STEREO REleASE+: Adding Robustness to the Solar Proton Event Forecasting in the Heliosphere by Means of Automated Recognition of Type-III Radio Bursts

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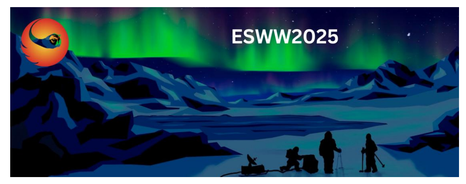
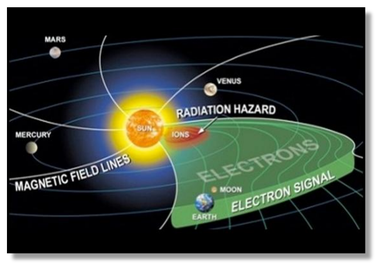


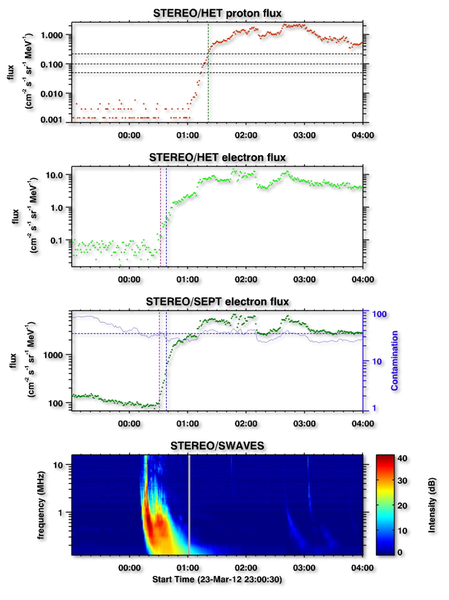
Overview



- ✓ The STEREO REleASE+ forecasting system uses the finding that relativistic electrons provide the "earliest indication" that a solar particle event has started, arriving at near-Earth distance earlier than protons at ~30% of the speed of light [1].
- ✓ In addition to relativistic electrons, we use a requirement of a radio burst of type III to be observed before issuing a proton alert.
- ✓ A similar system, HESPERIA REleASE+ (already implemented using electrons observed by SOHO and ACE near Earth), creates local forecasts for the Earth-moon system. The same STEREO-A radio observations are used in both systems, as radio bursts in part of the emission spectrum can be observed all around the Sun.
- ✓ Usefulness of adding a radio burst requirement to an electron-based forecasting system lies in the potential for suppression of known sources of false alarms.
- ✓ Forecasts based on STEREO, currently located between Earth and Earth-Sun L4, adds an additional safeguard for exploration of the moon, in particular from solar particle events originating behind the western limb of the Sun.
- ✓ The two parallel local forecasts allow us to test how far away from the spacecraft the validity and usefulness of the local forecasts extend.

Inputs for STEREO REleASE+

- ✓ Real-time near-relativistic electrons in the 0.125-0.255 and 0.7-4.0 MeV energy ranges, detected respectively by the Solar Electron Proton Telescope (SEPT) and the High Energy Telescope (HET) onboard STEREO.
- ✓ HET and SEPT 30-min, 60-min, and 90-min proton forecasted fluxes, derived with the HET and SEPT forecasting matrices constructed from an analysis of STEREO beacon electron data from 2008 to mid-2024.
- ✓ Real time 21-40 MeV HET protons.
- ✓ 1-min cadence STEREO S/WAVES radio beacon data with proper background noise subtraction and frequency gap filling, analyzed in two frequency ranges: the low-frequency band (LFB: 125 kHz to 1.975 MHz) and the high-frequency band (HFB: 2.025 MHz to 16.025 MHz).

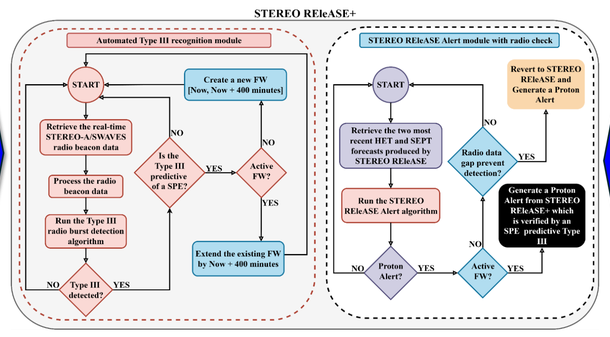


STEREO proton, electron and radio data for the SEP event of March 24, 2012. The dashed green vertical line indicates the 0.22 cm^{-2} s^{-1} sr^{-1} MeV^{-1} threshold crossing time and purple vertical lines indicate the derived electron event onset times. The blue curve in the SEPT electron flux shows the contamination level percentage.

