Contrib. Astron. Obs. Skalnaté Pleso **53/3**, 138 – 147, (2023)
https://doi.org/10.31577/caosp.2023.53.3.138

Energetic solar flare events in relation with subionospheric impact on 6-10 September 2017: data and modeling

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Received: September 15, 2023; Accepted: October 11, 2023

Abstract. Solar flares are among main extraterrestrial events that are well known to severely affect both space weather and near-Earth surrounding conditions. Under incident X-ray solar flare radiation, ionospheric plasma undergoes perturbations clearly and distinctly observable on ground-based monitoring systems' recordings. Mid-latitude lower ionosphere under influence of energetic solar flare events was examined by employing different numerical modeling procedures, including Machine Learning, relying on ground-based Very Low Frequency (VLF) radio signal recordings from Belgrade VLF database and solar soft X-ray irradiance satellite measurements taken from Geostationary Operational Environmental Satellite (GOES) database.

Key words: Solar activity – Solar X-ray flares – radio signal perturbations – GOES – data – modeling

1. Introduction

Through complex solar–terrestrial interactions, Earth is continually under Sun's emitted radiation influences, both of the electromagnetic and corpuscular nature (Kelly, 2009). As the major source of numerous and diverse driving agents related with Earth's magnetospheric and ionospheric perturbations, Sun's varying activity is under ongoing increasingly extensive research (see Hayes et al., 2021; Rycroft et al., 2000, and references therein). As modern society progressively becomes more and more dependent on complex technological systems including satellite, telecommunication and power grid networks, solar activity as potentially hazardous to these systems and consequently potentially threatening to an urban way of life, gained also in recent years more attention outside pure scientific community (Yasyukevich et al., 2018).

As still reliably unpredictable to current knowledge, solar activity especially in terms of high and extreme energetic solar events' occurrences, such as e.g. energetic eruptions of high class solar flare (SF) events and coronal mass ejections (CMEs) and their interactions, is often presented through analyses of separate events which make case studies very important in the sense of a comprehensive overview of evolution of such complex natural phenomena and their impacts on near Earth's surroundings (Srećković et al., 2021a; Kolarski et al., 2023). Here, solar activity during the most active period of the descending branch of the solar cycle (SC) 24, with the respect of high class X-ray solar flare events with geo-effective implications, is presented as a case study of solar conditions throughout a period enclosing the strongest SF events in September 2017, as observed by ground-based systems located in Belgrade (Serbia) at the Institute of physics Belgrade (44.85°N; 20.38°E), through subionospheric Very Low Frequency (VLF) propagation disturbances (e.g. Šulić et al., 2016) recorded on signal emitted from UK, employing four numerical techniques developed for retrieving lower ionospheric plasma parameters (Silber & Price, 2017; Arnaut et al., 2023).

Table 1. X-class SFs from September 2017, from GOES15 database.

Fare date	Class	Region	Time UT			Ix^{max}
			Start	Max.	End	(10^{-4} Wm^{-2})
6 September 2017	X2.2	2673	08:57	09:10	09:17	2.2658*
6 September 2017	X9.3	2673	11:53	12:02	12:10	9.3293
7 September 2017	X1.3	2673	14:20	14:36	14:55	1.3880
10 September 2017	X8.2	2673	15:35	16:06	16:31	8.2808

* GOES13 data

2. Observations

Year of 2017 belongs to the descending branch of the SC 24, the cycle characterized by morphology notably decreased compared to several previous cycles, and with the intensity that is fourth smallest since the solar cycle 1 (Kolarski et al., 2022; Grodji et al., 2022). Even though it is placed close to the solar minimum between SCs 24 and 25, regarding solar flare activity year of 2017 stands out from other surrounding years from this descending branch, especially taking into consideration very active periods during months of September (when in total 99 SFs occurred, with 27 M-class and 4 X-class events, from which 2 of them were the strongest of SC 24) and April (when in total 52 SFs occurred, with 7 M-class and without X-class events). Solar conditions during September 2017 are mainly related to active region 2673 (AR12673) from which the strongest, 4 X-class SFs of intensity in range X1.3-X9.3 occurred during days of 06, 07 and 10 September (with X2.2 & X9.3 on 06 September, X1.3 on 07 September and X8.2 on 10 September). This active region with complex evolution appeared on 29 August on the south-eastern limb of the Sun and on 11 September disappeared from the Earth-view of the Sun, producing in total 77 SFs, of which 1 B (B9.8), 45 C in range C1-C9.8, 27 M in range M1-M8.1 and 4 X-class flares in range X1.3-X9.3. It is important to note that all M- and X-class SFs from September 2017 are related to this active region. Regarding the rest of the September, only

