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Geomagnetic Storm Impacts on Communication, Navigation, Surveillance, and Air Traffic Management (CNS/ATM)

Eid A.[1], M.S. ELNawawy[2] and S.M. Robaa[3]

[1]Air Traffic Controller at The National Air Navigation Services Company (NANSC), Cairo, Egypt.
[2]Professor of Astrophysics, Astronomy, Space Science and Meteorology Dept., Faculty of Science, Cairo University, Egypt.
[3]Professor of Environmental Meteorology, Astronomy, Space Science and Meteorology Dept., Faculty of Science, Cairo University, Egypt.

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ABSTRACT

In this paper, we are studying the impacts of geomagnetic storms on Communication, Navigation, Surveillance, and Air Traffic Management (CNS/ATM) by researching and analyzing the number of hours in a geomagnetic storm per year. According to Dst (<-50 nt) in the period from 2015 to 2021 has been analyzed, associated with (Dst) less than (-50 nT), using Dst records that tabulate the amount and vigor of geomagnetic storms, Sunspot Number (SSN) it is period connects the end of the solar cycle 24 and the beginning of the cycle 25 With comparison the deterioration and interruptions of communications (D*i*) at Cairo international airport Geomagnetic Storm events occur when the Sun causes disruptions to aviation Communications, Navigation, and Surveillance (CNS) systems, and elevates radiation dose levels at flight altitudes. Space weather events may occur on short time scales, with the effects occurring from seemingly instantaneous to a few days hence. The sole exceptions are the brilliant auroras, spawned by energetic electrons and ions. Energized auroras indicate the deposition of energy into the upper atmosphere, and may herald the degradation of communications, navigation, and surveillance of aircraft in the vicinity. Therefore, decision- makers in the field of aviation should be aware that the phenomena of space weather can pose a threat to the safety and efficiency of flight operations, as the answer is to know what are the effects, the potential and consequent risks of electromagnetic storms, and the options available to mitigate those risks.

Keywords: Geomagnetic storms, Sunspot Number (SSN), Communications, Navigation, Surveillance (CNS) and satellite solar outage.

1. Introduction

These solar events and variations can give rise to the following effects the aurora, ionospheric disturbances, Solar Particle Events (SPEs), and geomagnetic storms. Probably the most well- known effect of the solar-induced geomagnetic storms is the aurora borealis (northern lights) and aurora austral (southern lights). Aurorae begin between 60° and 80° latitude. As a storm intensifies, the aurorae spread toward the equator. During an unusually large storm in 1909, an aurora was visible in Singapore, on the geomagnetic equator. The aurorae provide pretty displays, but they are just a visible sign of atmospheric changes that may wreak havoc on technological systems. The bursts of electromagnetic radiation (ultraviolet and x-ray) from a solar flare journey at the speed of light and arrive at Earth just 8 minutes after leaving the flare site. Unaffected by the Earth's magnetic field, these emissions directly affect the upper atmosphere (becoming significant below 100km) by producing a temporary increase in ionisation in the sunlit hemisphere of minutes to hours duration called a "sudden ionospheric disturbance" Certain major solar flares and CMEs can shower the Earth, within 30 minutes, with energetic particles (primarily protons). In this case, the Earth's magnetic field does offer some protection, but some of these particles spiral down the field lines, entering the upper

Corresponding Author: Abdullah Eid, Air Traffic Controller at The National Air Navigation Services Company (NANSC), Cairo, Egypt. E-mail: abdalha_eid@hotmail.com

atmosphere in the Polar Regions where they produce additional ionisation in the ionosphere and below. Veryenergetic and intense events can also lead to increases at lower latitudes. One to four days after a major solar disturbance occurs, a slower cloud of solar material and magnetic field reaches Earth,buffeting the magnetosphere and resulting in a geomagnetic storm. The bi-polar magnetic field of the Earth points north but the field contained within the material expelled from the Sun can point in any direction. When the field is orientated in the opposite direction to that of the Earth's, the two magnetic systems interact and the solar material can enter the Earth's magnetosphere.

These interactions can produce very large electrical currents, of up to a million amperes, flowing through the ionosphere and magnetosphere, which can change the direction of the Earth's magnetic field at the surface by up to 1 or 2 degrees, mainly in the aurorally regions. (Space Weather effects on airline operations (Captain Bryn Jones, (2022) VAA Cosmic Radiation Project Manager), n.d.)