STEREO REleASE+ architecture

Two modules running in parallel

Radio module detecting real-time type-III radio bursts and identifying SPE-predictive ones



Alert module detecting if the necessary conditions are met to generate a proton alert

STEREO REleASE+ radio module

Detection of type-III radio bursts

Identification of type-III bursts considers the following radio burst properties:

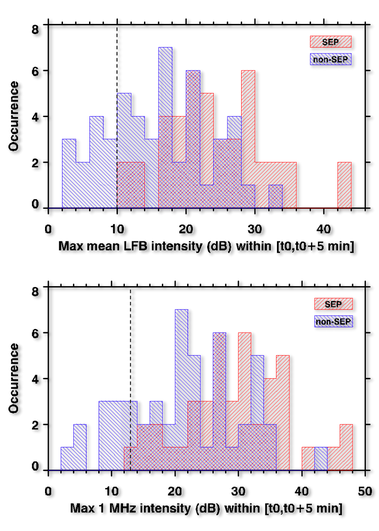
- Thresholds of mean intensities at a) HFB at radio burst onset time (=1.175 dB), and b) at LFB (=1.5 dB) with the next 5 minutes after the onset, derived from the analysis of ~7200 visually identified type-IIIs from Sep 2021 to Dec 2023 [2].
- Drift rates at LFB ≥ 10^{-4} MHz s^{-1} corresponding to type-III radio bursts

SPE predictive thresholds

Defined LFB and 1-MHz flux density thresholds of 10 and 13 dB, respectively, for type IIIs associated with significant proton events (SPEs) crossing the 0.22 cm^{-2} s^{-1} sr^{-1} MeV^{-1} flux value, by:

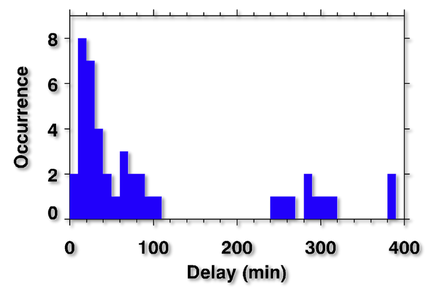
- Identifying relevant electron events related to 55 STEREO proton events (23 SPEs and 32 non-SPEs) that occurred from 2008 to mid-2022
- Identifying the associated 92 type-III events related to the derived STEREO electron event onsets of these 55 STEREO proton events and analysing their LFB and 1-MHz values

When radio data gaps (>3 min) prevent type-III identification the forecasting system reverts to STEREO REleASE (forecasts on electron data alone) [3].



Forecast window (FW)

The identification of an SPE-predictive type-III opens a Forecast Window (FW) within which a proton event alert should occur, followed afterwards by the SPE itself. From the distribution of time delays between relativistic-electron based proton alert times and the relevant onset times of SPE-predictive type-III radio bursts for the analyzed SPEs, the FW is initially set to 400 min and extended accordingly if a new SPE-predictive type-III occurs within it.



STEREO REleASE+ alert module

- The module processes the two most recent HET and SEPT 30-min, 60-min, and 90-min proton forecasted fluxes and triggers a proton alert when:
  - ✓ any of the three HET forecasted proton fluxes crosses the 0.22 cm^{-2} s^{-1} sr^{-1} MeV^{-1} SPE flux value threshold, or
  - ✓ when the SEPT forecasted proton flux exceeds this value and the forecasted HET flux exceeds a secondary threshold of 0.11 cm^{-2} s^{-1} sr^{-1} MeV^{-1} [3]
- When a proton alert is issued, the alert module queries the radio module for the existence of an active FW, and if one is already open STEREO REleASE+ generates a proton alert verified by an SPE-predictive type-III
- The Alert state is set for a fixed duration of 20 hours, but if an SEP event is confirmed during this period the Alert state remains active until the real-time one-hour averaged proton flux drops below 0.044 cm^{-2} s^{-1} sr^{-1} MeV^{-1}

Performance assessment of STEREO REleASE+

- When we solely involve radio criteria, the chosen SPE-predictive thresholds fulfil our goal to maximize POD and minimize FAR, resulting to POD and FAR values equal to 1 (100%) and 0.521 (52.1%) for the analysed 55-proton event sample; FAR is rather high.
- The integration of radio and proton alert criteria in STEREO REleASE+, modifies the definition of categorical values