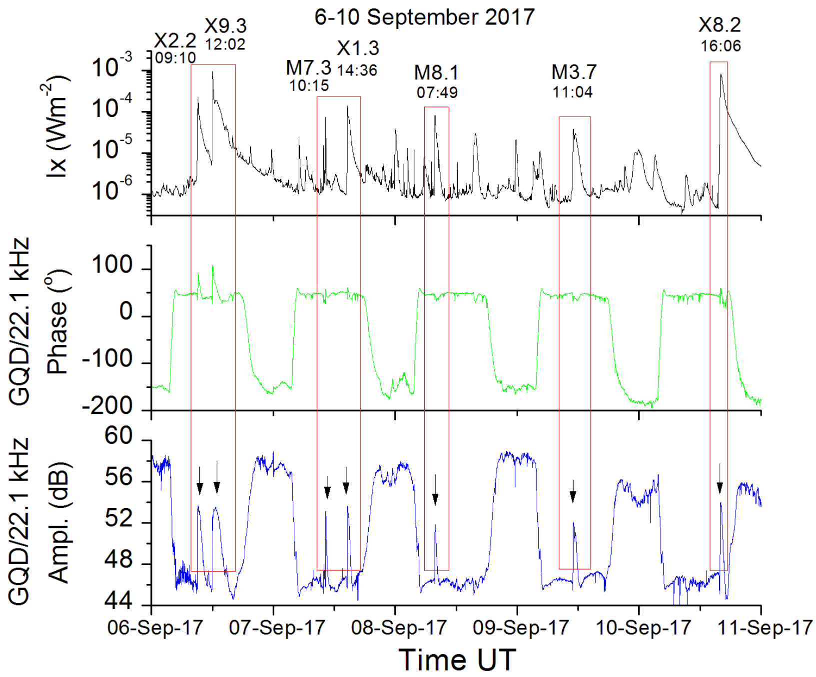

Figure 1. GQD signal perturbations registered in Belgrade during period of high solar activity from 06-10 September 2017 and GOES solar X-ray flux data as shown in the panels from lower to upper, respectively. Detected strong solar flares are marked with red rectangle.

weak flare activity of B- and C-class related to active regions 2677, 2680, 2681, 2682 (re-designated former active region 2673 which reappeared on 24 September and became again visible at the eastern limb of the Sun) and 2683 was reported, with total of 38 SFs in range B1-C3, with just 5 B-class SFs in range B2.2-B4.2 from active region 2682. There were also some days without reported flare activity, of which 6 days in a row 14-19 September and 2 days of 21-22 September. Main characteristics of X-class SFs from September 2017 are given in Table 1, with solar soft X-ray flux (0.1-0.8 nm) taken from Geostationary Operational Environmental Satellite (GOES) archive database (https://satdat.ngdc.noaa.gov/sem/goes/data/avg/).

Solar flare event of class X9.3, that occurred during solar cycle's declining branch relatively close to the solar minimum, particularly is interesting since event of X-class was not occurred as far back as on 05 May 2015 (X2.7), and of similar strength as far back as on 05 December 2006 (X9). If we exclude some weaker X-class SFs (e.g. as on 06 August 2011 (X6.9), 06 December 2006 (X6.5), 09 September 2005 (X6.2) and 08 September 2005 (X5.4)) and some significantly stronger SFs (e.g. as on 07 September 2005 (X17+), 04 November