Space weather effect correction models applied within the standard satellite positioning service are not capable of tackling the effects of severe space weather conditions and local ionospheric characteristics. Severe space weather effects on the GPS ionospheric delay are intensely studied to provide advanced models of the space weather effects on GPS positioning performance. Hereone study of severe space weather conditions and their consequences on the GPS ionospheric delay in Croatia is presented. The study takes advantage of the availability of the space weather indices and the GPS pseudo-range measurements (taken at the reference site at Osijek, Croatia) related to a major severe space weather event lasting from early October 2003 to late November 2003. (Filjar, 2007) Space weather impacts occur to communications, navigation, surveillance, radiation-sensitive electronics, and human exposure the system impacts may include: (ICAO, n.d.).

a) Unexpected loss of communications;

- HF voice and HF data link, i.e. Controller Pilot Data Link Communication (CPDLC), on routes where HF is employed;
- Poor or unusable performance of L-band SATCOM;

b) Degraded performance of navigation and surveillance that rely on GNSS;
- Automatic Dependent Surveillance-Broadcast (ADS-B) and/or Automatic DependentSurveillance – Contract (ADS-C) anomalies;
- Sporadic loss-of-lock of GNSS, especially near the equator, post-sunset;

c) Unanticipated non-standard performance of on-board electronics, resulting in reboots and anomalies; and
d) Issues related to radiation exposure by aircrew and passengers.

2. Methodology

Identify and manage the risks that threaten the management of air traffic by responding quickly and positively to mitigate the effects of electromagnetic storms that cause disruption and deterioration of communication, navigation, and Surveillance based on satellites (CNS).
Therefore, the researcher believes that the strategic objective of the research is an investigation of:

a) Safety by enhancing global civil aviation safety.
b) Security by enhancing the security of the Air Traffic Management (ATM)
c) Efficiency by enhancing Air Traffic Flow Management (ATFM)
d) Continuity by maintaining the continuity of flight operations

Space weather events impact aviation operations by degrading the performance of Communication, Navigation, and Surveillance services and solar radiation can be detrimental to the health of crews and passengers. (Kejian1.cmatc.cn, n.d.) Communication and Navigation satellites can be disabled by significant solar events and more commonly, in the Polar Regions; space weather conditions can blackout high-frequency satellite communication and satellite navigation services for periods from minutes to several hours. (www.ICAO.int, n.d.).

2.1. Communications issues related to recent space weather events are reported below:

A- Thirteen overdue position reports for flights over Central East Pacific and Central West Pacific (1830-1930Z Jan 27, 2012, R3 radio blackout).
B- HF service degraded for over two hours (Oct 19, 2003, R3 radio blackout)
C- Degradation of high latitude (Oct 24, 2003, G3 geomagnetic storm)
D- Widespread HF communications problems in Alaska (Jan 22-23, 2012 S3 solar radiationstorm)
E- Communications problems in Asia and the Pacific (Jan 22, 2012, daytime R2 radio blackout)
F- Communications problems off U.S. East Coast and West Coast (Jan 27, 2012 daytime radio blackout).

2.2. Data sources

The data used for this study is classified and retrieved with the permission of the Air Traffic Control System (ATCS). Is a device in the French THALES system (Thales Group, 2022 n.d.) that identifies errors and threats that affect air traffic management, which is recorded in the air safety department and followed up periodically through the International Civil Aviation Organization to develop and raise efficiency. We have collected the events with the number of hours Dst (< - 50nT) during the period 2015–2021. A list of magnetic storms based on the Dst indices provided by Kyoto University's Data Analysis Center for Geomagnetism and Space Magnetism Graduate School of Science (wdc.kugi.kyoto 2022-u.ac.jp, n.d.), the number of days with a geomagnetic storm per year. According to the finalized KP-index GFZ Potsdam periods from 2015 to 2021, the KP index We used the monthly SSN provided by the Solar Influences Data Analysis Center (sidc.oma.be) and the solar polar field throughout the solar sunspot cycle provided by the Wilcox Solar Observatory (wso.stanford.edu, n.d.). The source of the data is taken from (c=AU; co=Commonwealth of Australia; ou=Department of Sustainability, n.d.) The total sunspot number data is provided by the Royal Observatory of Belgium, Brussels, and can be downloaded from the SILSO website (www.sidc.be, n.d.). In addition, it can be found at (www.ngdc.noaa.gov, n.d.).

