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Analysis of the Samos Earthquake Using Swarm Satellite Data

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Abstract

Making use of the geomagnetic field and the electron density data from the ionosphere observed by the three Swarm satellites that were recorded through 2020, 303 days before and 62 days after the Samos earthquake were investigated, which occurred at 11:51 UTC on Oct 30, 2020, happened in an offshore location around 60 km southwest of Izmir, western Turkey, and 16 km north of Samos Island, Greece 37.897°N 26.784°E. Magnetic and electron density data abnormalities were examined using the Analysis of Magnetic Swarm (AMSW) and the Analysis of Electron Density Swarm (AEDSW) algorithms. The quiet time abnormalities during nighttime within the Dobrovisky region showed exciting results. It showed an enhancement in the cumulative number of tracks (acceleration) approximately 150 days before the mainshock of the earthquake in the magnetic and electron density data. In addition, magnetic and electron density data results matched the ground-based observatory data recorded within the same period and the Dobrovisky region.

Keywords: Earthquake Precursor, Low Earth Orbit, Magnetic Field Data, Samos, Swarm Satellite.

التحقيق في زلزال ساموس باستخدام بيانات الأقمار الصناعية سوارم

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الخلاصة

من خلال الاستفادة من بيانات المجال المغناطيسي الأرضي وبيانات كثافة الإلكترونات بطبقة الايونوسفير والتي تم تسجيلها حتى عام 2020 بواسطة الأقمار الثلاثة المسماه سوارم. قمنا بالتحقيق في 303 يومًا قبل زالزال ساموس و 62 يومًا بعده الذي حدث في الساعة 11:51 بالتوقيت العالمي في 30 أكتوبر 2020. تم البحث عن الشذوذ الناتج عن الزلزال في البيانات المغناطيسية باستخدام خوارزمية (AMSW) وكذلك الشذوذ الناتج عن الزلزال في كثافة الإلكترونات باستخدام خوارزمية (AEDSW). قد بينت

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النتائج الخاصه بالشذوذ في الأوقات الهادئة جدًا أثناء الليل داخل منطقة دوبروفسكي نتائج مثيرة للاهتمام، حيث أظهرت أن هناك زيادة في العدد التراكمي للمسارات التي بها شذوذ زلزالي تقريبًا في كلا من البيانات المغناطيسية وكثافة الإلكترونات في اليوم 150 قبل حدوث الزلزال (EQ) في البيانات المغناطيسية وكثافة الإلكترونات. ايضاً بينت الدراسة أنه يمكن الاستدلال علي حدوث زلزال ساموس من كلا من البيانات المغناطيسية وكثافة الإلكترونات في طبقة ألايونوسفير، حيث وجد أن هناك تطابق في الزيادة للعدد التراكمي للهزات الأرضية التي تم تسجليها داخل منطقة دوبروفسكي. أيضا وجدنا تسارع في العدد التراكمي للهزات الزلزالية الكبيره التي تم تسجليها في المحطات الأرضية لكل الزلازل التي تزيد قوتها عن 5.5 درجه على مقياس ريختر.

1. Introduction

Recently, several authors have focused on earthquake precursors using the Low Earth Orbit (LEO) satellites. The researchers presented evidence regarding small EQs that could be seen days, weeks, or months before major EQs [1]. The researchers used data from the Swarm satellites to analyze several specific case studies of EQs [2, 3]. They discovered distinct magnetic fluctuations in the ionosphere linked to significant EQs. The discovered abnormalities have probably been caused by the significant earthquake occurrences, as evidenced by the distance between the satellite and the earthquake epicenter matching the observed distance-time transfer of the perturbation from the ground to the ionosphere [2, 3].

Large earthquakes (EQs) cause seismo-traveling ionospheric disturbances, which are co-seismic ionospheric disturbances (STIDs), from the EQ's center to the ionosphere. The STIDs travel in a circle pattern that can be identified by instrumentation onboard space missions and on the ground [4, 5]. Some researchers investigated that certain occurrences might occur well before the enormous earthquake and with various routes to the ionosphere. All these events are referred to as Lithosphere Atmosphere Ionosphere Coupling in general (LAIC), as mentioned by [6, 7], who suggested a different theory to describe the LAIC impacts, primarily mostly on gases and liquids flowing to the earth’s surface during the early stages of the earthquake. Their study offered some evidence for subsurface fluid movement, characterized by the emission of gas from the earth's crust associated with changes in surface temperature and moisture particle ionization of the atmosphere.

The authors of [8, 9] observed a series of magnetic abnormalities by the Swarm satellite in succession during the M7.8 (2015) Earthquake in Nepal and M7.8 (2016) Ecuador earthquake. Their results indicated an increase in the anomalies of all data sets several days before the EQs. Results of five EQs studied using Swarm magnetic and surface temperature showed increased surface temperature and magnetic anomalies before the EQs [10].
Furthermore, [11] used a general statistical correlation method to shallow earthquakes using the first eight years of Swarm magnetic field and electron density data observations. They showed that the frequency of the Swarm magnetic field signals increases with approaching the earthquake. In addition, the signal frequency of land earthquakes is lower than the sea earthquake signal frequency. The researchers investigated the Samos earthquake using ground and space-based data using the Magnetic Swarm Anomaly Detection by Spline analysis (MASS) [8]. They showed an increase in magnetic anomalies before the mainshock of the EQs. The same algorithm for the same event showed the existence of high linearity (~ 0.9) between the cumulative number of anomalous points and the date [9].

The current study uses the AMSW algorithm [10] and the new Analysis of Electron Density Swarm (AEDSW) algorithms set by the current authors of this work to identify EQ anomalous before and after the Samos earthquake during quiet geomagnetic circumstances.

The primary goal of this study is to investigate the evidence of the Samos earthquake in the ionosphere using an anomalous magnetic field and electron density data acquired from the European Space Agency (ESA) mission denoted by the Swarm spacecraft mission/constellation and in addition to ground-based observatories before the mainshock.