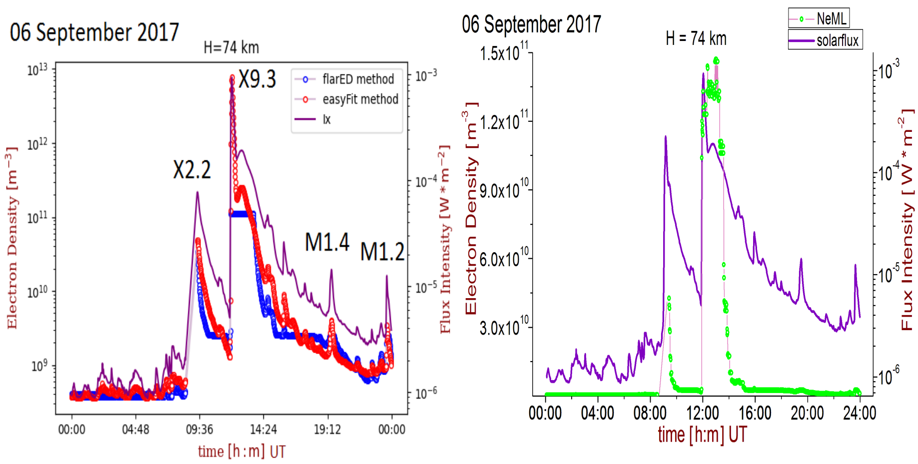

Figure 2. Variations of GOES X-ray flux (in violet) and Ne ($h = 74$ km) in function of UT on 06 September 2017 obtained by FlarED and easyFit methods (in blue and red, respectively) on the left and from ML method (in green) on the right.

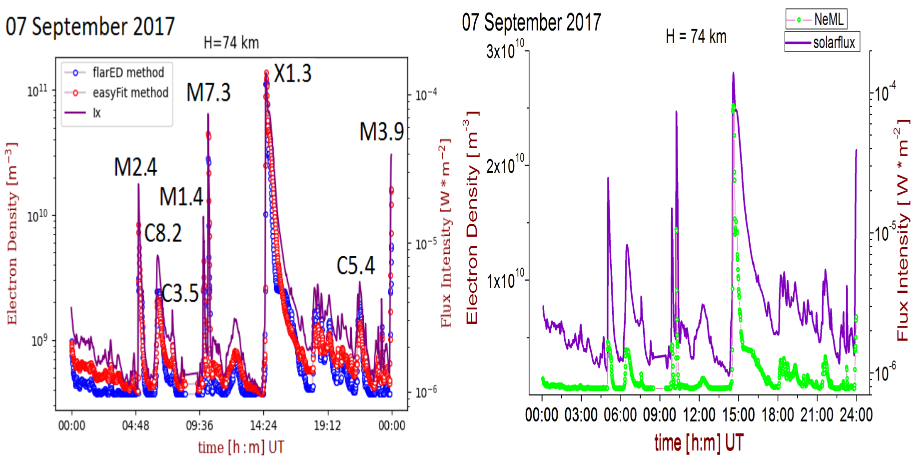

Figure 3. Variations of GOES X-ray flux (in violet) and Ne ($h = 74$ km) in function of UT on 07 September 2017 obtained by FlarED and easyFit methods (in blue and red, respectively) on the left and from ML method (in green) on the right.