3. Results and Discussion

We have followed the duration of (Di) at (CANC) in the period for study from 2015 to 2021 by monitoring and following up on all the days of the interruption during the previous years It is observed in all the monitoring years from 2015 to 2019 the rise in the ($\boldsymbol{Di}$) is the observed year 2015 and then the gradual decline and disappearance the year 2019 It is noted that the duration of($\boldsymbol{Di}$) increased in Cairo year 2020 and 2021, the beginning of the index rises again and we noted that communications have been repeatedly deteriorated and interrupted at Cairo Air Navigation Center. The equation (1) below is used to calculate the total duration ($\boldsymbol{Di}$) for every year from 2015 to 2021.

$$\boldsymbol{D_i} = \sum_{j=1}^{k} C_{ij} \quad i = 1,2,\dots,7 \qquad (1)$$

Where $\boldsymbol{D_i}$,=1,2,⋯,7. Is the total duration of the deterioration and interruptions of the communications during a specific year from 2015 to 2021, respectively, and $\boldsymbol{C_{ij}}$,=1,2,⋯,7. $\boldsymbol{j}$=1, 2, ⋯, is the duration of the deterioration and interruptions of the communications during the specified year $\boldsymbol{i}$, and $\boldsymbol{k}$ refers to the number of days of the specified year.

Table 1: Shows the total number of deterioration and interruptions of communications that happen annually in minutes, over the study period (2015 - 2021) at (CANC).

Year	2015	2016	2017	2018	2019	2020	2021
Duration(MIN)	575	493	380	360	250	355	370

Figure (1) shows the duration of (Di) at (CANC) the maximum in the year 2015 is 575 MIN, and the minimum in the year 2019 is 250 MIN, which indicates the beginning of the indexrise again in the year 2020 and 2021.