2. Data Sets

2.1 Swarm Satellite Data

The Swarm mission consists of three corresponding satellites (SW-A, SW-B, and SW-C), which were launched into an LEO at an original height of roughly 510 km on November 22, 2013, [11, 12] and [13]. SW-A and SW-C were orbiting the earth at 460 km altitude side by side, which were longitudinally separated by 1.50 degrees in longitude. Both orbits were inclined by 87.40 degrees. SW-B is flying at 510 km altitude with a tilt of 87.80 degrees.
The satellite data were being utilized to detect ionospheric anomalies before significant earthquakes. The Swarm mission is one of the most successful LEO satellites investigating EQ anomalies. This work used MAGx_LR_1B and the EFIx_PL_ 1B data to examine the EQs anomalous in the electron density data. MAGx_LR_1B product includes magnetic vector and scalar data at a 1 Hz rate. To produce MAGx_LR_1B data at precise UTC seconds, the spacecraft data were processed, including interpolating vector (VFM) and scalar (ASM) data. Any gaps can impact the error estimate of the related product element, however.

A more detailed explanation of the data file can be found on the ESA website (https://earth.esa.int/eogateway/missions/Swarm/product-data-handbook/level-1b-product-definitions). The geomagnetic indices **Ap** should be less than ten, and |**Dst**| should be within the range of ±20. These geomagnetic conditions were implemented according to the criteria set by [3]. to ensure that the anomalous EQ event is unrelated to external noise.

2.2 Ground Observatories Data

This data was acquired from the United States Geological Survey (USGS) website https://earthquake.usgs.gov/earthquakes; the selected list of EQ ground data events used in our analysis was downloaded from this website and was observed through stations located within a circle of radius equal to the Dobrovolsky radius calculated according to equation 1. The center of this circle is the epicenter of the EQ.

3. Methodology

Several approaches were implemented in the current work to identify pre-EQ abnormalities. The AMSW and ANENW algorithms were used in the current work to evaluate magnetic field and electron density receptively before and after the Samos earthquake. The steps of the AMSW and algorithm are as follows:
1- The data must match the nighttime and quiet time criteria; here, the |Dst| index < 20 nT and Kp ≤ 1.
2- Subtract the internal and external source of the observed magnetic field data using the CHAOS model. It is worth noting that the CHAOS model is the most accurate and updated, relying on the Swarm magnetic data [14].
3- The first-time derivative was applied with knot points every 20 s to the residual representing the difference between the observed and the internal fields.
4- Finally, the derivative of the vector, Bx, By, and Bz, components (corresponding to North, East, and Earth center directions, respectively) within the Dobrovolsky area must be checked to investigate the existence of anomaly variations in the data.
The AMSW algorithm was used to identify the magnetic field abnormalities from Swarm satellite data. More details regarding the AMSW algorithm are presented in [10]. In addition,

we used the ANESW algorithm to detect abnormalities in the electron density data recorded by the Swarm satellite. This algorithm was implemented using the MATLAB code. The steps for identifying the EQ abnormalities using ANESW were achieved through the following steps:
- The night-time quiet times paths within the Dobrovolsky area were chosen.
- The electron density data was fitted to the cubic spline function with a piecewise constant of 30 observation points.
- The residual, the difference between the observed data and the fitting, was visually inspected to identify abnormalities.
- Abnormalities were recorded for statistical analysis and a cumulative number of tracks.

A typical example illustrating the abnormalities in the electron density data using the ANESW algorithm is shown in **Figure 1**. The left panels illustrated the original (raw) electron density and fitted data in black and red, respectively. The middle panel shows the residual, demonstrating EQ abnormalities from 35° to 45° latitudes. The rightest panel is the path of the satellite within the Dobrovolsky area.

