REVIEW ARTICLE

The future of air navigation reliability dependent on space weather

El futuro de la fiabilidad de la navegación aérea dependiente del clima espacial

O futuro da confiabilidade da navegação aérea dependente do clima espacial

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ABSTRACT

The world aviation activity rises constantly, increasing aircraft density in all geographic territories. For this reason, there is a tendency of new navigation technologies to arise that, attending requirements of integrity, accuracy, availability, and continuity, will promote maintenance of air safety, even with increasing flight numbers. The means of positioning determination most used today in aircraft are dependent on satellites. The constellations GPS (Global Positioning System) and GLONASS (Global Navigation Satellite System – in Russian), and the augmentation systems WAAS (Wide Area Augmentation System) and European Geostationary Navigation Overlay Service (EGNOS), for example, are compounds of the Global Navigation Satellite System (GNSS). All the mentioned, are dependent on Earth geomagnetic and ionosphere equilibrium. Both are targets of solar and cosmic radiation bombardments, i.e. space weather. Depending on that phenomenon intensity, serious damages could occur on positioning systems, as in several others, such communications and power grids. In retrospect, space weather already led to losses such as in the events of 1989 and October 2003 on the CONUS American region. The forecast quality for such occurrences is still poor, while society complacency associated with this subject is high, which further extends to aviation, considering the potential damages.

Keywords: Space weather; ionosphere; GNSS; aviation.

RESUMEN

La actividad aérea mundial está creciendo de manera constante, aumentando la densidad de aeronaves en todo el territorio geográfico. Por ello, existe una tendencia hacia las nuevas tecnologías de navegación que, cumpliendo con los requisitos de integridad, precisión, disponibilidad y continuidad, permitirán el mantenimiento de la seguridad aérea incluso con el aumento del número de vuelos. Los medios más utilizados para determinar el posicionamiento en las aeronaves en la actualidad dependen de los satélites. Navegación global - en ruso), y los sistemas de aumentación WASS (Sistema de aumento de área amplia) y EGNOS (Servicio de Superposición de Ngeoestacionaria Europea), por ejemplo, son los medios que componen

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The acronyms and abbreviations contained in this article correspond to the ones used in the original article in Portuguese.

el Sistema de Navegación por Satélite global (GNSS). Todo lo anterior depende del equilibrio geomagnético de la Tierra y del medio electrónico de la ionosfera. Ambos son objetivos de bombardeos de radiación solar y cósmica, es decir, el clima espacial. Dependiendo de la intensidad de estos fenómenos, pueden ocurrir daños graves a los sistemas de posicionamiento, así como a varias otras áreas, como las comunicaciones y las redes eléctricas. En retrospectiva, el clima espacial ya ha causado un gran daño, como en los eventos de 1989 en América del Norte y en octubre de 2003 en la región americana de CONUS. La calidad de la previsión de estos sucesos sigue siendo baja y la complacencia de la sociedad con respecto al problema es alta, incluso en la aviación, teniendo en cuenta los posibles daños.

Palabras clave: *Clima espacial; ionosfera; GNSS; aviación.*

RESUMO

A atividade aérea mundial cresce de forma constante, o que aumenta a densidade de aeronaves em todo o território geográfico. Por esse motivo, existe uma tendência para novas tecnologias de navegação que, atendendo requisitos de integridade, precisão, disponibilidade e continuidade, vão permitir a manutenção da segurança aérea mesmo com o aumento do número de voos. Os meios de posicionamento mais utilizados hoje são dependentes de satélites, que abrangem o Sistema de Satélites de Navegação Global (GNSS). O sistema é dependente do equilíbrio geomagnético da Terra e do meio eletrônico da ionosfera. Ambos são alvo de bombardeamentos de radiação solar e cósmica, i.e. clima espacial. O presente trabalho tem como objetivo ser uma fonte informativa, ou review, da relação entre clima espacial e aviação, para auxiliar na conscientização dos leitores, principalmente àqueles pilotos, principais responsáveis pela segurança dos voos. Será apresentada uma forma simplificada da teoria dos fenômenos do clima espacial, como estes podem afetar a aviação e as tecnologias, o histórico de eventos que atingiram o planeta e as iniciativas que foram e estão sendo desenvolvidas para sua mitigação e seu monitoramento. Como metodologia, foram consultados artigos científicos, livros teóricos, manuais, reportagens, sites de agências de pesquisa e apresentações de organizações. Essas fontes permitiram concluir que os estudos são recentes, há pouca conscientização para os usuários destas tecnologias e, visto a complexidade da origem dos fenômenos do clima espacial, existe uma falta de qualidade na sua previsão. Essa falta de qualidade, atrelada à necessidade de tecnologias mais confiáveis para o futuro do espaço aéreo, eleva a pertinência do objetivo deste trabalho.

Palavras-chave: *Clima espacial; ionosfera; GNSS; aviação.*

1 INTRODUCTION

The main interference in aircraft positioning and communication systems comes from the electronic ionosphere equilibrium(ICAO, 2019a). This layer of the atmosphere is an essential intermediary of modern social life, since it influences all satellite-dependent technologies, as well as electrical networksand communications. Solar flares, coronal mass ejections (CMEs) and cosmic radiation - components of space weather, have always been present as a source of this imbalance. If events reach the planet, depending on their intensity, they are likely to influence, in a cascading effect, the Earth's geomagnetic balance, causing atmospheric disturbances, impairing the integrity of all radio signals and possibly causing material damage and enormous financial losses.In aviation, they can affect high-frequency (HF) and satellite communication systems (SATCOM), navigation and GNSS surveillance, and the radiation increase at flight altitudes may occur (HAPGOOD, 2017; ICAO, 2019 a).

During a meeting of the scientific technical subcommittee of the United Nations (UN), held in 2013, it was determined that space weather is a potential cause of natural disasters (UNITED NATIONS, 2013). Space phenomena are being monitored, their intensities are being analyzed, as well as areas of occurrence and possible damages. There are several initiatives and ongoing studies that seek better accuracy in the predictions of events related to space weather, which will be detailed in this article.