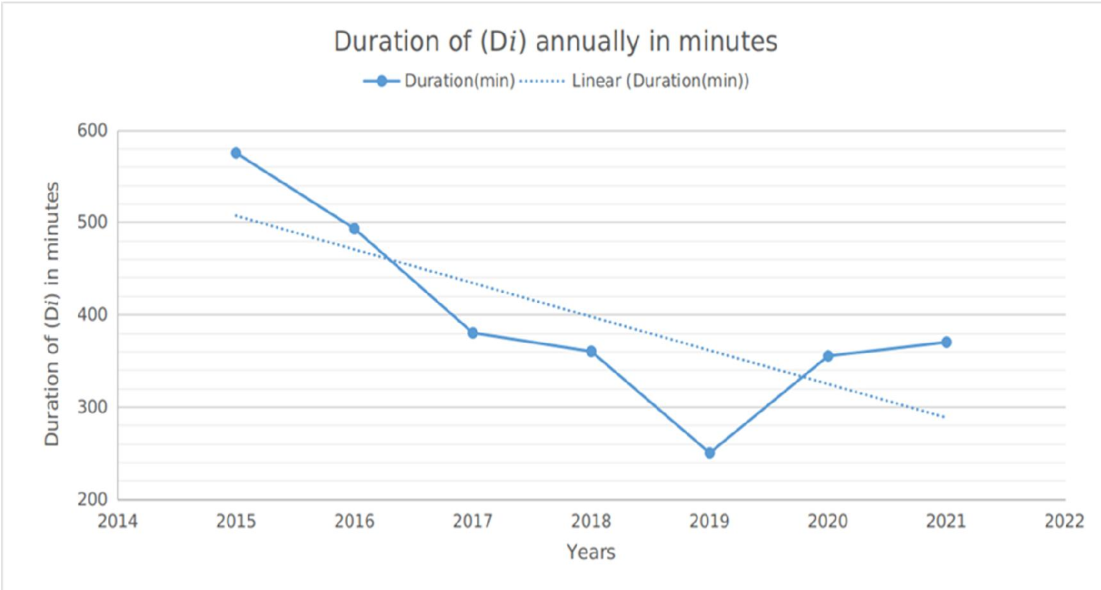

Fig. 1: The duration of (Di) at (CANC) in the periods from 2015 to 2021

3.1. Satellite Solar outage impact

The duration of ($\boldsymbol{Di}$) at (CANC) in the periods from 2015 to 2021 during Satellite Solar Outage [See Figure 3.3] It is noted high of the duration of ($\boldsymbol{Di}$) during Satellite Solar Outage has increased in Cairo in 2015 and gradually decreased until 2020 and indicates the beginning of theindex rise again in the year 2021(Guo *et al.,* 2012).

The equation (2) below is used to calculate the total duration (D_i) during periods I and II forevery year from 2015 to 2021.

$$\boldsymbol{D_i} = \sum_{j=1}^{m} C_{i1j} + \sum_{j=1}^{n} C_{i2j} \quad {}_{i=1,2,\ldots,7} \qquad \ldots\ldots (2)$$

Where $\boldsymbol{D_i}$,=$\mathbf{1},\mathbf{2},\cdots,\mathbf{7}$. is the total duration of the deterioration and interruptions of the communications during a specific year from 2015 to 2021, respectively $\boldsymbol{C_{i1j}},\boldsymbol{i}=\mathbf{1},\mathbf{2},\cdots,\mathbf{7},\boldsymbol{j}=\mathbf{1},\mathbf{2},\cdots,\boldsymbol{m}$ is the duration of the deterioration and interruptions of the communications during the period I in the specified year i and m refers to the number of days of February and March in the specified year i, and $\boldsymbol{C_{i2j}},\boldsymbol{i}=\mathbf{1},\mathbf{2},\cdots,\mathbf{7},\boldsymbol{j}=\mathbf{1},\mathbf{2},\cdots,\boldsymbol{n}$ is the duration of the deterioration and interruptions of the communications during period II in the specified year i, and n refers to the number of days of September and October in the specified year i. Notated that period I starts from the first day of February till the end day of March in the specified year i, while period II starts from the first day of September till the end day of October in the specified year i.

Table 2: Shows the total number of deterioration and interruption of communication that happens annually in minutes, to the Satellite Solar Outage (period I and II) (2015-2021).

Year	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**
Duration(min)	434	381	324	294	239	198	240

Figure (2) shows the duration of (Di) at (CANC) in the periods from 2015 to 2021 during

Satellite Solar Outage (period I and II)) the maximum in the year 2015 is 434 MIN, and the minimum in the year 2020 is 198 MIN, which indicates the beginning of the index rise again in the year 2021.

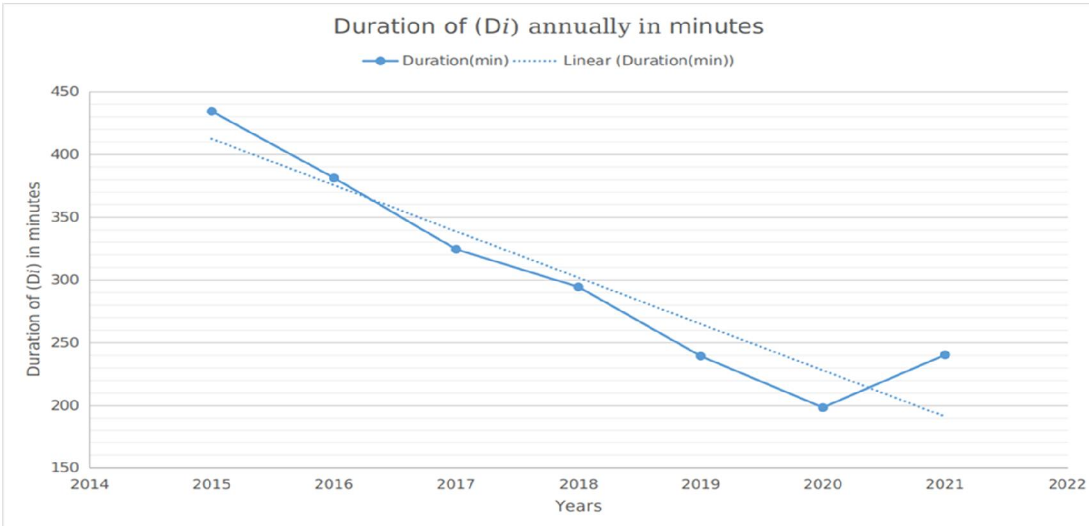

Fig. 2: Shows the duration of ($\boldsymbol{Di}$) at (CANC) in the periods from 2015 to 2021 during SatelliteSolar Outage (period I and II)

