Radio Signatures of in Situ Observed ACE/EPAM Electron Fluxes

Miteva R. [1], *Samwel S. W.* [2]

[1] Space Research and Technology Institute, Bulgarian Academy of Sciences (SRTI-BAS), Sofia, Bulgaria
[2] National Research Institute of Astronomy and Geophysics (NRIAG), Helwan, Cairo, Egypt
E-mail: rmiteva@space.bas.bg

Abstract.

We present the preliminary results on a correlation study between RSTN radio flux and the peak intensity of ACE/EPAM 103–175 and 175–315 keV solar energetic electrons. Data over the period 1997–2017 is considered. For this analysis, we collected the reported radio flux at all eight RSTN frequencies (in the range 245 MHz–15.4 GHz), usually at the time of the identified flare origin. Pearson correlation coefficients are calculated between the reported radio flux at each frequency and the identified by us electron amplitude. Thus, for the first time the remotely observed radio signatures of electrons can be directly compared with the in situ observed electron flux over nearly two solar cycles. Comparison of the results with SOHO/ERNE protons over several energy channels is also presented and discussed.

Introduction

The aim of this work is the comparison of the space weather conditions before the onset of Solar energetic particles (SEPs) are in situ observed fluxes in the range 10–100s of keV for the electrons, from few to 100s of MeV for the protons and heavy ions that are originally accelerated in the solar corona and/or (re-accelerated) in the interplanetary (IP) space. SEP events are considered an important ingredient of space weather research [*Schwenn* 2006]. Improved knowledge of the particle acceleration, escape, transport and detection is needed to successfully forecast the particles in order to mitigate not only the technological risk [*Pulkkinen* 2007], but also the radiation hazard for future space travelers to Mars [*Semkova et al.* 2018]. The above chain of phenomena, which SEPs undergo from the Sun to the particle detector, is currently difficult to simulate. Thus, numerous proxies are utilized to quantify the observed particle flux from the properties of their solar origin, namely solar flares (SFs) and coronal mass ejections (CMEs).

The classical approach is to use the SEP peak identity and to perform Pearson correlation coefficients with the parameters of the SEP-associated SFs and CMEs. On the particle side, the majority of the statistical reports in the literature deal with energetic protons [*Miteva et al.* 2018]. Due to its long-term availability, GOES flare soft X-ray emission, so-called flare class, is primarily used to quantify the flare contribution to SEPs. Reports considering radio emission do exist (e.g. *Miteva et al.* [2017] and the references therein), however they always relate in situ observed protons with the remote signatures of electrons (e.g. radio flux). For the CMEs, their projected linear speed, angular width, acceleration, etc. are among the investigated quantities.

For the first time here, we start with the identification of in situ electrons and perform the correlations with the flare radio emission signatures using data over nearly two solar cycles. For that purpose, ACE/EPAM electron and RSTN metric to microwave (MW) radio wavelengths are selected. GOES flare class and CME linear speed are also used. Additionally, we compare the results with protons from the SOHO/ERNE instrument, in order to relate the obtained results to other studies.

Data selection and analysis

In this study we use electron data from ACE/EPAM [*Gold et al.* 1998] and proton data from SOHO/ERNE [*Torsti et al.* 1995] instruments as provided during solar cycles 23 and 24.

Solar electron events in the 103–175 (low) and 175–315 keV (high) ACE/EPAM energy channels are identified and the background-subtracted flux of the in situ observed electrons is calculated. These are in fact the preliminary results from the ACE/EPAM electron catalog, currently under completion (http://www.nriag.sci.eg/aceepam-electron-event-catalog-2/).

Similar procedure is applied for the proton events using the preliminary results from the SOHO/ERNE catalog (http://newserver.stil.bas.bg/SEPcatalog/) in five energy channels: 17–22, 26–32, 40–51, 64–80, 101–131 MeV.