There is little awareness of such facts in society, especially in aviation, because consequences of severe events are rare and occur once or twice in a 100 years (NATIONAL RESEARCH COUNCIL, 2008). This work aims to inform and raise awareness of users such as pilots, operational flight dispatchers and controllers. This article warns about the lack of quality in the forecast, due to the complexity of the origin of space weather events. It is relevant since the airspace, under non-contingency conditions, is increasingly dense and requires greater reliability.

1.1 Historic

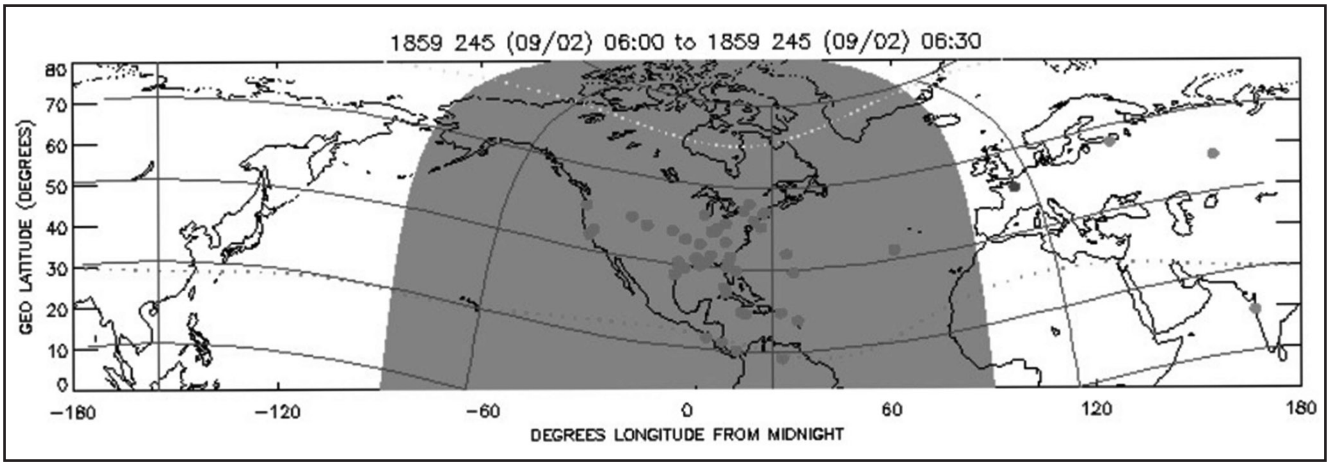
The most severe space weather event on record, which occurred on September 1, 1859, turned 160, according to the National Research Council (2008). The event is known as the “Carrington event” because it was observed by the English astronomer Richard Carrington, in Redhill, UK (SHEEHAN, 2014). If the same magnitude of the phenomenon had occurred today, with the modern and complex infrastructures, the consequences would have been “profound”[1] (NATIONAL RESEARCH COUNCIL, 2008, p. 20, our translation). The event, i.e. the solar flares, was also observed by the amateur astronomer Richard Hodgson in London, England, who confirmed Carrington’s discovery (HOCKEY, 2014). The influences of solar flares were widely observed between midnight and early morning of day 2. The colors in the sky, whose tones were reddish and green, were different from the ones which are commonly seen in aurora. The glow was also much more intense and people reported that they thought it was daylight. This effect was observed in several locations, in latitudes where there are no visible ionospheric effects, such as Cuba, Bahamas, Jamaica, El Salvador, Hawaii and French Guiana, very close to the great circle, as shown in Figure 1. The same effect was also observed in other regions of South America (to northern Chile), Europe, Asia and Australia (BARBOSA, 2015).

The damage caused by the solar flares was less extensive, since electrical inventions were rudimentary. However, at that time, the telegraphs were greatly influenced, from spontaneous sparks to unreadable morse code messages. If the device was disconnected from the battery, the “codes” continued to be transmitted due to the induced current in the system cables. This current is also known as Eddy currents or Foucault currents.

From this important event, in the 1860s, researchers started to link the phenomenon of aurora to sunspots and the earth’s magnetism. These researchers noticed that the three phenomena were interrelated. However, the understanding of the phenomenon was not clear. The greatest scientific advance on this subject only occurred during the cold war, with the space race. In 1957, the Union of Soviet Socialist Republics (USSR) launched the first artificial satellite called Sputnik-1, which provided information about the upper atmosphere.After that, Explorer 1 was launched by the US in 1959 with the same goals as Sputnik-1. These satellites, which were the first ones to be launched, were essential for the study of the solar and cosmic radiation effects, as well as for the science of the ionosphere composition. In the 1970s, coronal mass ejections were discovered (GOSLING, 1993; HAPGOOD, 2017; NATIONAL RESEARCH COUNCIL, 2008; TOUSEY, 1973).

Serious consequences of space weather are rare. As an example, there were other records of strong influences, such as during the Second World War. Radar observations were interrupted during solar radiation emissions, which were only recognized as a solar cause in 1946 (NATIONAL RESEARCH COUNCIL, 2008). In 1972, there was loss of communication in the state of Illinois, USA. On March 13, 1989, another heavy solar bombardment caused extensive damage in North America, mainly in the area of electrical networks. The bombardment caused failures in generators and transformers. The power was off during this eventin the province of Quebec, Canada.

Figure 1 - Locations where dawn was observed in 1859.



Source: (NATIONAL RESEARCH COUNCIL, 2008, p. 21).

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[1] Translation of “profound”.

In 2003, 2005, 2015 and 2017 there were also strong events with broad influences on technologies, according to the following author's works: (DOHERTY; COSTER; MURTAGH, 2004), (BARBOSA, 2015), (BLAŠKOVIĆ, 2015) e (REDMON et al., 2018). The consequences of these events in aviation will be detailed in this article.