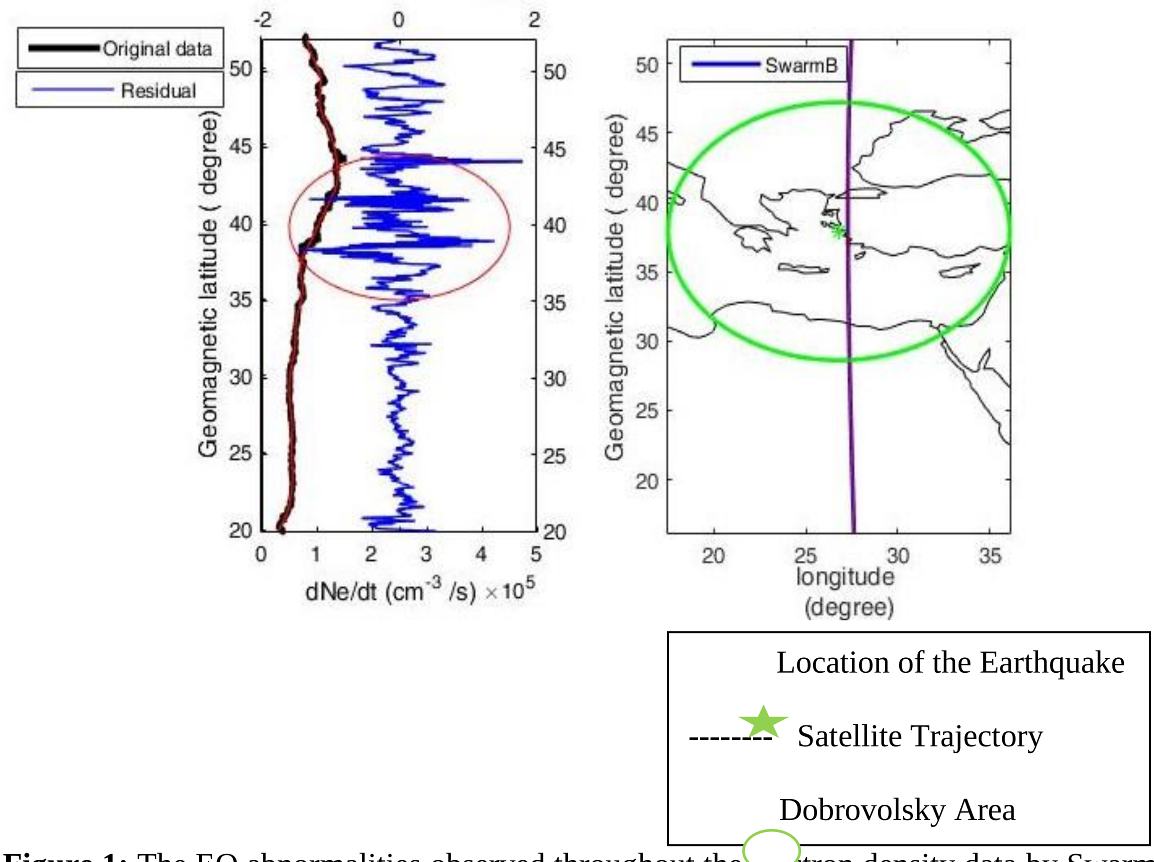


Figure 1: The EQ abnormalities observed throughout the electron density data by Swarm-B on 26 May 2020.

4. Results

Figure 2 shows the daily variation of the (Ap index, Kp index, Dst index, and IMF -Bz component) indices for 2020, and these indices were plotted. The red line indicates the day of the main shock of the EQ occurred on October 30, 2020, and the blue arrow indicates the day of EQ anomaly for the magnetic field and electron density data. Figures 2a, 2b, and 2c show Kp, Dst, and Ap indices, respectively. The change in magnetic activity varies from 0 to 3.9 in Kp, 38 nT <Dst<19 nT, and 0 <Ap< 30 nT during 2020. On day 297 of 2020, an anomaly occurred in the magnetic field seven days before the Samos earthquake, and the three indices are calm at the (Dst = –7 nT, Ap = +2 nT, Kp= 0 nT). Figure 2.d shows the interplanetary magnetic fields (IMF-Bz); it detected an anomaly in the electron density data, the IMF from –2.6 nT to +2.6 nT. On day 148 of 2020, the anomaly happened in the electron density 155 days before the Samos earthquake, and the IMF index is quiet time IMF-Bz = + 1.

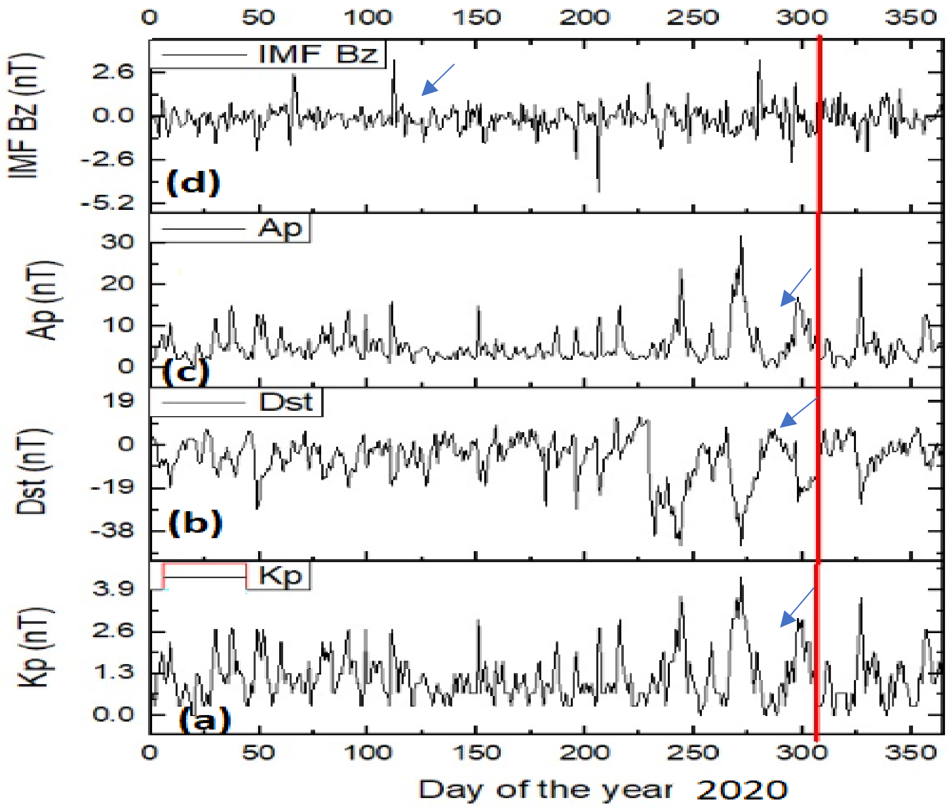


Figure 2: Daily variation of (a) Kp; (b) Dst; (c) 3-hour average Ap; (d) IMF-Bz from the day of 2020; the red line is the day for the main chock on October 30, 2020.

Figure 3 depicts the SW-C Spacecraft's track on October 23rd,2020. The geomagnetic parameters are quiet throughout track acquisition (Dst = –7 nT, Ap = 2 nT, Kp= 0 nT). The track is seven days ahead of the sequence's first large earthquake. The correct figure is the geographical map of the EQ, as depicted with the yellow vertical line (SW-C track) and the green circular representing Dobrovolsky's region. Figures 3a,3b and 3c are the magnetic field elements B_x, B_y, and B_z, respectively. In the B_y element, the red-circled anomaly might be a potential candidate for earthquake precursor because the track is regarded anomalous if the pick amplitude Y component residuals exceed 0.3 nT/s with persistence of 10s [2, 15] ; [10]. The AMSW technique outputs for the three magnetic field elements B_x, B_y, and B_z were averaged at UTC=01:30 and average LT=03:35.

