in flare prediction than individual predictor terms [14]. At another approach, using a master equation for flares with some minimum energy E that also includes an energy–input factor $\alpha(E, E')$, [15], investigated flare–like analytical solutions and derived a size distribution of flare energy. Furthermore, there are methods that aim to address whether it is possible to know if an AR will flare prior to its emergence? According to [16, 17] it is, and a way to achieve this is by local helioseismology, providing the subsurface kinetic helicity and results of ring-current analysis, respectively. From a different angle, an interesting advance warning of major solar flares was suggested by [18] focusing on the nuclear decay rates of the radioactive nuclide ^{54}Mn. The study reported significant (several σ) anomalous decreases of these rates at Earth that appeared well correlated with flaring activity in the Sun.

Finally, despite developments in fully automated solar flare forecasting, NOAA/Space Weather Prediction Center (SWPC) insists on a human–interactive, expert–based flare prediction system. Forecasters on duty inspect a lookup table and issue a prediction probability that depends on climatology, persistence, and the forecasters experience to extract flare probabilities [19].

1.2. Solar Energetic Particle Forecasting

There are several prediction schemes of SEPs and energetic storm particles (ESPs) currently available. One large category includes physics-based numerical models of particle injection, shock evolution, and SEP acceleration at shocks, such as the SOLar Particle Engineering Code (SOLPENCO) [20]. SOLPENCO can also accurately capture the arrival at 1 AU of low–energy ESP ions travelling along with the CME shock and is a tool able to predict the flux and the cumulative fluence profiles of gradual SEP events associated with interplanetary shocks, originating anywhere between the solar western limb and far eastern locations. However, such efforts have not yet matured to a level that suffices for operational purposes.

On the other hand, empirical models that rely on observations of associated precursor phenomena, have been developed over the years. In particular, examples of such operational systems include: the *UMASEP* (University of Malaga Solar Energetic Particle) system [21], that predicts in real time the time interval on which the integral proton flux is expected to meet or

surpass the SWPC–set SEP threshold $J(E > 10MeV) = 10pfu$ ($1pfu = pr\ cm^{-2}sr^{-1}s^{-1}$) and the intensity of the first hours of SEP events. Furthermore, using solar flare observations, *PPS* – an empirical SEP prediction system [22] – predicts, for > 5, 10 and 50 MeV SEP events at 1 AU, characteristics such as the occurrence, timing, intensities, spectra and elemental abundances. To fulfil its purpose, *PPS* is based on empirical correlations between the properties of a large number of SEP events observed by the IMP satellites and their correlated flare signatures (GOES soft X-rays, $H\alpha$ flare location, and GOES proton fluxes) [23]. Moreover, based on the assumption that there is a relationship between solar flare emissions and SEP events the *PROTONS* system assumes that the particles are produced at or near the flare site and subsequently diffuse through interplanetary space. This is an operational proton prediction tool in use at the NOAA/SWPC [24]. At a higher energy limit of SEP events (E > 433 MeV), *GLE Alert Plus* – another operational forecasting tool – issues alerts pertaining to the start time of a ground level enhancement (GLE) event utilizing the real-time data from the Neutron Monitor Database (NMDB) (www.nmdb.eu) [25]. Furthermore, *RELeASE* (Relativistic Electron Alert System for Exploration) system is an operational empirical system that issues short-term forecasting of the appearance and intensity of solar ion events by means of relativistic, near light-speed electrons [26]. It utilizes the recordings of the Solar and Heliospheric Observatory (SoHO)/Comprehensive Suprathermal and Energetic Particle Analyzer (COSTEP) electrons within the energy range 0.3–1.2 MeV and issues a forecast for the expected proton intensity of 30–50 MeV. Finally, the technique proposed by [27] yields an estimate of the probability of occurrence of a SEP event whose integrated intensity surpasses the SWPC SEP threshold of 10 pfu. It is based on the "big flare syndrome" [28], i.e. the fact that the larger the flare, the more probable it is to produce a significant SEP event at 1 AU. Hence, it predicts the probability of a SEP occurrence only for flares higher than M2. It also aims at maximizing warning time and for this reason it uses real–time data available at SWPC such as flare location ($H\alpha$ data), flare size (GOES soft X-rays) and SEP acceleration and escape (type III radio burst data). To summarize, most of the current operational prediction schemes assume a relation between SEPs and their parent solar events and are based on empirical and/or statistical relationships between the SEP parameters and the characteristics of associated precursor parent solar events [29, 24, 27, 30].