The association between SEPs and their solar origin is performed following the widely-adopted guidelines: the closest in time before the SEP onset at 1 AU and the strongest in SXR intensity/speed SF/CME pair is pre-selected. In case of eastern origin events (indicated by a slowly rising SEP profile) or when an alternative origin is indicated by the occurrence and strength of the accompanied type III radio bursts, a correction in the solar origin selection is performed.

GOES flare information is used from the flare reports, https://hesperia.gsfc.nasa.gov/goes/goes_event_listings/ and the CME speed is adopted from the SOHO/LASCO CME catalog, https://cdaw.gsfc.nasa.gov/CME_list/.

Finally, for the RSTN radio emission, we used the NOAA-SWPC daily reports on the edited events (ftp://ftp.swpc.noaa.gov/pub/warehouse) that include also radio fluxes in 8 frequencies: 245, 410, 608 (606 in solar cycle (SC) 23, 610 in SC24), 1415, 2695, 4995, 8800, 15400 MHz.

Results

During the investigated period 1997–2017, we identified ~1240 ACE/EPAM electrons in the low energy channel and ~990 in the high energy channel, respectively. Solar origin is associated for 70–80 % of them.

The results for the Pearson correlations between the electron flux and the reported radio flux are listed in Table 1 for the two electron channels. In addition, the results are given graphically in Fig. 1, denoted with red for the low and blue color for the high energy channel, as a function of the RSTN frequencies. The vertical bars at each data point represent the uncertainties based on 1000 calculation using the bootstrapping method. The obtained trends rise to a maximum at about 2695–4995 MHz and then follows a decline. With horizontal lines are given the averaged value for the correlations with SFs and CMEs, denoted in the plot. They are based on 0.40±0.03 (897) and 0.38±0.04 (727) for the SF class and 0.43±0.04 (766) and 0.40±0.04 (625) for the CME speed for the low and high electron energy channels, respectively. In brackets are given the respective sample size for each calculation. In general, the results for the two electron energy channels are rather close in value.

Table 1. Pearson correlation coefficients and its bootstrapping uncertainty between the election peak intensity at two energy channels and the RSTN radio flux. In brackets are given the sample size over which the respective correlation is made.

Electron flux	245 MHz	410 MHz	608 MHz	1415 MHz	2695 MHz	4995 MHz	8800 MHz	15400 MHz
103–175 keV	0.25±0.07 (426)	0.32±0.05 (361)	0.40±0.05 (307)	0.43±0.05 (328)	0.51±0.05 (339)	0.52±0.04 (355)	0.50±0.04 (351)	0.43±0.04 (766)
175–315 keV	0.26±0.06 (371)	0.34±0.05 (324)	0.39±0.05 (280)	0.44±0.05 (301)	0.54±0.05 (312)	0.53±0.04 (328)	0.51±0.04 (324)	0.40±0.04 (625)