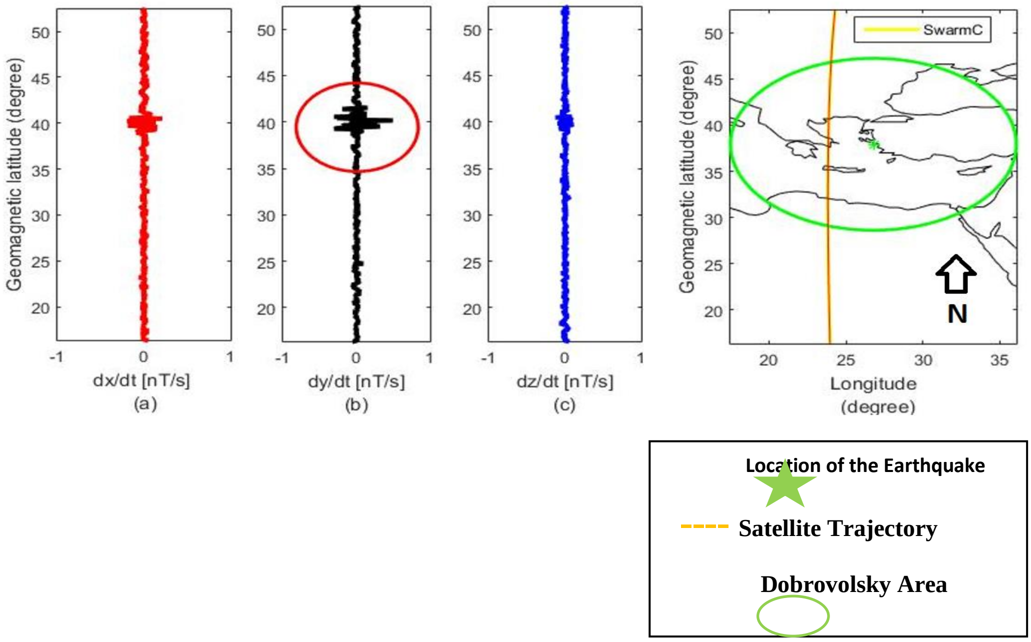


Figure 3: The AMSW algorithm detects anomalous events at 01:30 UTC and 03:35 LT on October 23, 2020, at SW- C, seven days before October 30, 2020, M = 7.0. Dobrovolsky's region is the green circle surrounding the epicenter, and the redline is the orbit of the Swarm satellite.

Figure 4 illustrates the SW-B spacecraft electron density trace, which comes closer to the epicenter 155 days before the earthquake. The trace was obtained at 01:20 UTC and 02:52 LT on May 26, 2020, during the very clam geomagnetic parameters (Dst = –1 nT, Ap = +4 nT, Kp= +1 nT). It indicates a distinct anomalous, denoted by a black square, in Figure 4b. in the Y magnetic element inside the Dobrovolsky region. The results of the ANDSW method for the electron density are given in Figure 4a, the black color is electron density data, and the red line is the fitting data. In Figure 4b, the blue line is the resulting residual data.

Moreover, the black circle indicates an anomaly in the electron density, the geographical map of the EQ is highlighted in Figure 4, the purple specified length of the SW- B track, and the green circular one represents Dobrovolsky's region. The cumulative number of apparent tracks noticed by the AMSW algorithm in the Y element of the magnetic field for the Swarm Three spacecraft is shown in Figure 5**.** To reduce solar ionosphere disturbance, use Dst and Ap ($|Dst| \leq 20$ nT and $Ap \leq 10$ nT) to keep solar variations of the ionosphere is minimum. Each of the three Swarm satellite abnormal tracks was indicated by a spot on the cumulate of this figure (Alpha, Bravo, and Charlie). The cumulative graph was created by starting with 0 and adding (or cumulating) the number of anomalous tracks within the next day whenever an anomaly is detected. It is always a harmonic rising because it is a sum of positive values. Figures 5a, 5b, and 5c showed the three Swarms, and the red solid line corresponds to the smooth spline fitting of the cumulative number of anomalous tracks of the SW-A, SW-C, and SW-B, respectively. The blue point is the cumulative number of anomalous tracks during the geomagnetic quiet time. The black line is the day of the main chock on October 30, 2020. The vertical dashed line corresponds to the day of the Samos Earthquake, and the blue arrow indicates the acceleration in 2020 .

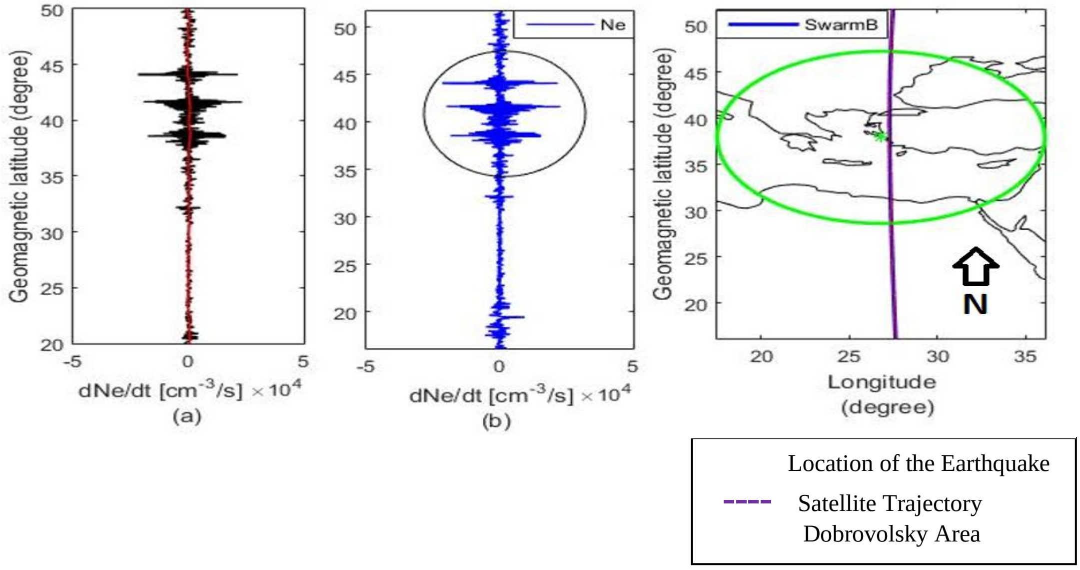


Figure 4: The AMSW algorithm detects anomalous events at 01:03 UTC and 02:30 LT on May 26, 2020, at SW- B, 155 days before Oct 30, 2020, with M = 7.0. Dobrovolsky's region is the green circle surrounding the epicenter, and the redline is the orbit of the Swarm satellite.