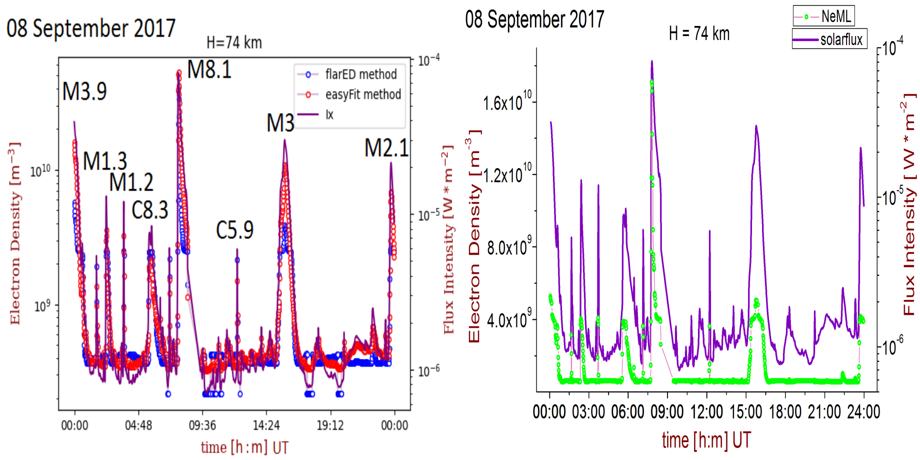

Figure 4. Variations of GOES X-ray flux (in violet) and *Ne* ($h = 74$ km) in function of UT on 08 September 2017 obtained by FlarED and easyFit methods (in blue and red, respectively) on the left and from ML method (in green) on the right.

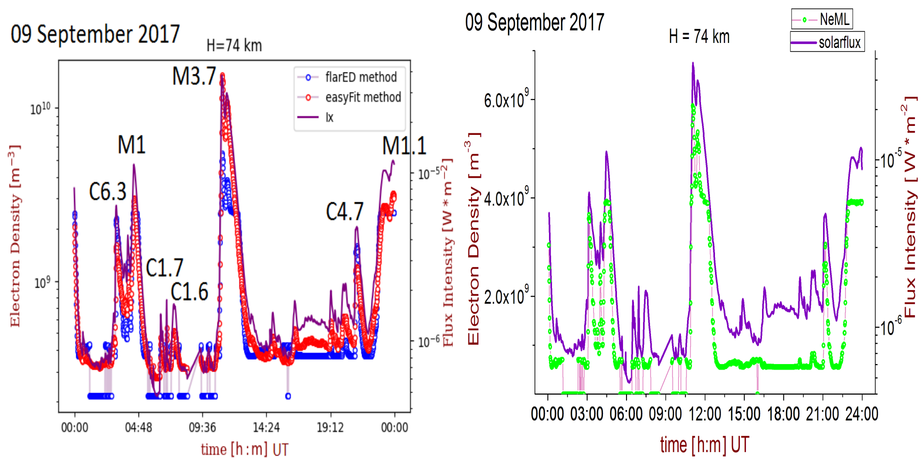

Figure 5. Variations of GOES X-ray flux (in violet) and *Ne* ($h = 74$ km) in function of UT on 09 September 2017 obtained by FlarED and easyFit methods (in blue and red, respectively) on the left and from ML method (in green) on the right.

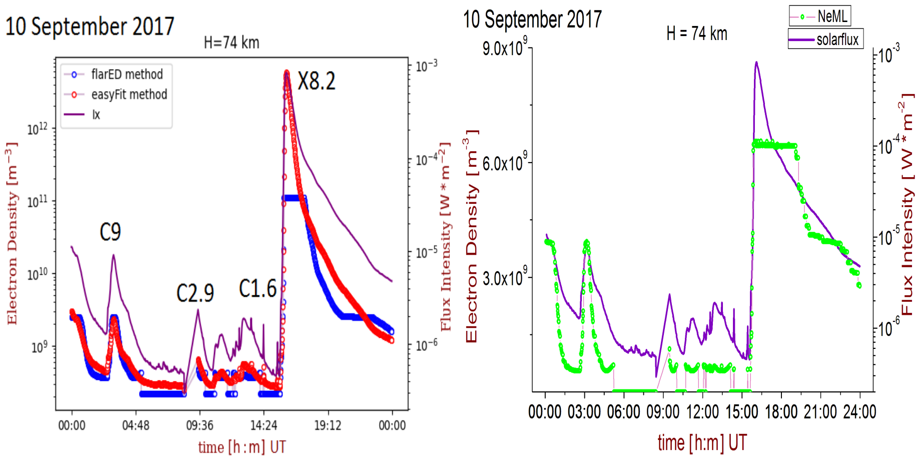

Figure 6. Variations of GOES X-ray flux (in violet) and Ne ($h = 74$ km) in function of UT on 10 September 2017 obtained by FlarED and easyFit methods (in blue and red, respectively) on the left and from ML method (in green) on the right.