However, it is necessary to improve the forecasting capabilities for both solar flares and SEP events and at the same time to combine independent tools into one integrated solution. Such an integrated solution has been developed, aiming at forecasting X– and M–class flares, CMEs, and SEP events. That is MAG4, which forecasts the AR's rate of producing each kind of event from a proxy of the AR's free magnetic energy. This proxy is measured from a magnetogram of the AR, for ARs within 30 heliocentric degrees from the disk center [31, 32].

The subject of this study is the FORSPEF activity, whose objectives are to advance our knowledge on the underlying physical mechanisms that drive solar radiation storms and to develop reliable and interconnected tools for the prognosis of SEPs, solar flares and CMEs, providing forecasts evolving with time as more information becomes available.

2. The FORSPEF System
The FORSPEF (Forecasting Solar Particle Events and Flares) system will provide nowcasting and forecasting of solar eruptive events, such as solar flares with a projection to CMEs (occurrence and velocity), likelihood of a SEP event as well as the complete SEP profile - including its peak flux and duration [33]. To this end, forecasts will be made available up to 24 hours in advance and near real-time assessments (typically ∼15-20 minutes) of the near Earth environment will be made available, including a qualitative description of significant changes in the space environment (such as solar flares, CMEs) which in turn will be used as input for SEP warnings and alarms. Moreover, the outputs of FORSPEF will put interested parties on alert, and consequently help lower the risk for spacecraft and payloads. They may further be used for

planning critical orbital manoeuvres by launch operators. FORSPEF offers a 24–hour forecast of SEPs, up to 70° EW covering practically the entire course of the AR toward the limb (up to $\sim85^o$), under the assumption that the active region does not change significantly over this course. Finally, FORSPEF, providing the expected SEP flux will also meet the requirement of spacecraft operators by enabling them to take preemptive and recovery measures in case of predicted significant disruptions.
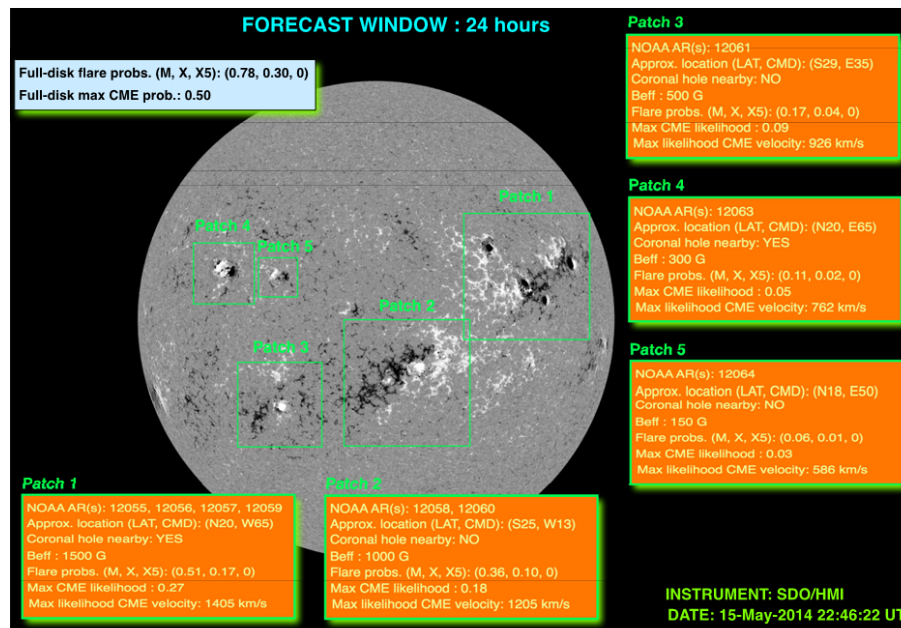

Figure 1: The output of the FORSPEF flare prediction module with a 24-hour forecast window on a recent full-disk SDO/HMI magnetogram.

2.1. Prediction of Solar Flares to Automatically Detected Solar Active Regions

The Solar Flare Prediction will rely primarily on a *morphological method* (see subsection 1.1), namely on the *effective connected magnetic field strength* (B_{eff}) prediction metric [7] and secondarily, from 50° to 70° EW, to a proxy of B_{eff} provided by the existing statistical association between the unsigned flux of the AR and the respective B_{eff} value. The Solar Flare Prediction algorithm will be part of a module designed for automatically detected solar active regions. Detection will be performed on periodically downloaded latest full-disk line-of-sight (LOS) solar magnetogram data from Solar Dynamic Observatory (SDO) / Helioseimisc and Magnetic Imager (HMI) [34]. A typical forecast window will be of the order 24 hours, with forecasts renewed every three (3) hours or more.