2 SPACE WEATHER

WMO (World Meteorological Organization)defines space weather as: "The physical and phenomenological state of the natural space environment, including the Sun and the interplanetary and planetary environments"[2] (ICAO, 2019a, p. 5, our translation). Therefore, space weather includes the Sun and other stars, such as supernova events, which emit intergalactic radiation that reaches the Earth, known as cosmic radiation, or GCR (Galactic Cosmic Rays) (ICAO, 2019a).

2.1 The Sun

The solar origin of space weather includes solar winds, CMEs and solar flares. These phenomena are originated from the sun atmosphere, which can generate large clouds of magnetized plasma and/or radiation from highly energized particles, which propagate through space (HAPGOOD, 2017). CMEs and solar flares have the potential to interfere with aviation safety.

The particles expelled from this astro, propagate via space through magnetic field lines (BOWHILL, 1971), which is produced through the dynamo process. This process allows the explanation of the magnetic field generation of all planets, in which ions are released due to the core intense heat. Hence, this process generates electrically charged fluid that has a constant rotation and convection movement, producing a magnetic field.

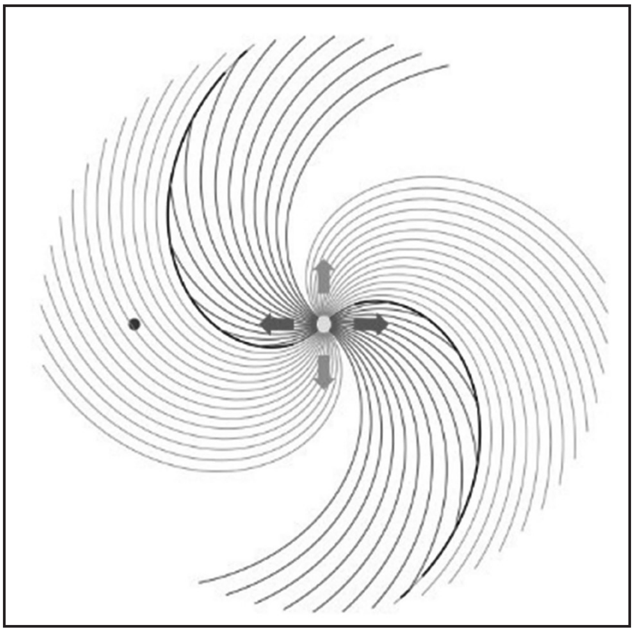
Solar winds, CMEs and solar flares are produced through a process called magnetic reconnection. This process takes place in the solar atmosphere when two magnetic fields with converging directions cross each other, transforming and releasingmagnetic energy into kinetic energy in a sudden way. Such process can also occur outside the solar atmosphere between the Earth's magnetic fields and interplanetary space, which is opposite the Sun (Dungey Cycle), contributing to geomagnetic storms by sending plasma back to the planet (HAPGOOD, 2017; HESSE; CASSAK, 2020).

The magnetic field is carried by both the CME and the solar winds. This is similar to the foundation of the dynamo process described earlier. Plasma has high conductivity, allowing the conduction of magnetism through space. The term "frozen in" is used for the magnetic field when it is transported along with the plasma release (HAPGOOD, 2017, p. 17; MENK; WATERS, 2013, p. 2).

Solar winds are plasma that continually escapes from the coronal region of the Sun, as they overcome gravitation due to high temperatures[3], and do not pose a safety risk to aviation. They have average speeds ranging from 500 to 800 kilometers per second and, when they reach Earth, they interact with the Earth's magnetic field through the Lorentz force, shaping it and forming the magnetosphere (HAPGOOD, 2017; MENK; WATERS, 2013). However, due to the process of magnetic reconnection on the solar surface, the release of high-speed solar winds may occur, disturbing the Earth's geomagnetic field (ICAO, 2019a). In this context, they are the main responsible for the aurora, which is the manifestation of space weather visible to the eyes and is the absorption and conduction of solar energy by the ionosphere.

The rotation of the Sun interferes with the release of solar winds so that, when they emerge from the atmosphere, they follow a trajectory similar to the water from a garden sprinkler, as shown in Figure 2. The shape of this trajectory is also known as the "Parker Spiral"(MENK; WATERS, 2013). This term emerged in the 1950s and was created by Eugene Newman Parker when he was studying such solar phenomena.

Figure 2 - Schematic of the solar wind trajectory.



Source: (HAPGOOD, 2017, p. 7).

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[2] Translation of: "The physical and phenomenological state of the natural space environment, including the Sun and the interplanetary and planetary environments".

[3] It is believed that the release of kinetic energy, through magnetic reconnection, is the cause of the rise in temperatures in the solar corona, which reach a million Kelvin, compared to 6000K at the surface (HAPGOOD, 2017).

CMEs are solar winds in the form of plasma clouds that have very high energy, with mass that can have billions of tons and speeds of up to 3,000 km/s. They can reach Earth in less than a day, or even more than 4 days, after their release from corona. CMEs have targeted release and the chance of hitting Earth is small. They represent a great risk to aviation and technologies, as they can trigger geomagnetic storms, which are disturbances in the Earth's magnetic field, due to the absorption of plasma in the magnetosphere, which generate magnetic reconnection cycles on the side of the globe opposite the Sun. These cycles send plasma back to the planet and can be called the Dungey Cycle or sub-storms. Due to the process, a large amount of energy is dissipated in the ionosphere, contributing to the physical characteristic alterations of the satellite signals, when they cross this atmospheric layer. This reduces the accuracy of aircraft positioning (which can lead to loss of positioning) and harms HF and SATCOM communication systems (HAPGOOD, 2017; ICAO, 2019a; MENK; WATERS, 2013; NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION, [s.d.]).

Another process triggered by geomagnetic storms is the induction of ground currents (GIC[4]), that can affect electrical infrastructure such as power grids and rail systems. Great losses would be generated if these systems were damaged, as detailed in TAKAHASHI et al., (2015, p. 33).