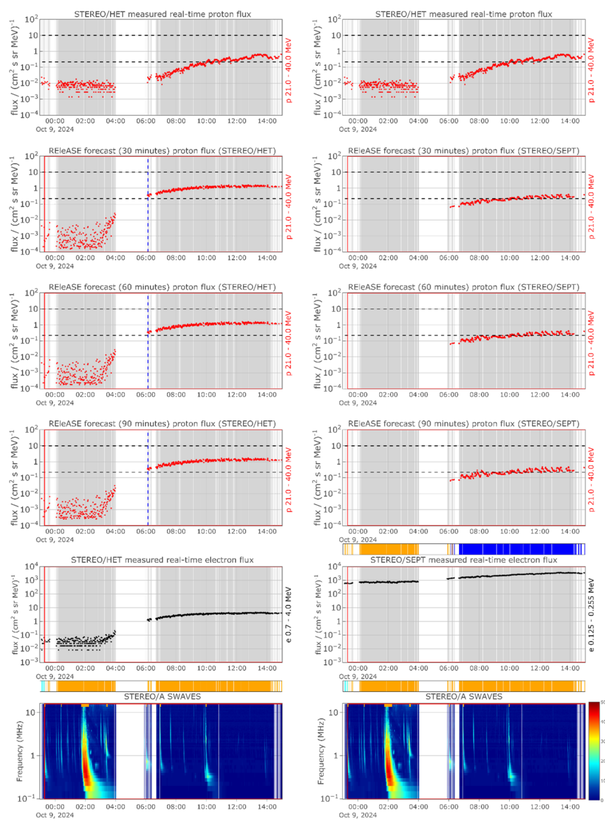
Detection of SPE-predictive type III	Proton event occurrence	Categorical value	
		Proton alert issued	No Proton alert issued
Yes	Yes	Hit A	Missed event C_1
Yes	No	False alarm B	Correct null D_1
No	Yes	Missed event C_2	Missed event C_3
No	No	Correct null D_2	Correct null D_3

- Therefore, the absence of a proton alert in this combined system, filters out most of non-SPEs that pass the radio module by converting them from false alarms to correct nulls, thus reducing FAR (e.g., 28 out of the 32 considered non-SPE events).
- Early performance assessment of STEREO REleASE+, by retroactively running the STEREO REleASE+ during the 2023 – mid 2025 solar cycle 25 maximum period (the training for the radio module excludes this performance testing period), shows that:
  - ✓ 28 SPEs were identified and a total of 9 false alarms generated in aggregate by STEREO REleASE (SR) and STEREO REleASE+ (SR+)
  - ✓ The POD of the combined system of SR and SR+ is 85% (23/27), while the POD for SR-only is 96% (26/27) and for SR+ is 80% (16/20).
  - ✓ The FAR for the combined system is 26% (8/31), while the FAR for SR-only is 24% (8/34) and for SR+ only is 20% (4/20). Note that POD and FAR for SR only is 87% and 25%, respectively, for the validation period of 2008 – 2022 [3].

Due to the limited number of events, false alarms and missed warnings there is significant statistical uncertainty, therefore firm conclusions regarding performance improvements cannot yet be drawn.

STEREO REleASE+ indicative forecast

A successful STEREO REleASE+ forecast



STEREO HET proton fluxes and the corresponding 30-min, 60-min and 90-min forecasted proton fluxes (top four panels), for the corresponding STEREO/HET (left column) and STEREO/SEPT (right column) electron fluxes shown in the fifth panel. STEREO S/WAVES radio flux density is shown in the bottom panel. Vertical dashed blue lines: proton alert issue time. Red rectangle: temporal range of the open FW. Thin bar at top of fifth-row right panel: contamination status of STEREO/SEPT electron data (orange for periods of contamination >35% when forecasts cannot be generated using SEPT, blue segments for periods of clean electron data). Thin bars at the top of the bottom panels: forecasting system in operation (orange when STEREO REleASE+ actively runs, blue when STEREO REleASE is in operation due to significant gaps in STEREO/A SWAVES data).

STEREO REleASE+ available at:

https://hesperia.astro.noa.gr/index.php/results/real-time-prediction-tools/stereo-release-plus

References

[1] Posner (2007). Up to 1-hour forecasting of radiation hazards from solar energetic ion events with relativistic electrons, *Space Weather*, 5, S05001

[2] Posner *et al.* (2024). HESPERIA REleASE+: Improving solar proton event forecasting by means of automated recognition of type-III radio bursts, *Space Weather*, 22, e2024SW004013

[3] Dröge *et al.* (2025). Solar energetic proton forecasting in the heliosphere: The STEREO REleASE system, *Space Weather*, 23, e2025SW004434

Other relevant ESWW posters:

APL1: Operational Real-Time Forecasting of Solar Energetic Particle Events: Enhancing Radiation Hazard Warnings and Space Weather Services with the HESPERIA Products, *Malandraki et al.*
SWR2: Using Type III radio bursts as evidence of particle escape from the Sun for enhancing solar proton forecasting capabilities: HESPERIA REleASE and beyond, *Malandraki et al.*
CD6: IMAP REleASE: Long-term continuation of REleASE forecasting driven by real-time data from the NASA Interstellar Mapping and Acceleration Probe mission, *Malandraki et al.*
CD6: Solar energetic proton forecasting in the heliosphere with REleASE, *Dröge et al.*

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Relevant publication: Posner *et al.* *"STEREO REleASE+: Adding Robustness to the Solar Proton Event Forecasting in the Heliosphere by Means of Automated Recognition of Type-III Radio Bursts"*, Space Weather Journal, 2025, under review