Figure 1 depicts a mock-up image of the flare-prediction process with a 24–hour forecast window on a full-disk SDO/HMI magnetogram. This is the output that the user of FORSPEF will obtain from the online service. The background includes the envisioned Active Region Identification Algorithm (ARIA) result on the magnetogram and each of the orange inset boxes contains the result for each identified active–region patch on the solar disk. The B_{eff} value for each patch (calculated separately) was assumed for the purposes of the probability calculation while the probabilities and CME velocities rely on existing statistics and scaling laws. Cumulative, full-disk probabilities for flares and CMEs within the given forecast window are shown in the cyan inset box.

Figure 2 depicts the derived conditional–probability histogram for flares of all sizes (C1.0 – X10) for a given AR target, under the condition of a B_{eff} equal to 1500 G (red histogram). The flare probabilities are to be understood as cumulative, in the sense that they refer to a

given flare size "and above" (for example, the M1.0 conditional flare probability corresponds to flares of class $\geq$ M1.0). Figure 2 also shows the respective CME–likelihood for each flare class (blue histogram) that corresponds to the superposition of two sigmoidal-fitting curves, namely, that of the conditional flare probability and that of the flare–CME association. Statistically, it expresses the likelihood that a given flare (of a given class and above) is eruptive, i.e., associated with a CME. Notice from the figure that the superposition of the two fitting curves gives rise to a peak CME likelihood of $\sim$0.27 for a flare-class of M2.0 and above - this can be viewed as the maximum CME likelihood. Besides the CME likelihood, a projected near–Sun CME velocity relying on the given B_{eff} value has been inferred independently by [35] and is shown in the inset. A plot, such as the one of Figure 2, will be provided for each automatically identified AR in the earthward solar hemisphere at the time of the processing.
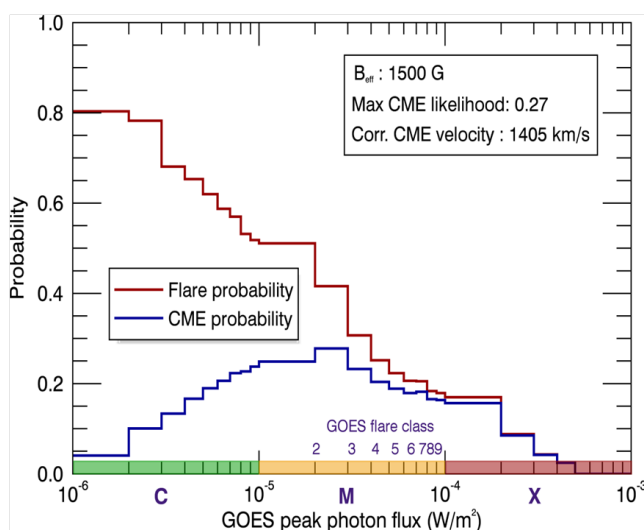

Figure 2: Predictions for an assumed B_{eff}= 1500 G: The derived range of probabilities for different flare classes (red histogram). Also shown is the respective CME likelihood curve (blue histogram).

2.2. Prediction of Solar Energetic Particle Events

The core of the FORSPEF SEP events prediction is based on a purely statistical approach that has been proven to be the key ingredient for SEP prognosis in a number of cases (see subsection 1.2). For the first time, our statistics are built from recently re-calibrated GOES proton data and cover an interval of nearly 30 years, from 1984 to 2013 [36]. A new database of solar flares, CMEs and SEPs was implemented by exploiting all available information within this time period.