The geomagnetic storms can also be identified by various other parameters such as the symmetric disturbance of the magnetic field H (SYM-H); the interplanetary electric field (IEF); and the interplanetary magnetic field (IMF), where IMF-Bz is the most important parameter for the study of geomagnetic storms, as the energy input into the magnetosphere, depends on Bz orientation and its magnitude (Desai and Shah, 2018) Although these indexes provide extra information regarding the space conditions, some of them are related to The Dst-index. For instance, a relationship has been shown between Dst and Bz (Gonzalez *et al.,* 1994). The response of the ionosphere to geomagnetic-induced disturbances is known as an ionospheric storm (Mendillo, 2006; Joshua *et al.,* 2014). The ionosphere plasma density is mainly determined by the chemistry/composition, transport due to electric fields, transport due to neutral wind, and transport due to ambipolar diffusion. During geomagnetic storms, the variations of chemistry or the thermospheric composition, the interaction with the neutrals (neutral wind) (Cai *et al.,* 2021) and (Yu *et al.,* 2021 and/or variations of electric field and ambipolar diffusion (Tsurutani *et al.,* 2008) are the final cause that alters the ionosphere plasma density.

Nevertheless, the response of the ionosphere during a geomagnetic storm is complex and difficult to predict accurately, and the physical nature of many underlying mechanisms needs abetter understanding to obtain precise forecasting of its behavior based on geomagnetic storm parameters (Samed, 2020). In addition, the effects of these physical processes on the ionosphere have also been reported to vary with solar activity, storm intensity, storm duration,season, location, local time, and altitude of the observing station, which increases the forecast uncertainties (Liu *et al.,* 2008).

The table 3: below shows the number of days with a geomagnetic storm per year from 2015 to 2021 and how strong those storms were (www.gfz-potsdam.de, n.d.) during the end of the SolarCycle 24 and the beginning of the Solar Cycle 25. The Source of the Kp index is the Kp-websiteof GFZ (www.gfz-potsdam.de, n.d.).

Table 3: Shows the Number of days with a geomagnetic storm per year According to finalized KP-index GFZ Potsdam, over the study period (2015-2021).

Year	G1	G2	G3	G4	G5	Total
2015	43	18	5	3	0	68 days
2016	45	18	0	0	0	63 days
2017	37	12	2	2	0	53 days
2018	12	7	2	0	0	21 days
2019	16	2	0	0	0	18 days
2020	8	1	0	0	0	9 days
2021	19	4	1	1	0	25 days

Year	2015	2016	2017	2018	2019	2020	2021
Number of Day	68	63	53	21	18	9	25

Figure (3) shows the number of days with a geomagnetic storm per year and how strong those storms were. This will give you an idea of which years there were many geomagnetic storms in the periods from 2015 to 2021. The Source of the Kp index is the Kp-website of GFZ(www.gfz-potsdam.de, n.d.) the maximum in the year 2015 is 68 Days, and the minimum in theyear 2020 is 9 days which indicates the beginning of the index rise again in the year 2021.