2003 (X28+), 28 October 2003 (X17.2+), 02 April 2001 (X20+) and 15 April 2001 (X14.4)), SF of similar strength as X9.3 from September 2017 occurred about two decades in the past i.e. on 06 November 1997 (X9.4). During 06, 07 and 10 September R3 radio blackouts related to X-class SFs were reported.

3. Results and discussion

VLF signal's response to strong solar X-ray flare events from September 2017 was monitored in Belgrade (44.85°N; 20.38°E) on signal transmitted from UK (GQD/22.1 kHz), using recordings from BEL AWESOME (Atmospheric Weather Electromagnetic System for Observation Modeling and Education) receiving system operating in narrow-band mode (Šulić et al., 2016). Response of GQD signal to these X-class SF together with corresponding solar X-ray irradiances during the most active days in September 2017 are given in Figure 1. Under strong solar X-ray radiation in soft range, GQD signal's amplitude and phase responded by following incident X-ray flux with time delay corresponding to the sluggishness (e.g. Mitra, 1974; Hayes et al., 2021; Žigman et al., 2023), with perturbations of complex morphology, characteristic for this signal as recorded in Belgrade (Kolarski & Grubor, 2014; Grubor et al., 2008). Amplitude and phase perturbations induced by these 4 X-class SFs reached up to 8 dB in amplitude and up to a few tens of degrees in phase, compared to unperturbed ionospheric conditions. Based on recorded GQD signal's amplitude and phase perturbations, modeling of propagation parameters (Wait & Spies, 1964) was conducted using Long Wave Propagation Capability (LWPC) software (Ferguson, 1998), with goal that modeled and real conditions within waveguides match as close as possible. Aside LWPC, for obtaining lower ionospheric plasma parameters, three other numerical techniques were applied: FlareED and easyFit (Srećković et al., 2021a,b) and also novel method based on Machine Learning (ML) approach.

Table 2. Analyzed intense SF events from September 2017.

(dd/mm/yy) Class Ix^{max} time (UT)	Ne_{LWPC} (m^{-3})	$Ne_{easyFit}$ (m^{-3})	Ne_{FlarED} (m^{-3})	Ne_{ML} (m^{-3})
06/09/17 X2.2 09:10	$2.06 \cdot 10^{11}$	$3.49 \cdot 10^{11}$	$1.12 \cdot 10^{11}$	$1.23 \cdot 10^{11}$
06/09/17 X9.3 12:02	$1.15 \cdot 10^{12}$	$7.67 \cdot 10^{12}$	$1.12 \cdot 10^{11}$**	$1.33 \cdot 10^{11}$*
07/09/17 M7.3 10:15	$1.11 \cdot 10^{11}$	$4.45 \cdot 10^{10}$	$2.85 \cdot 10^{10}$	$1.44 \cdot 10^{10}$
07/09/17 X1.3 14:36	$1.76 \cdot 10^{10}$	$1.37 \cdot 10^{11}$	$1.12 \cdot 10^{11}$	$2.52 \cdot 10^{10}$
08/09/17 M8.1 07:49	$6.59 \cdot 10^{10}$	$5.25 \cdot 10^{10}$	$4.17 \cdot 10^{10}$	$1.66 \cdot 10^{10}$
10/09/17 X8.2 16:06	$2.12 \cdot 10^{11}$*	$5.79 \cdot 10^{12}$	$1.12 \cdot 10^{11}$**	$6.44 \cdot 10^{9}$*

*Unreliable result
***Saturation

In contrast to other energetic SFs reported within this active period, which were directed towards the Earth, main difference of X8.2 SF is in terms of geoeffective potential, since this event was the only one SF that erupted almost on the far side of the Sun's surface and did not directly affected the Earth. However, since this event was highly energetic, Earth was still affected in great deal, which can be clearly seen in perturbations of subionosphericaly propagating GQD signal. Another specific feature related to this event is that during the occurrence of X8.2 SF on GQD signal recorded in Belgrade there was a transition period from stable daytime to stable nighttime ionospheric conditions related to terminator period of sunset. Although process of modeling lower ionospheric response related to high class SFs based on VLF parameters is challenging by itself, some special circumstances, such as e.g. SF's occurrence during stable daytime ionospheric conditions (such in case of e.g. X2.2 SF) and relatively not so high absolute amount of amplitude and/or phase perturbations (such in cases of some mid class SFs) etc., can go in favor especially when classical approach using LWPC software is employed. However, in conditions related to terminator periods modeling of SFs is especially challenging, which is emphasized in much greater deal when energetic ones are processed. Since classical approach in cases like X8.2 SF event is far from an ideal choice giving unreliable results, application of other numerical techniques, such as e.g. FlareED and easyFit methods, can be beneficial providing needed data.