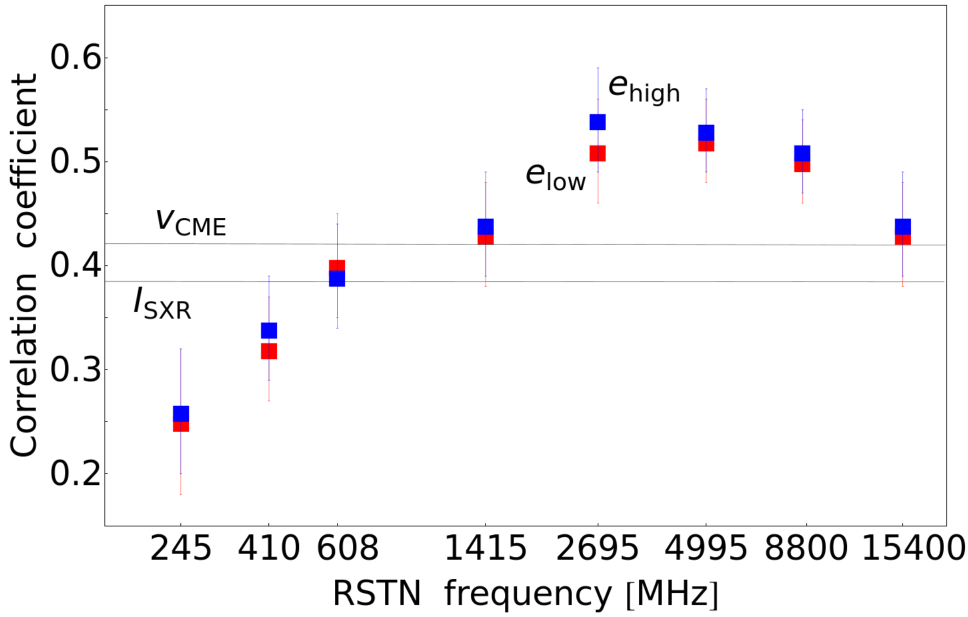

Fig. 1 Dependence of the correlation coefficients between the in situ electrons and the RSTN radio emission plotted as a function of the RSTN radio frequency, in MHz. Color code used: red: 103–175 keV electrons, blue: 175–315 keV electrons.

For comparison, we perform the similar correlation study using the SOHO/ERNE protons. We calculate the respective correlations with the RSTN radio flux for each of the 5 proton energy channels, denoted in different color, and present the results as a function of the radio frequency only graphically, see Fig. 2. Similar trend, compared to the electrons is observed, with the exception of the correlation at 245 MHz which is enhanced.

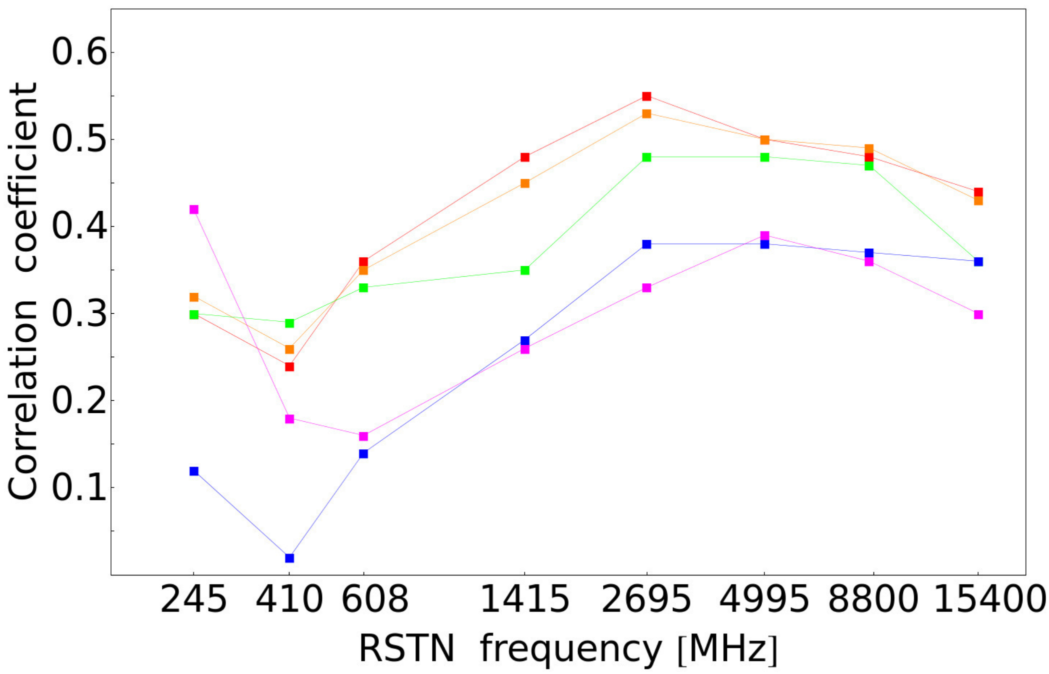

Fig. 2 Dependence of the correlation coefficients between the in situ protons and the RSTN radio frequency plotted as a function of the RSTN radio frequency, in MHz. Color code used: red: 19.5 MeV, orange: 29 MeV, green: 45.5 MeV, blue: 72 MeV, purple: 116 MeV.