Figures 6a, 6b and 6c depict the cumulative number of abnormal tracks found in the electron density data by the ANDSW algorithm for the three Swarm spacecraft for the day of 2020 for the SW-A, SW-C, and SW-B, respectively**.** As mentioned, the tracks are categorized as unusual only during geomagnetically calm times defined by the threshold value mentioned earlier.

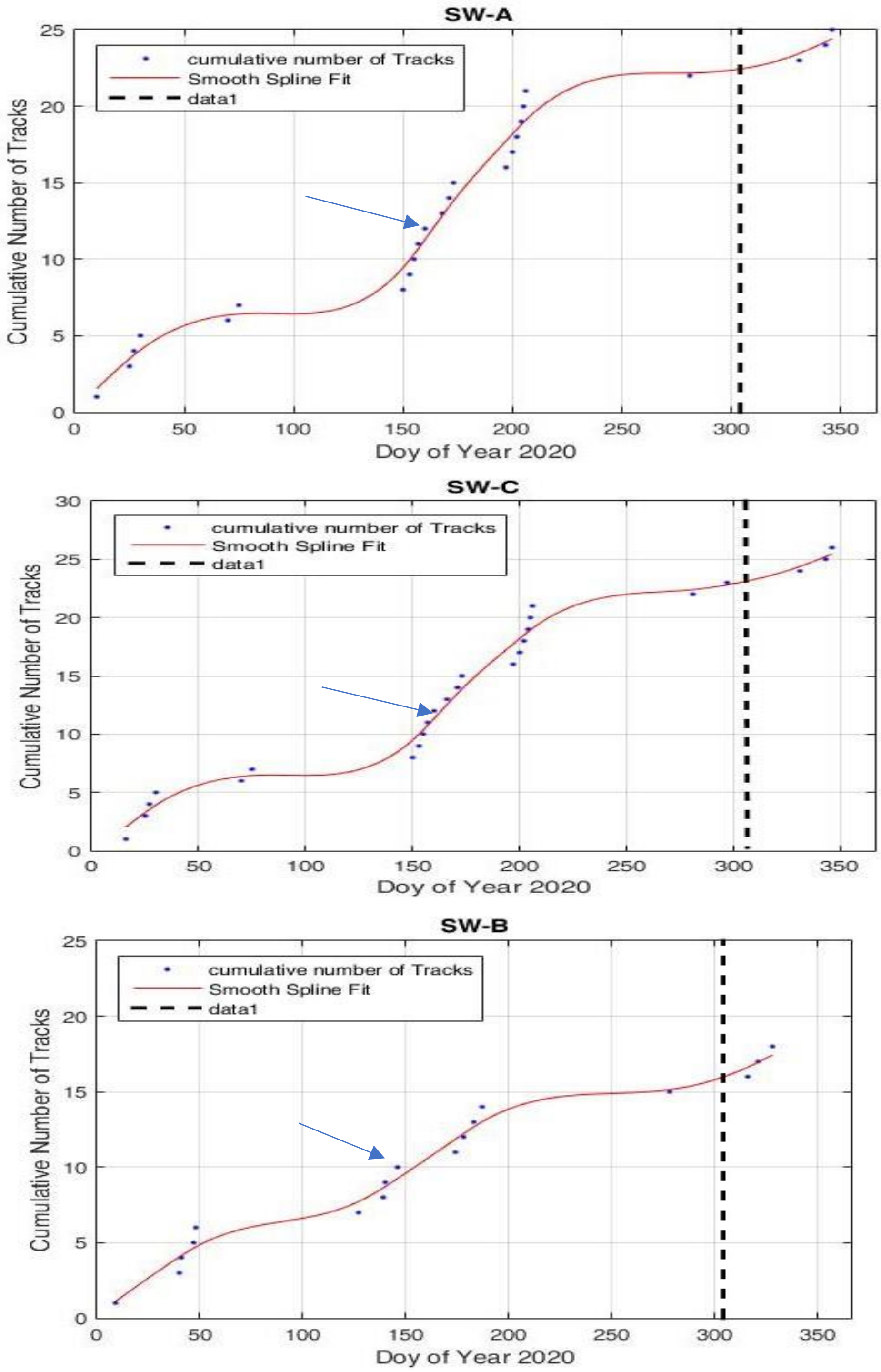
Moreover**,** the red line in Figures 6a, 6b, and 6c shows the red line that depicts the SW-A, SW-C, and SW-B Swarm tracks. The dark points are the EQ anomalous for the geomagnetic quiet time. The black line represents the primary shock date, October 30, 2020. Anomalous tracks were not chosen during disturbance time; therefore, this approach impacts the cumulative number of abnormal tracks over time. To eliminate this, the cumulative number rises by the same slope as it is during the disrupting hours outside. Similarly, the red solid line corresponds to the smooth spline fitting of the track's cumulative number of earthquakes. The black point is an anomaly for the geomagnetic quiet time.

The black line is the day of the main shock, which occurred on Oct 30, 2020. The vertical dashed line corresponds to the day of the Samos earthquake, and the blue arrow indicates the acceleration in the number of cumulative tracks in 2020. The cumulative number of abnormal paths created (Figure 5,6) shows an enhancement that began 303 days before the M7.0 Samos earthquake on Oct 30, 2020. The authors think this is the graph's average slope since the trace returns to the prior incline around 62 days following a similar earthquake.