Solar flares are energy emissions on a smaller scale in the form of electromagnetic radiation (EUV wavelengths and X-rays[5]). Energy deposits are fast, reaching the Earth in minutes. Deposit occurrence is related to CMEs, as they can be an antecedent indication of the coronal ejection release, but they can also occur separately. They have the potential to influence, only in the regions of the Earth illuminated by the sun, the HF communications and monitoring systems, which use frequencies between 1-20 Mhz, onboard electrical systems and crew health. In the polar regions, their effects are greater, due to the terrestrial magnetic behavior that allows greater deposition of protons at higher latitudes. Through this characteristic, the radiation reaches lower altitudes and interferes more significantly in HF communication systems, mainly on arctic routes, used for flights between America and Asia. Radiation can also be received at low latitudes and altitudes[6], due to more complex equatorial ionospheric phenomena (HAPGOOD, 2017; ICAO, 2019a).

The number of electrons deposited in the ionosphere, after the arrival of the plasma, has a unit called TEC (Total Electron Content). TEC values are determined by the number of electrons in a 1m^2 column between a satellite signal and its receiver, which traverses the ionosphere. The TEC variation causes a proportional oscillation in the electronic balance of the ionosphere, causing changes in the speed, polarization, phase and amplitude (ionospheric scintillation) of the radio waves propagated by the GPS. Changes may indicate erroneous position of the receiver, as well as loss of satellite signal (AGUIAR, 2010; COSTER; KOMJATHY, 2008). One unit of TEC, equal to 10^{16} electrons/m^2, corresponds to 0.163 m of delay in gauging the position of the receiver. Therefore, it is a good indicator for the quality of the positioning. TEC varies regularly due to the sunspot cycle, time of year, time of day and geographic location (KOMJATHY et al., 2003).

These ejections of solar energy occur most frequently in a cyclical period of the Sun's activity, when there is greater activity. This cycle of greater activity lasts approximately 11 years (GOSLING, 1993; WEBB, 1991). Solar activity is directly proportional to visible sunspot groups, which are constantly monitored by observatories, such as NASA, SOHO and STEREO-A space agency satellites. During the period of maximum activity, solar flares are emitted, on average, 25 times a day and CMEs, 5 times a day. Energy density is released similarly between solar flares and CMEs. However, the chance of Earth being influenced by a CME is lower as it has a targeted release. In contrast, the damage would be greater through the CMEs due to the strong magnetic field attached to the plasma (HAPGOOD, 2017; ICAO, 2019a; NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION, [s.d.]).

2.2 Cosmic Radiation

Cosmic rays, which come from outside the solar system, hit the Earth constantly, with intensity that varies little with the passage of time. The interference of cosmic rays on Earth is inversely proportional to solar activity, as CMEs and solar flares interact with cosmic radiation in order to reduce their interaction with the Earth's atmosphere.

Like solar radiation, their effects will be greater at higher latitudes (above 55° magnetic latitude), cas at

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[4] Stands for Ground-Induced Currents.

[5] EUV stands for Extreme Ultraviolet with a wavelength range of 10nm – 121nm (nanometers). X-rays are 1nm – 20nm.

[6] Close to flight level 300 (10-12km).

the poles, and increase with altitude, peaking between 60-65,000 feet. Depending on the intensity, they can be harmful to electronic equipment on board and, with long exposure, to the crew health (ICAO, 2019a; NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION, [s.d.]).

2.3 Brazil

Brazil is one of the regions in the globe with the greatest ionospheric influences and the greatest values and variations of TEC. It is located in an equatorial region and part of its territory is close to SAMA (South Atlantic Magnetic Anomaly). The magnetic equator presents, together with the poles, greater ionospheric irregularities, mainly after the local sunset, with more often scintillations in the satellite signal frequency. These irregularities are caused by the increase of the ionospheric electric field in the post-evening period, due to a greater movement of the plasma (Fountain Effect), also giving rise to plasma bubbles (SPOGLI et al., 2013).

SAMA is a region where the geomagnetic field has the lowest intensity values, contributing, similarly to the poles, for a larger deposit of radiation. Such characteristic allows greater disturbance in the ionosphere, which also contributes to scintillation in GNSS satellite signals(SPOGLI et al., 2013). This ionospheric behavior over Brazil is very harmful to positioning accuracy (KOMJATHY et al., 2003; MATSUOKA; DE OLIVEIRA CAMARGO; BATISTA, 2006).

3 TECHNOLOGIES FOR AVIATION THAT REDUCE SPACE WEATHER EFFECTS

ICAO (International Civil Aviation Organization) requires that systems related to air navigation have accuracy, integrity, availability and continuity for all phases of flight. These requirements are set out in Annex 10 of the Convention on International Civil Aviation through SARPs (Standards and Recommended Practices). New technologies were required in order to meet these demands on navigation performance, through advances in research related to space weather.

In 2003, in the USA, SBAS (Satellite Based Augmentation System) was certified, called WAAS (Wide Area Augmentation System). It is a positioning augmentation system, focused on correcting the ionospheric effects in the American territory, in addition to satellite clock delays and orbit errors. The systemconsists of ground GPS stations, with their positions precisely defined and that measure, continuously, the differences in relation to the satellite calibration. These data are sent to a central station, which generates the corrected messages. The messages are transmitted to geostationary satellites which, in sequence, relay to the receivers on board the aircraft. With this system, the aircraft are able to perform precision procedures through the LPV (Localizer Performance with Vertical Guidance) in different locations across the American territory, where there are no radio aids for navigation (COSTER; KOMJATHY, 2008; FAA, 2019).Similar to WAAS, there are other systems that make up SBAS and operate in the same way. In Japan, MSAS (MTSAT Satellite Augmentation System) is used since 2007. In Europe, EGNOS (European Geostationary Navigation Overlay Service) system is used since 2011. GAGAN (GPS Aided Geo Augmented Navigation), certified in 2014, is used in India. The four systems mentioned above are operational, while other are under implementation, such as SDCM (System for Differential Corrections and Monitoring) in Russia and SNAS (Satellite Navigation Augmentation System) in China (DENNIS; HEMSTA D, 2016). The operating systems are part of IWG (Interoperability Working Group) and meet ICAO requirements to offer augmentation services with free transition between them. Therefore, precision improvement technology is unified across the hemisphere (EUROPEAN SPACE AGENCY, 2011).