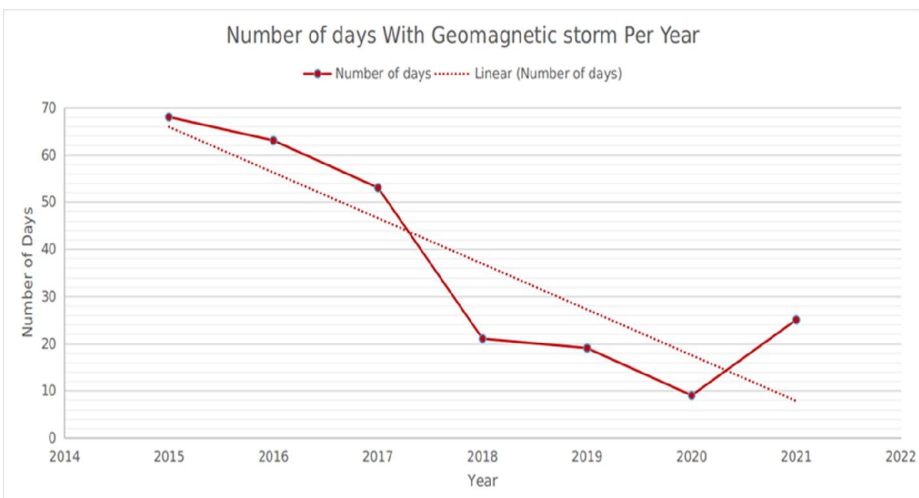

Fig. 3: The Number of days with a geomagnetic storm per year According to finalized KP-index GFZ Potsdam periods from 2015 to 2021.

The disturbance storm time (Dst- index) is a measure in the context of space weather. It gives information about the strength of the ring current around Earth caused by solar protons and electrons. The ring current around Earth produces a magnetic field that is directly opposite Earth's magnetic field, i.e. if the difference between solar electrons and protons gets higher, thenEarth's magnetic field becomes weaker (Clette *et al.,* 2015). A negative Dst value means that Earth's magnetic field is weakened. This is particularly the case during Geomagnetic storms. (Kyoto-u.ac.jp, 2022) The Dst-index has been used historically to characterize the severity of a geomagnetic storm. Depending on the Dst value, the storms are usually classified in ranges such as weak (−30 nT and −50 nT), moderate

(−50 nT and −100 nT), intense (−100 nT and −200 nT),very intense (−200 nT and −350 nT), and great (Dst below −350 nT), (Borovsky and Shprits, 2017) and Our study will depend on the intensity of the geomagnetic storm. Depending on the value of Dst, storms are classified as moderate (−50 nT) periods from 2015 to 2021 during theend of Solar Cycle 24 and the beginning of Solar Cycle 25.
To get the number of hours with a Geomagnetic Storm per year ($N\boldsymbol{i}$), we present the following equation (3).

$$\boldsymbol{N_i} = \sum_{j=1}^{k} G_{ij} \quad i = 1,2,\dots,7 \qquad \text{.........(3)}$$

Where $\boldsymbol{\mathcal{N}_i}$,$\boldsymbol{i}$=1,2,⋯,7 is the total number of hours with a Geomagnetic Storm during a specific year from 2015 to 2021, respectively and $\mathbf{G}_{ij}$, $\boldsymbol{i}$=1,2,⋯,7, $\boldsymbol{j}$ =1,2,⋯,$\boldsymbol{k}$ is the number of the hours with a Geomagnetic Storm during the specified year $\boldsymbol{i}$ with, $Dst< -50\ nt$ and $\boldsymbol{k}$ refer to the number of days of the specified year $\boldsymbol{i}$.

The year 2015 was chosen because it is the highest in the number of hours with a geomagnetic storm per year According to Dst (< -50 nt) The period from 2015 to 2021 connects the end of thesolar cycle 24 and the beginning of the cycle 25. We have followed the Number of hours with a geomagnetic storm per year According to Dst (< -50 nt) in the period for study from 2015 to 2021 by monitoring and using Equation (2) We found the number of hours with a geomagnetic storm per year According to Dst (< -50 nt) have increased in 2015 and gradually decreased until2019 and increased during the year 2020 and 2021, i.e. the beginning of the index rise again The graph below shows the number of hours with a Geomagnetic Storm per year According to Dst (<
-50 nt) in the period from 2015 to 2021.

Table 4: Shows the number of hours with a geomagnetic storm per year According to Dst (< -50nt), over the study period (2015-2021)

Year	2015	2016	2017	2018	2019	2020	2021
Number of hours	560	182	89	64	14	25	55

The graph below shows the number of hours with a Geomagnetic Storm per year According to Dst (< -50 nt)in the period from 2015 to 2021, the maximum in the year 2015 is 560 hours, andthe minimum in the year 2019 is 14 hours which indicates the beginning of the index rise again in the year 2020 and 2021.