Figure 7 shows earthquakes that occurred in 2020 in the Dobrovolsky area and were detected by ground stations. The green mark is the epicenter of the Samos EQ, while blue circles correspond to EQs with magnitudes smaller than 5.5, while red circles correspond to EQs with magnitudes larger than 5.5. It is worth noting that only considering EQs with a magnitude greater than 4 in the framework of the Dobrovolsky area. The radius (R) of the Dobrovolsky area in kilometers is calculated according to Equation 1.

$$R = 10^{0.34M} \quad (1)$$

where **M** is the magnitude of the Earthquake, which equals 7.0 for our potential Samos earthquake that occurred on Oct 30, 2020**.** Figure 8 depicts the cumulative number of daily observed ground earthquakes in 2020. Also, it shows that three acceleration steps occurred around 26, 155, and 304 days of the year 2020, respectively. The third step corresponds to the Samos earthquake, while the second step of Figure 8 agrees with the acceleration observed in



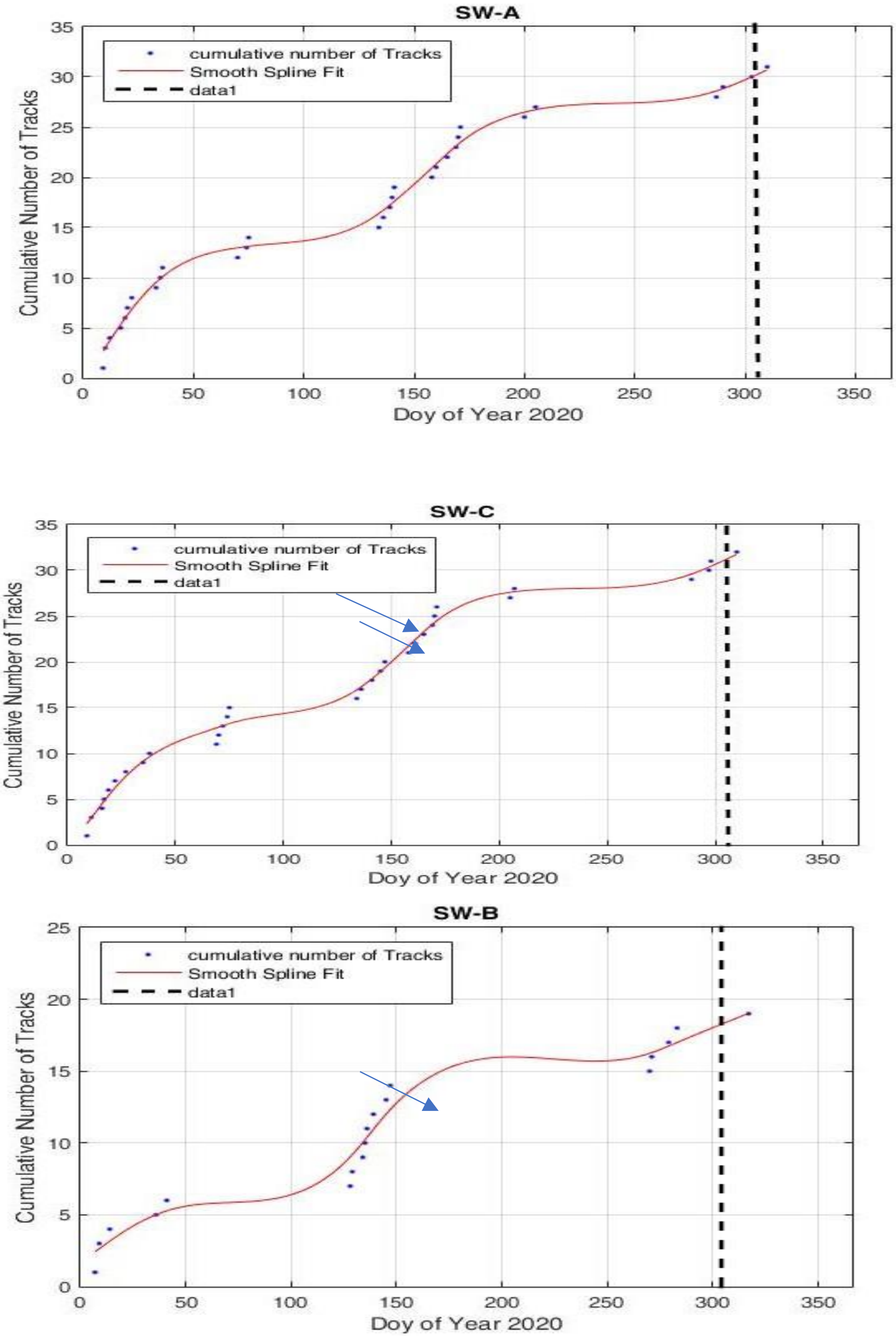
(a)

(b)

(c)

Figure 5: The cumulative number of anomalous paths/tracks discovered by the AMSW technique for Swarm (A, C, and B) satellites ten months before and two after the Samos earthquake with magnitude 7.0. Anomalous tracks are chosen during the low-level geomagnetic activities ($|Dst| \leq 20$ nT and $Ap \leq 10$).

Swarm magnetic and electron density data close to 155 days of 2020.



(a)

(b)

(c)

Figure 6: The cumulative number of anomalous paths/tracks discovered by the ANESW technique for Swarm (A, C and B), ten months before and two after the Samos earthquake with magnitude 7.0. Anomalous tracks are chosen during the low-level geomagnetic activities (|Dst| ≤ 20 nT and Ap ≤ 10).

Figure 9a demonstrates the time derivative of the cumulative EQs every ten days. It demonstrates two large accelerations before the EQ on days 30 and 140 of 2020. In addition to these two peaks, enhanced acceleration in the number of EQs prolongs for about a month until the Samos EQ, which occurred on Oct 30, 2020. Figure 9b shows the magnitude of EQs concerning the day of the year 2020 for EQs observed within Dobrovolsky Area.