The ground-based augmentation system (GBAS) is a second GNSS augmentation system designed to improve positioning accuracy through differential corrections by ground equipment. Through this system corrections, the common ionospheric errors become negligible. When the system is installed at airports, precision instrument approaches and landings can be performed, called GBAS Landing System (GLS). Depending on the type of GBAS (GAST) approach service, approaches can be performed with even greater accuracy (CAT II/ III). For example, in the USA the GBAS systems are LAAS (Local Area Augmentation System) and SLS (Satellite Landing System),developed by the Federal Aviation Administration (FAA) and Honeywell, respectively. The first GBAS was approved in 2012 at NewarkInternational Airportin the United States (YOON et al., 2019).

In addition to these augmentation technologies, the vast majority of commercial aircraft have a reversing system, in case the GNSS signals fail. The aircraft position will be determined based on the combination of signals from the aircraft inertial system and radio signals (VOR/DME). The crew can make exclusive use of conventional navigation or, if there are no radio signals available in the region, the crew can ask ATC for assistance. These are reduction strategies as long as there are no appropriate contingency procedures for the occasion (EUROCONTROL, 2020; ICAO, 2018).

4 REMAINING INTERFERENCES IN AVIATION

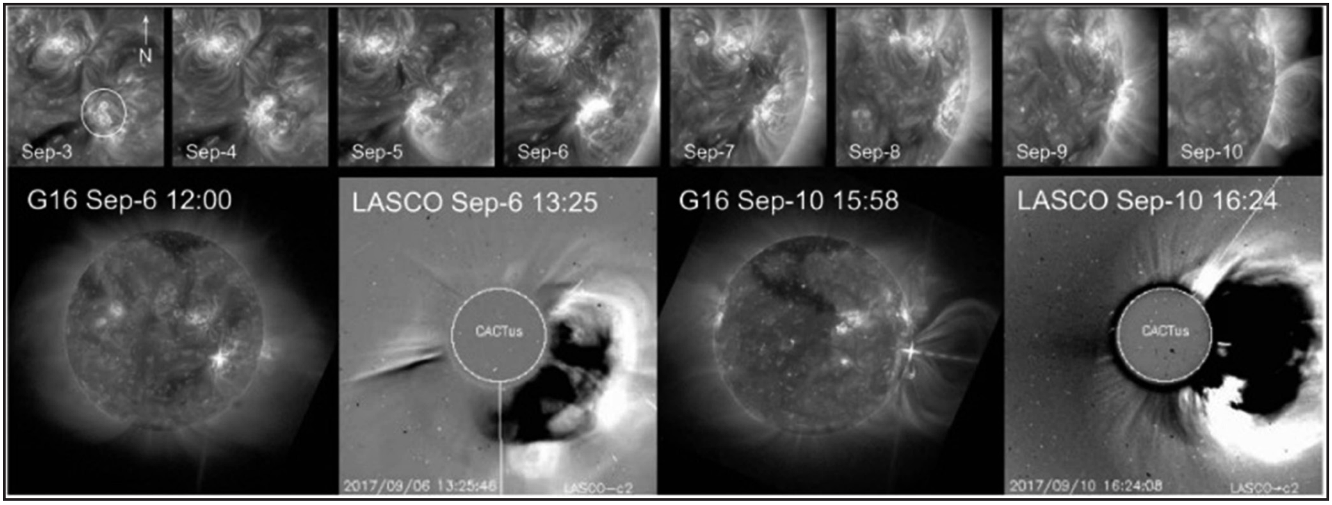
On October 29, 2003, the event, known as Halloween Storms, began and hit several regions of the United States. The event disabled the WAAS precision approach service, which was unusable for 15 hours on the 29th and for 11.3 hours on the 30th (DOHERTY; COSTER; MURTAGH, 2004).

In December 2005, there was disruption to GPS navigation systems that lasted 10 minutes, causing disorientation in aircraft, ships and oil rigs (BARBOSA, 2015). On November 4, 2015, the Swedish air traffic service reported that aircraft were not showing up on their radars. The problem lasted approximately 1 hour and it was caused by a solar storm (BLAŠKOVIĆ, 2015).

On September 3, 2017, an event overlapped the US and Europe SBAS. The solar region categorized as region 46 of the Catania group, which is a denomination given by the American agency NOAA (National Oceanic and Atmospheric Administration), initiated a more complex magnetic activity, generating a series of solar flares and CMEs, whose effects were felt on September 6th, 7th and 10th (REDMON et al., 2018). In Figure 3, there are images of this solar activity development. A solar wind of magnitude X9.3[7] was emitted in the region. One of the strongest solar winds occurred in September 2005, with intensity X17[7] in solar cycle 23 (REDMON et al., 2018). During the event occurred in 2017, the most severe warnings were issued by NOAA for the risk of loss of communications, geomagnetic storms, and high particle radiation. Loss of in-flight HF communication was reported on the 6th and loss of capability for WAAS and EGNOS LPV procedures on the 8th (REDMON et al., 2018). In addition, during this period, the Caribbean communities were facing Hurricane José. Due to the space weather event, they had difficulties in relation to the communication services for emergency response, which were reported by HWN (Hurricane Weather Net) and DGAC (French Civil Aviation Authority) (REDMON et al., 2018).

There was a considerable reduction in the European EGNOS augmentation system availability in 2017, as shown in Figure 4. On September 6, there was a loss of approximately 10% of the availability rate, which affected the safety of LPV procedures (BERDERMANN et al., 2018). This decrease occurred because CME hit the planet, deposited plasma in the ionosphere region and suddenly increased TEC values. That makes it difficult for receivers to maintain signal corrections and, in most cases, loss of connection between the satellites occurs. This loss is called "loss of lock" (BERDERMANN et al., 2018).

Figure 3 - Evolution of solar eruptions captured by SDO, GOES and SOHO sattelites, between 3 and 10 of September.