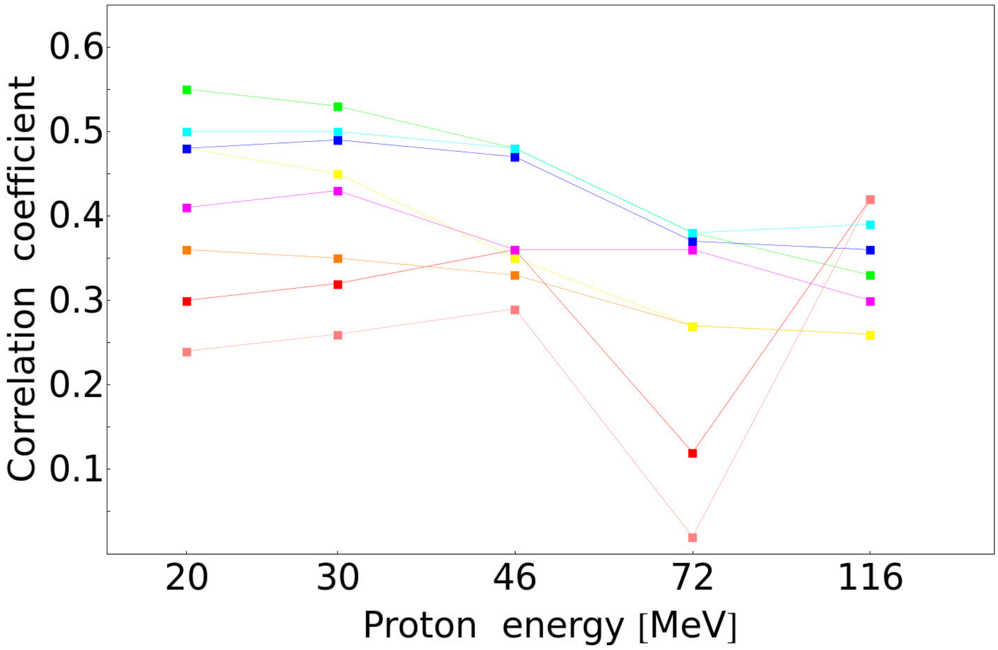

Fig. 3 Dependence of the correlation coefficients between the in situ protons and the RSTN radio frequency plotted as a function of the proton energy, in MeV. Color code used: red: 245 MHz, pink: 410 MHz, orange: 608 MHz, yellow: 1415 MHz, green: 2695 MHz, cyan: 4995 MHz, blue: 8800 MHz, purple: 15400 MHz.

Finally, we show alternative representation of the above results, this time as a function of the proton energy, in each of the five channels, Fig. 3. A slightly declining trend is noticed for all 8 RSTN frequencies (plotted with different colors), with a steep drop at 64–80 (~72) MeV channel for some of the frequencies.

Summary and discussion

We perform, for the first time, correlation analysis between in situ observed electron fluxes and the remote electron signatures in terms of radio emission from RSTN stations in solar cycles 23 and 24. Apart from the 15.4 GHz we obtain an increasing trend of the Pearson correlation coefficients with the increase of the radio emission frequency of the electron related flares. The correlations for the 2695–8800 MHz emission are statistically larger compared to the cases when GOES SXR flare class and CME projected speed are considered. The trend is kept when the correlations are done both for low and high energy electron fluxes. The differences between low (245 MHz) and higher frequencies (2695–8800 MHz) are statistically significant.

With respect to the protons, similar trend with a peak at 3 GHz is obtained, although the steady increase starts from 410 MHz. In contrast to the two electron channel where no difference is notices, there is a slightly decreasing trend (with a steep drop at 64–80 MHz) of the correlations with the increase of the proton energy.

This analysis will be repeated when the background subtracted radio flux is carefully analyzed by us for each event.

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