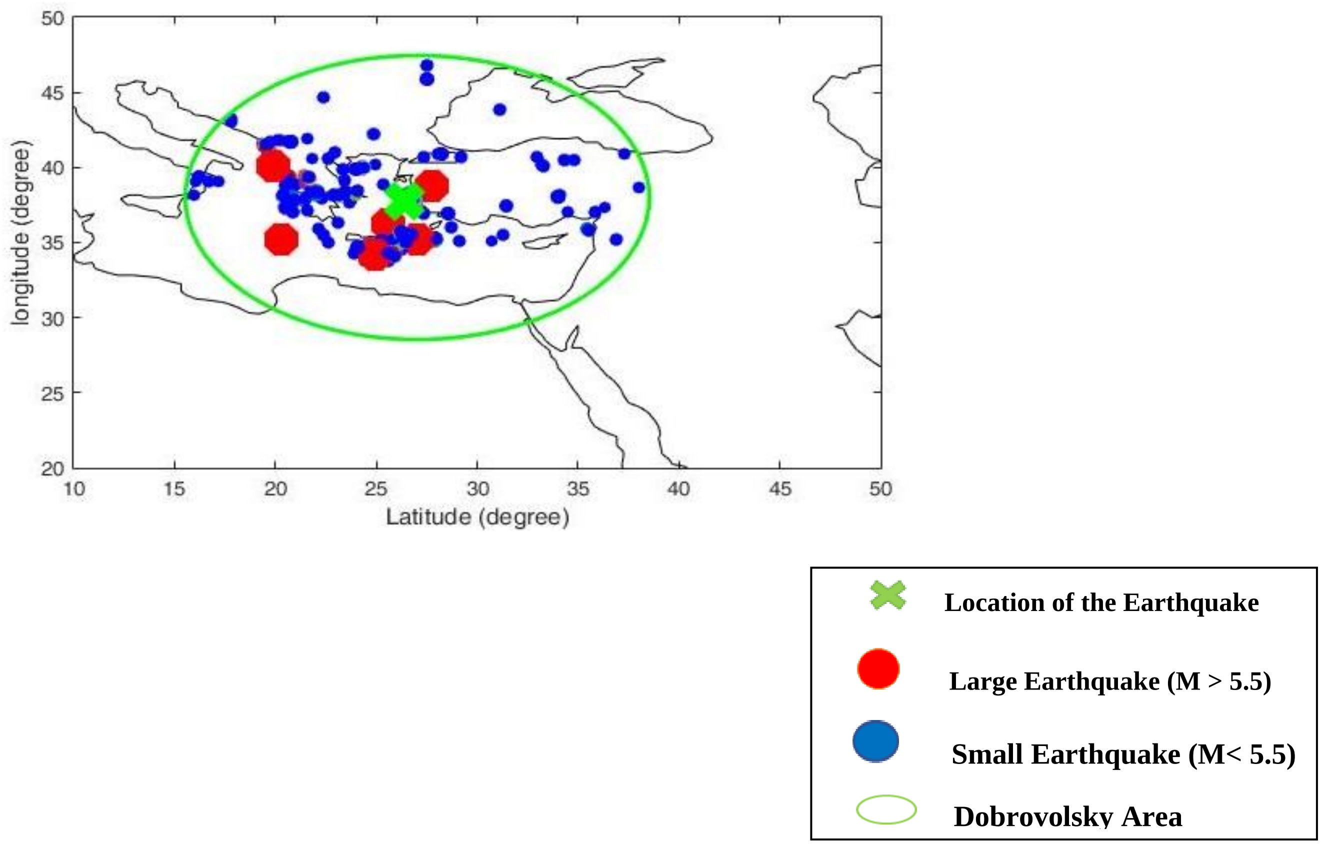


Figure 7 : Geographic map of the earthquakes that occurred in 2020 within Dobrovolsky's region**.**

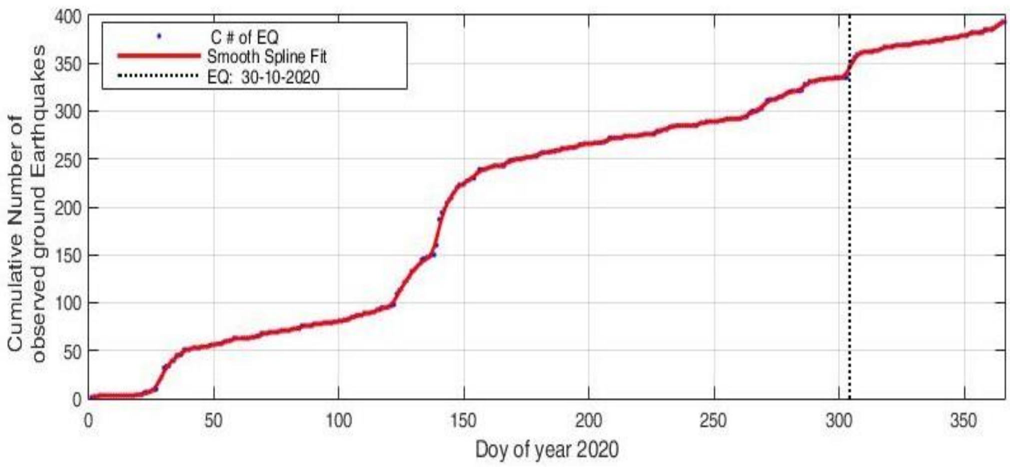
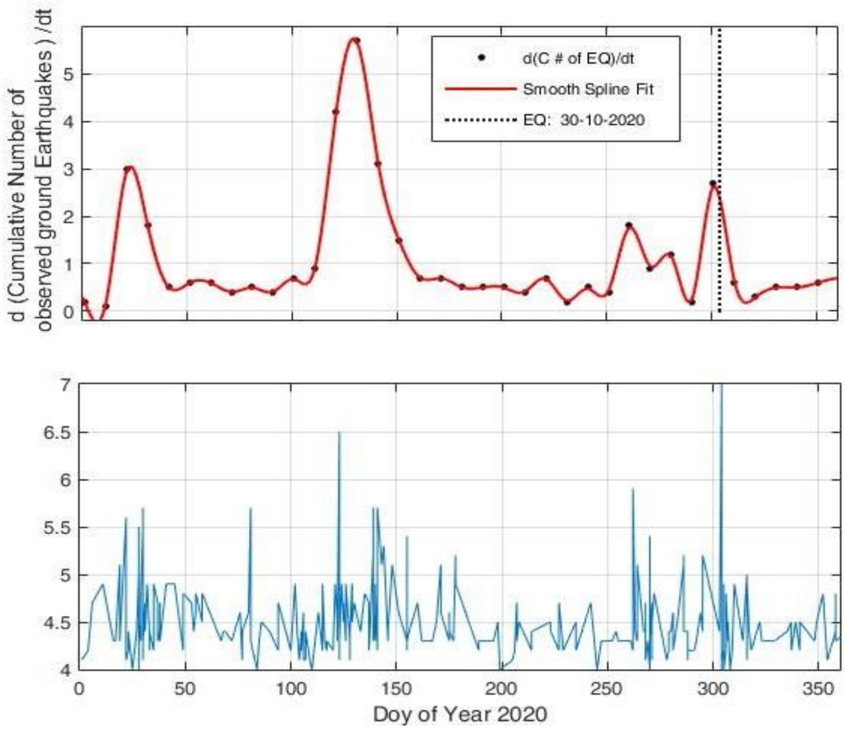