Source: (REDMON et al., 2018, p. 4).

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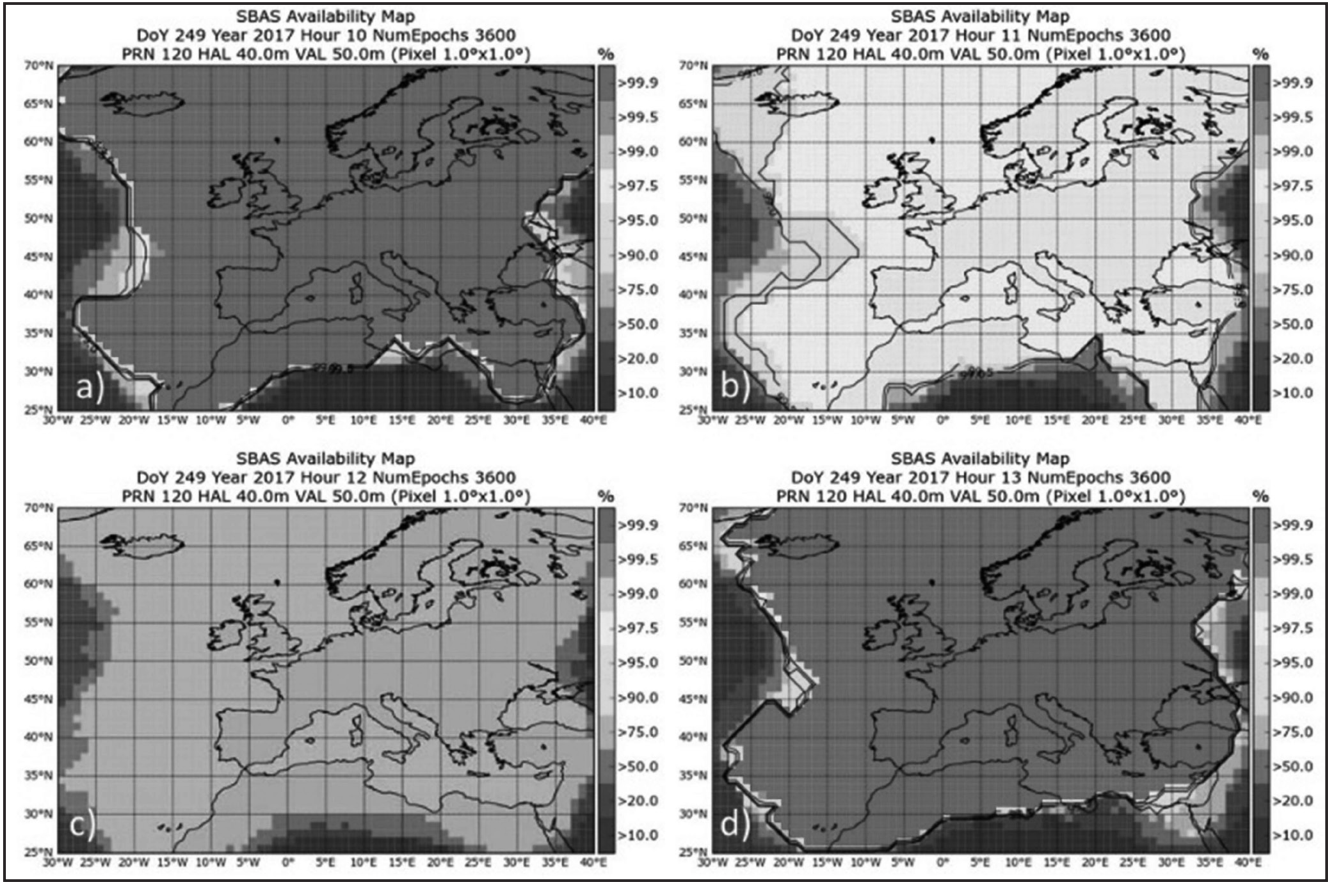
[7] NOAA scale, available on the SWPC portal (Space Weather Prediction Center).

Figure 4 - Scale map of European SBAS EGNOS availability between 10:00 and 13:00 (UTC) of September 6 2017. Darkest gray indicatess high availability and light gray indicates low availability.



Source: (BERDERMANN et al., 2018, p. 9).

A space weather event, similar to the one occurred in 1859, has never taken place again. In practice, damage is unknown, although there are some intensity predictions, as in (BAKER et al., 2013). Using a predictive model, the damage that a CME could have done to the planet was measured in 2012. This CME did not reach the globe as a matter of a week of solar rotation. Through the method, the authors concluded that the intensity of the coronal ejection had been more intense than the one occurred in 1859, Carrington event, and damage similar to the analogy of (NATIONAL RESEARCH COUNCIL, 2008): that society would still be "picking up the pieces"[8] (BAKER et al., 2013, p. 590).

5 MONITORING SCOPE OF THE CURRENT SPACE WEATHER

The damage caused by space weather, as well as the potential damage, generated initiatives aiming to understand its origin, carry out observations, collec data and predict phenomena. Currently, the central world organization for aviation that carries out studies on this subject is the WMO (World Meteorological Organization). It works along with ICAO, improving the world forecasts issued by the WAFS (World Area Forecast System). Nowadays, the main objective is to reduce the space weather impacts (WORLD METEOROLOGICAL ORGANIZATION, [s.d.]).

There are some information delivery organizations in the USA, such as SWPC (Space Weather Prediction Center), under the administration of NOAA. At this center, daily scales that demonstrate technologies and systems affected by space weather events are available on the website <https://www.swpc.noaa.gov>. There are three measurement scales: impact on radio systems (HF and satellites); levels of radiation from solar storms and levels of geomagnetic storms (NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION, [s.d.]).

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[8] Translation of "picking up the pieces".