The database was constructed on the basis of soft X-ray measurements from GOES and CME information from SoHO/ Large Angle and Spectrometric Coronagraph Experiment (LASCO). Our initial sample consisted of 35306 C, M and X solar flares and 22143 CME events. By applying temporal criteria [37], a set of 3680 CME-flare pairs, with a relative timing indicative of a causal relationship, was established. Moreover, the application of spatial criteria [38] led to a sub–sample of 888 CME–flare pairs that fulfilled both criteria (out of which 68 were X-class, 235 M-class and 585 C-class flares). The cross–calibrated (with IMP-8) GOES data [36] cover an energy range of 6–243 MeV. GOES proton data of $E_{eff} \sim 10$ MeV have been scanned and 314 well defined SEP events have been identified. For each SEP event, velocity dispersion analysis (VDA) has been performed in order to identify the estimated solar release time of the particles. Details on the mathematical formulation of VDA can be found at [39]. This methodology was used to associate SEP events to their parent solar sources. The improved quality of the data used in the analysis, the carefully inspected solar associations and the large number of the resulting SEP events have significantly improved the statistics and thus the
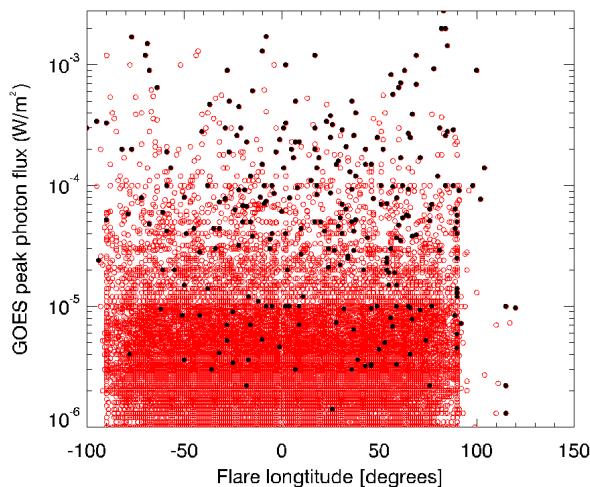
Figure 3: Peak flare photon flux vs. flare longitude. Flares associated with SEP events are presented by filled black circles while non-SEP flares by open red circles.

resulted forecasting/nowcasting of SEPs. Hence, the FORSPEF database is one of the most complete databases currently available.

In Figure 3 we present the peak photon flux of solar flares as a function of longitude, using the total sample of well defined events in our newly constructed database (i.e. 20429; this number was deduced from the initial flare sample, excluding flares with missing information). One may notice the relative lack of SEPs in the case of eastern and relatively weak flares whereas the majority of strong western flares are SEP–related. This result is anticipated and highlights the fact that the FORSPEF database performs as expected.

FORSPEF provides the probability of SEP occurrence based on information of solar flares with known characteristics. For a given location of an AR, the information stored in the FORSPEF database is used to derive the Distribution Functions (DFs) of the flare magnitudes associated and/or not associated to SEPs. The latter DFs are folded with the solar forecast (see subsection 2.1) leading to a weighted forecast. Using this scheme, statistical outputs (e.g. percentiles) for the SEP occurrence are derived. Moreover, the prediction can be further refined by including forecasts (and/or nowcasts) of CME occurrence. Preliminary outputs indicate that the occurrence of a SEP and the corresponding generated probability are controlled by the occurrence (or not) of a CME, based on our FORSPEF event database.