Figure 8: The cumulative number of observed ground earthquakes obtained from the (USGS in the blue dotted line). The red solid line corresponds to the smooth spline fitting of the cumulative number of earthquakes. The vertical dashed line corresponds to the day of the Samos earthquake.

(a)



(b)

Figure 9: a) The time derivative of the cumulative number of grounds EQs (every ten days). **b)** The magnitude of ground EQs concerning the day of the year 2020. The vertical dashed line illustrates the days of Samos EQ

5. Discussion

Many anomalous earthquakes were investigated in this study using different algorithms for space ionospheric magnetic field and electron density data. In addition to ground magnetic observation for the Samos earthquake. Unlike ÖZSÖZ and PAMUKÇU, the AMSW and ANESW algorithms analysis for 2020 were adopted to investigate earthquake anomalous.

Figure 3 is a typical example of earthquake anomalies detected by the magnetic swarm anomaly detection by Spline analysis (MASS) algorithm, which is well-matched with the previously published research work [2, 3, 8-10, 15, 16]. Using SW-C data, ÖZSÖZ found anomalies in the magnetic field data 37 days before the Samos earthquake occurred on Sep 22, 2020. Also, [8] noticed a disturbance in the magnetic field data (anomalies) one day on Oct 29, 2020, by SW-C before the Samos earthquake. The authors plotted the magnetic components (X, Y, Z, and F) and found no abnormalities in the track's X, Z, and F components. However, a single anomalous period in the Y component was found in Dobrovolsky's region on Sep 22, between 04:23 and 04:33 a.m. In the current work, anomalies were found in the magnetic field about seven days before the Samos earthquake occurred on Oct 23, 2020, using the AMSW algorithm.

Figure 4 is a typical example that illustrates the capability of the AMSW algorithm to detect anomalies as detected by the ANESW algorithm. The anomalies in the electron density were found to be occurred by 155 (May 26, 2020) before the mainshock. The cumulative number of tracks in Figures 5 and 6 indicated anomalies in the magnetic field and electron density data, consistent with previously published findings by ÖZSÖZ and PAMUKÇU. They observed a rise in magnetic anomalies before the EQ mainshock, from the beginning of Oct. Similarly, the observational study demonstrated an increase in anomalous tracks before the

Samos EQ, which began at the end of May. The anomalies in the ground data showed an increase in the cumulative number of earthquake anomalies around 26 155 days before the mainshock, Figure 8, which agrees with the cumulative number of tracks for the magnetic field and the electron density.

Figure 9 shows an acceleration of the EQ occurrence, as the enhanced acceleration on days 22,30,122, 138, and 140 of the year 2020 corresponds to the extensive EQ. The acceleration within days 20-40 of 2020 may be due to large EQs on days 22 and 30 of 2020 with M ≥ 5.5. Those two EQs occurred in Turkey and Greece, respectively. Similarly, the second acceleration within the period 120-150 corresponding to large EQs occurred in Greece on days 122, 138, and 140 of 2020. The epicenters of the EQs that occurred on days 122 and 138 are identical under Neanatoli, located 34.287°N,25.5222°E, while the last EQ on day 140 occurred under Methoni, located 35.154°N, 20.287°E.
Finally, the broad acceleration observed on day 261 of 2020 before the Samos EQ corresponds to the Arkalochori EQ, Greece, a preparation phase for our potential Samos EQ of magnitude equal to 7. This acceleration occurred before the Samos EQ is in agreement with that presented by [17], who demonstrated the existence of acceleration in the cumulative number of tracks of satellite magnetic data before the Nepal EQ occurred on April 25, 2015.

6. Conclusion

In this work, besides the Swarm satellite magnetic and electron density data, we inspected the ground magnetic data to investigate the EQ anomalous occurrences before and after the Samos earthquake on Oct 30, 2020. Results of EQ anomalous within Dobrovolsky's area of the EQ during the quietest conditions have drawn the following concluding remarks:

1) An enhanced number of anomalies was observed on day 155 of the year before the mainshock of the Samos EQ occurred on day 303, Oct 30, 2020.
2) The cumulative number of EQ anomalies in the magnetic and electron density data showed similar features, while the cumulative number of EQ anomalies in the ground stations showed more than one enhanced period before the Samos EQ.
3) As a final result, each EQ with magnitude (M>5.5) is preceded by an acceleration in the cumulative number of EQ anomalies.

This work is a preliminary study that should be extended by extra studies that may discuss the width of the acceleration period in relationship to the magnitude of the EQ. Deep learning technology can overcome such restrictions, which combines the remote sensing parameters of various time and space-related spheres and performing analysis based on a consistent spatial-temporal framework. This could provide global earthquake cases, effectively explain the earthquake coupling mechanism models, expand the capabilities of the tools currently used for earthquake monitoring and open new avenues for earthquake prediction.

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