FlareED and easyFit methods are already proven as efficient both in cases of moderate and high-class SF events (Barta et al., 2022; Kolarski et al., 2023). Together with this two methods, a novel technique employing ML procedures is developed and applied to the same cases of chosen energetic SFs from inspected period 06-10 September 2017, with aim to be tested and verified in conditions of strong solar X-ray radiation. Output results from FlareED and easyFit methods of electron density variations (at the arbitrary reference height of 74 km) covering entire days including cases of energetic SFs from inspected period 06-10 September 2017 are given on the left in Figures 2-6, with soft X-ray flux in violet and electron densities in blue and red for FlareED and easyFit methods, respectively. Results from novel technique relying on ML procedures are presented on the right in Figures 2-6, with soft X-ray flux in violet and electron density variations in green. Both FlareED and easyFit methods are sensitive to X-ray flux variations related to moderate and high-class SF events, with main difference that in case of very energetic SFs, like X9.3 and X8.2, FlareED method gave electron density that went into saturation, compared to output from easyFit method that successfully mimics input X-ray irradiance and gives much higher electron density values as well. Method relying on ML has also proven itself to be an efficient in cases of strong SFs, as other two methods, but also gave some results that went into saturation (especially related to X8.2 and in some sense to X9.3). Comparison between results, in cases of strongest SFs from inspected active period, obtained with applied different numerical methods is given in Table 2.

EasyFit method (Srećković et al., 2021a) gave electron densities higher than FlarED (Srećković et al., 2021b), while ML results are closer to these from FlarED than to easyFit. When compared to LWPC results, it can be said that easyFit method works better than other applied methods, except in the cases of X1.3 where results differ for about an order of magnitude and M7.3 about half an order of magnitude. Unfortunately in the case of M8.2 results from LWPC approach are not reliable, while results from FlarED and ML methods both went into saturation, just as in the case of X9.3, so only available result is from easyFit method. EasyFit gave result for X8.2 of the same order of magnitude but slightly lower than in the case of X9.3. In general, technique relying on ML procedures gives promising results, but also requires some further adjustments in order to provide correct output especially in cases of very strong SF events, like X9.3 and

X8.2. Developing novel numerical techniques that successfully represent lower ionospheric responses especially in cases of very strong SF events is of great importance since classical techniques such as LWPC has model limitations on one hand and VLF parameters are not always favourable on the other.

4. Conclusions and future studies

In this contribution numerical modeling of lower ionospheric response to energetic SF events during September 2017, in relation to subionospheric VLF propagation perturbations with analyzed GQD signal recordings from BEL VLF station, was conducted by employing four different numerical procedures: by classical approach using LWPC software, by approximate FlareED and easyFit methods and by novel procedure relying on ML techniques. Focus was on period 06-10 September 2017 covering especially active solar conditions with 4 X-class SFs in range X1.3-X9.3 and also including 2 strongest M-class SFs, of intensity M7.3 and M8.1, from September 2017. Results related to electron density variations obtained by FlareED, easyFit and ML methods are compared to each other and to these from classical approach using LWPC software. In general, when compared with LWPC output electron densities, best results were obtained by easyFit method. ML procedures gave promising results, but further work is necessary in order to provide better results just in cases of very energetic SFs, like these X9.3 and X8.2.

Acknowledgements. This work was funded by the Institute of Physics Belgrade through a grant by the Ministry of Science, Technological Development and Innovations of the Republic of Serbia. Authors appreciate comments expressed by referees, which improved this paper.

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