2.3. FORSPEF's Forecasting Work Scheme

The actual FORSPEF's forecasting work scheme is presented in Figure 4. For a given AR (in this case AR12157), the probabilities of flare and CME occurrence are first derived, (right top panel of Figure 4). Results stemming from the FORSPEF database are presented in the bottom left panel of Figure 4. The abscissa corresponds to the flare peak photon flux and the ordinate corresponds to the derived probabilities of SEP occurrence. These probabilities are also plotted with respect to the longitude of the flare for six (6) color-coded bins, from -89 to 89 degrees. This clearly illustrates the longitudinal dependence of SEP occurrence, with the probability increasing when moving from towards more western longitudes. The probabilities derived by the Solar Flare Prediction are folded with the probabilities derived by the FORSPEF database. This is illustrated at the bottom right panel of Figure 4 which has similar axis and colour–coded bins as with the previous panel. FORSPEF provides the maximum probability of SEP occurrence from that bottom right panel of Figure 4.
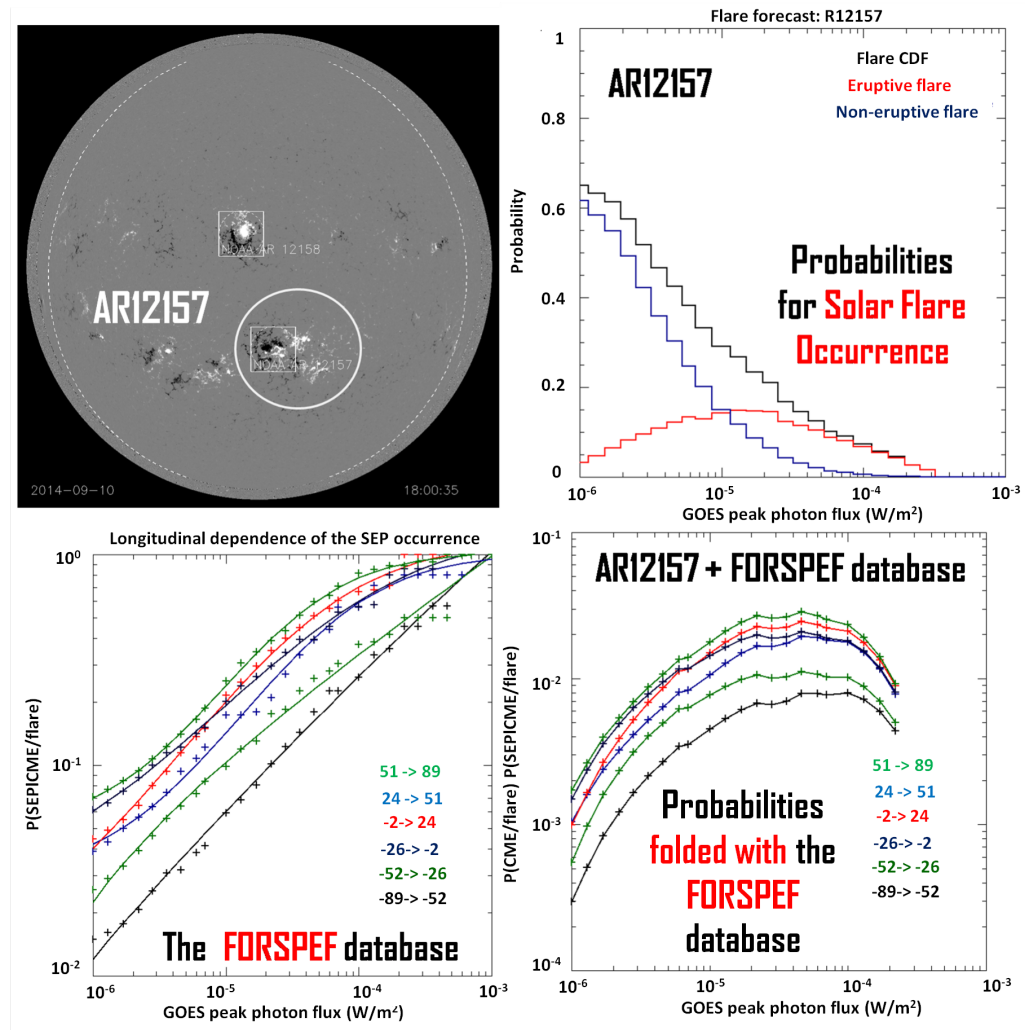
Figure 4: The FORSPEF forecasting work scheme.

3. Conclusions

We hereby introduce FORSPEF, a new forecasting system for eruptive solar flares and SEP events that is targeted towards launch operators and will soon be released. For the Solar Flare Prediction module, FORSPEF incorporates the *effective connected magnetic field strength* (B_{eff}) prediction metric that was never before set into an operational mode[1]. Furthermore, for the SEP prediction a new database of SEP events, solar flares and CMEs has been built. It makes use of a homogeneous SEP dataset (GOES), covering a large time span (1984–2013). This homogeneous data set uses the cross–calibrated GOES data (with IMP-8) and is augmented with the identification of the SEP characteristics (fluence, peak flux) in the time series at well defined effective energies. Both are used in the analysis for the first time. Due to its dual approach, FORSPEF will provide: a) forecasting of SEPs, including the probability of occurrence, peak flux and duration, using solar event data (i.e. flare and CME characteristics), as input and b) nowcasting of SEPs using solar event observations as input. This approach enables the refinement of predictions upon the availability of new data that characterize changes on the Sun and

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[1] The Athens Effective Solar Flare Forecasting (A-EFFort), an ESA/SSA service under implementation that is targeted exclusively on solar flare prediction, is also using B_{eff}. The service will be finalized within 2015.

the interplanetary space. Moreover the combined use of solar flare and SEP forecasting methods upgrades FORSPEF to an integrated forecasting solution.

Acknowledgments

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