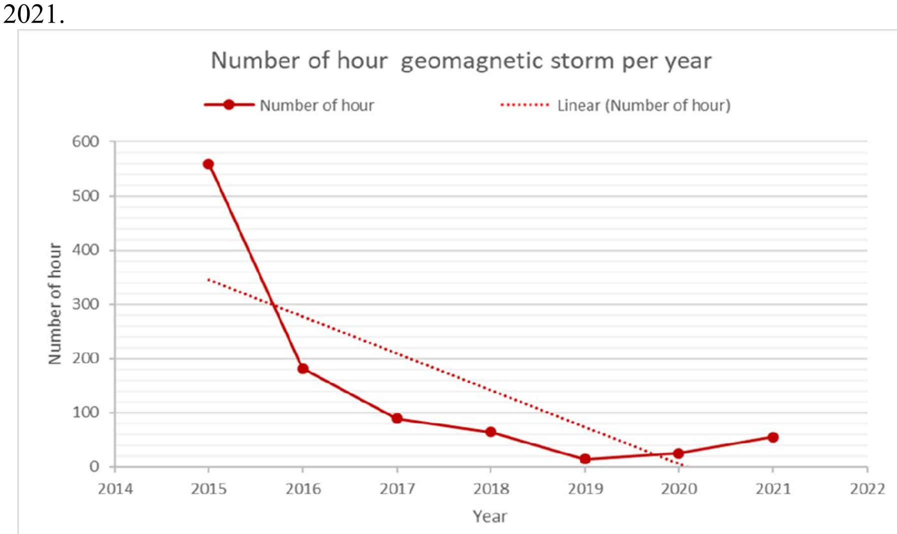

Fig. 4: The number of hours with a geomagnetic storm per year According to Dst (< -50 nt) inthe period from 2015 to 2021

4. Conclusions and Recommendations

After analyzing and monitoring the data of two geographically different stations within the Egyptian airspace, Cairo and Aswan International Airport, we found that the results are similar, The main results of this study, after comparing the number of hours of geomagnetic storms according to D_{st} (< -50 nt) the number of sunspots (SSN), as well as the deterioration and interruption of communications at the Cairo Aeronautics center from 2015 to 2021, confirmed that the relationship is direct. It gets worse and more dangerous during Satellite solar outages during periods I, and II In all years of monitoring and analysis, especially when there are severe and influential geomagnetic storms during the period of visiting sunspots (SSN), this will negatively affect the safety and efficiency of air traffic management within the Egyptian airspace.

The Egyptian aviation sector is vulnerable to the impacts of space weather, which can affect High-Frequency radio communication, satellites, avionics, and aircraft navigation and communication systems. Internationally, ICAO is requiring that certain standards be developed to assist aircrew and ground support in managing the potential impact of space weather. The main recommendation from this policy brief is that Cairo Air Navigation Center (CANC) shouldalign itself with international for the provision and access to space weather information to be ready to meet the ICAO recommendations by 2025 and to protect the vulnerable areas within aviation systems.

- Cairo Air Navigation Center (CANC) user forum, with participation from affected parties within the sector should be established to consider and make provision for space weather impacts on aviation.
- Cairo Air Navigation Center (CANC) should be requested to lead the aviation Community in defining and collecting operational data that can be used to assess the different Impact areas, andthe economic impact arising from space weather mitigation.
- The aviation industry, with the assistance of the Space weather monitoring Center (SWMC) in Egypt, should be requested to clearly define its requirements for space weather information and how these can be incorporated into the operational decision-making process.
- The Space weather monitoring Center (SWMC) should align itself to deliver space weather information in an internationally agreed-upon standardized format as defined by the aviation user requirements, and be given the mandate to assist the aviation sector in fulfilling the ICAO recommendations.
- The Egyptian Civil Aviation Authority (ECAA) should define a minimum set of requirementsfor incorporating space weather into operational training for Air Traffic Controllers (ATC), aircrew (pilots and cabin crew), dispatchers, meteorologists, and engineers.
- The Egyptian Civil Aviation Authority (ECAA) should mandate that space weather Information be received by aviation operators and be included as part of their planning andbriefing process. This information must meet a minimum set of standards.
- An annual assessment should be carried out of the service performance within the aviation Sector based on space weather events. These recommendations come from an understanding andawareness of the potential impacts of space weather on the aviation sector.

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