In Europe, a program was created by ESA (European Space Agency) in 2009 to improve users' awareness on the dangers of space. It was called SSA (Space Situational Awareness). From this program, a segment linked to the global security, called Space Weather Office, was created to study the space weather, aiming to reduce its effects. Within this segment, ESA Space Weather Service Network is under development and aims to provide products and services from five different areas to users. These five areas are managed by experts and are divided into: solar climate, heliosphere climate, space radiation, ionospheric climate and geomagnetic conditions. One of its main objectives is to provide more accurate and reliable products (EUROPEAN SPACE AGENCY, [s.d.]). In Brazil, some initiatives were also created to study and develop technologies in order to face the influences of space weather. EMBRACE program (Brazilian Study and Monitoring of Space Weather) was created by INPE (National Institute for Space Research) in 2007, aiming to propose alert mechanisms and defense procedures for satellite communication systems, GNSS, flight safety systems, large-scale energy systems, satellite protection and altitude control systems, among others. Daily scales, that demonstrate the potential damage to technologies, are available on the website <www2.inpe.br/climaespacial/portal/pt/>. Such availability is similar to NOAA through SWPC.The project is part of DIDAE (Division of Aeronomy), one of INPE projects, which also has other research initiatives, such as the EQUARS project (Equatorial Atmosphere Research Satellite), focused on monitoring and studying the equatorial region (NATIONAL INSTITUTE FOR SPACE RESEARCH, [s.d.]).

Brazil also has a robust infrastructure of station networks that monitor GNSS signals, mainly from the GPS and GLONASS constellations. It is made up of the Brazilian Network for Continuous Monitoring of GNSS (RBMC), the network of CIGALA and CALIBRA projects, LISN and GNSS-NavAer. The effects that the ionosphere, close to the magnetic equator, imposes on the positioning, are analized and studied, in order to better understand its characteristics and develop more accurate and reliable technologies, as well as new positioning methods. The Brazilian Network for Continuous Monitoring of GNSS (RBMC), under IBGE administration, has GNSS stations since 1996, which continuously store the code and phase observations of the carrier waves transmitted by the satellites of the GPS or GLONASS constellations (IBGE, [s.d.]) and the data are commonly used in research.

The CIGALA project (Concept for Ionospheric Scintillation Mitigation for Professional GNSS in Latin America), funded by the European Commission (EC)of the European GNSS Agency (GSA), was created to develop and test technologies to reduce ionospheric scintillation in South America, through GNSS ground stations. This project focused on analyzing the potential effects of the period of maximum solar activity in 2013. The project started in March 2010 and was concluded in February 2012. Such project was continued by the CALIBRA project (Countering GNSS high Accuracy applications Limitations due to Ionospheric disturbances in Brazil) whose objective was evolve the corrective algorithms for high precision GNSS positioning techniques, expanding the number of GNSS stations of the previous project CIGALA and was completed in February 2015 (AGUIAR, 2010).

LISN (Low-Latitude Ionospheric Sensor Network) is an international project which studies the ionospheric phenomena, through geophysical instruments which are located in South America, close to the magnetic equator and up to the 70°W meridian. There are several institutions, which cooperate with LISN and researchers from INPE as Brazilian representatives (GEOPHYSICAL INSTITUTE OF PERU, [s.d.]).

The GNSS-NavAer was created by the NIST (National Institute of Science and Technology) in 2017. The main objective is to improve the theoretical knowledge of ionospheric influences on the GNSS signal, for safe application in air navigation. It has GNSS network stations for collecting ionospheric data, called GNSS NavAer network, and are spread throughout the Brazilian territory, as illustrated in Figure 5. There are several institutions which cooperate with the project, including UNESP, INPE, ITA and UFRGS (NATIONAL INSTITUTE OF SCIENCE AND TECHNOLOGY, [s.d.]).

In June 2017, the States were questioned by ICAO about their interest in cooperating with information on space weather. From the States which showed interest,

Figure 5 - GNSS NavAer Network Station Map.

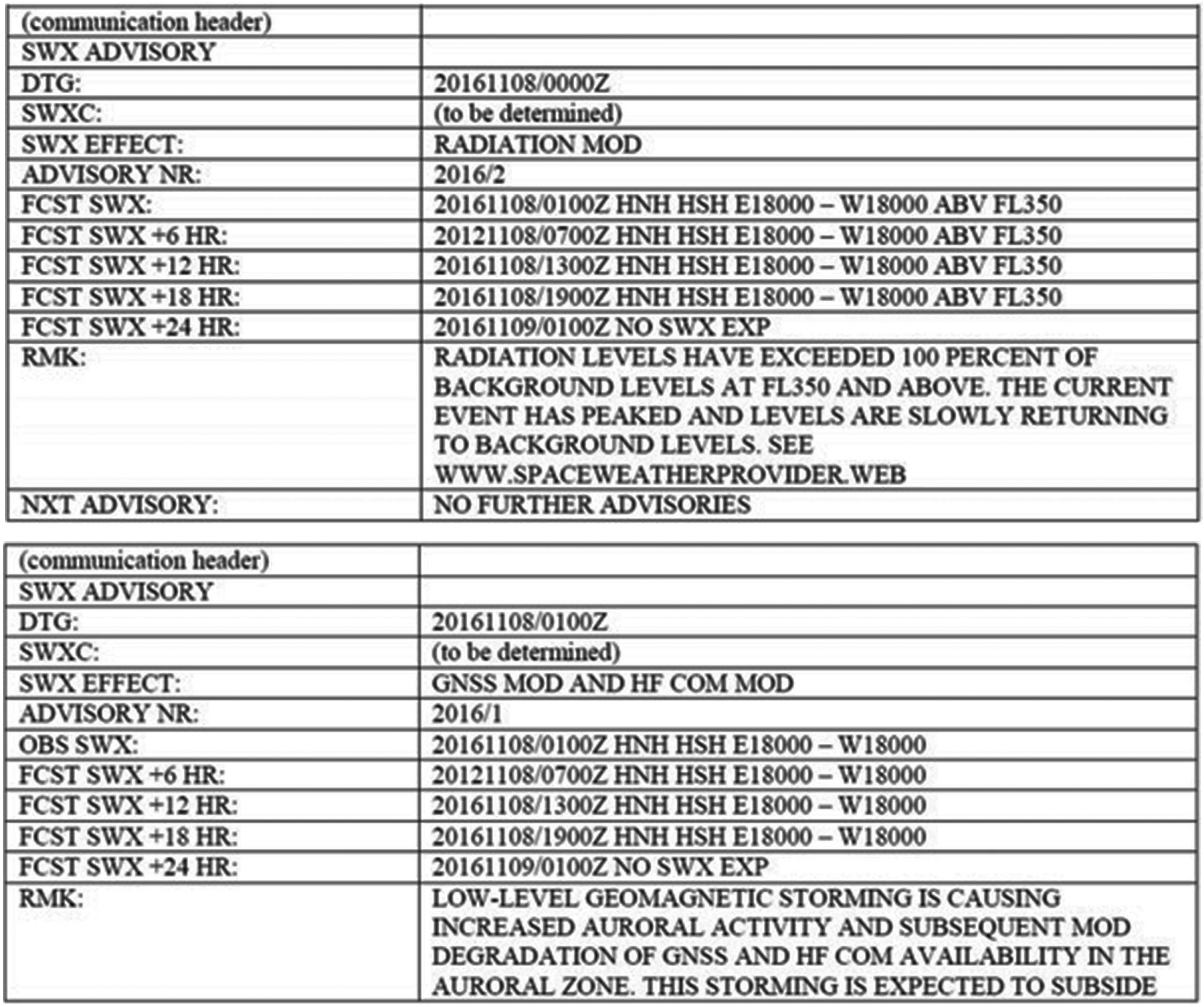
Source: NATIONAL INSTITUTE OF SCIENCE AND TECHNOLOGY, [s.d.].

three global centers were designated by ICAO council in November 2018: PECASUS (Finland, with partners from Belgium, Austria, Italy, England, Cyprus, Poland, Netherlands, Germany and South Africa), SWPC (NOAA, USA) and ACFJ (consortium between Australia, Canada, France and Japan) (ICAO, 2019b). The centers, named SWXC, without hierarchy, would commit to monitoring and providing information and recommendations, issuing warnings of space weather events that may affect communications, GNSS-based navigation and monitoring systems, as well as cases of radiation risk to the crew. The recommendations must follow the international regulations of the Convention on the International Civil Aviation, set out in Annex 3 – Meteorological Service for International Air Navigation. A guide material on space weather was released in 2019 by ICAO for aviation users specifically – Document 10100, Manual on Space Weather Information in Support of International Air Navigation(ICAO, 2019b).

Therefore, after the amendment 78 of Annex 3 to the Convention, in use in November 2018, thedocumentation required in the pre-flight includes the specification,of information related to the relevant weather events to the route, issued by SWXC. The language of information is abbreviated and the effects on HF communications, satellite communications (SATCOM), GNSS degradation and radiation exposure are classified, respectively, as HF COM, SATCOM, GNSS and RADIATION. Regarding to the intensity of the phenomena, MOD is used for moderate and SEV is used for severe. Examples of the messages issued are listed in tables I and II.

In accordance with the amendments to Annex 3, Brazil, through Ordinance 335 of January 25, 2021, established a technical-scientific cooperation between INPE and DECEA, through EMBRACE and CIMAER (Integrated Aeronautical Meteorology Center) respectively. The cooperation aims to improve the Aeronautical Space Meteorology Service, providing information and advice on space meteorological phenomena, as recommended in Annex 3, in order to become a regional SWXC in South America (BRAZIL, 2021; NATIONAL INSTITUTE FOR SPACE RESEARCH, 2021).

Tables 1 and 2 - Examples of event warnings that can be issued by SWXC.



(communication header)	
SWX ADVISORY	
DTG:	20161108/0000Z
SWXC:	(to be determined)
SWX EFFECT:	RADIATION MOD
ADVISORY NR:	2016/2
FCST SWX:	20161108/0100Z HNH HSH E18000 – W18000 ABV FL350
FCST SWX +6 HR:	20121108/0700Z HNH HSH E18000 – W18000 ABV FL350
FCST SWX +12 HR:	20161108/1300Z HNH HSH E18000 – W18000 ABV FL350
FCST SWX +18 HR:	20161108/1900Z HNH HSH E18000 – W18000 ABV FL350
FCST SWX +24 HR:	20161109/0100Z NO SWX EXP
RMK:	RADIATION LEVELS HAVE EXCEEDED 100 PERCENT OF BACKGROUND LEVELS AT FL350 AND ABOVE. THE CURRENT EVENT HAS PEAKED AND LEVELS ARE SLOWLY RETURNING TO BACKGROUND LEVELS. SEE WWW.SPACEWEATHERPROVIDER.WEB
NXT ADVISORY:	NO FURTHER ADVISORIES

(communication header)	
SWX ADVISORY	
DTG:	20161108/0100Z
SWXC:	(to be determined)
SWX EFFECT:	GNSS MOD AND HF COM MOD
ADVISORY NR:	2016/1
OBS SWX:	20161108/0100Z HNH HSH E18000 – W18000
FCST SWX +6 HR:	20121108/0700Z HNH HSH E18000 – W18000
FCST SWX +12 HR:	20161108/1300Z HNH HSH E18000 – W18000
FCST SWX +18 HR:	20161108/1900Z HNH HSH E18000 – W18000
FCST SWX +24 HR:	20161109/0100Z NO SWX EXP
RMK:	LOW-LEVEL GEOMAGNETIC STORMING IS CAUSING INCREASED AURORAL ACTIVITY AND SUBSEQUENT MOD DEGRADATION OF GNSS AND HF COM AVAILABILITY IN THE AURORAL ZONE. THIS STORMING IS EXPECTED TO SUBSIDE

Source: (RUTLEDGE, 2020).

Despite the advances and available systems, some events are still unpredictable. Losses of HF communication, which occur in the Earth's daytime regions, happen without warning. More intense radiation, caused by a solar storm, can be predicted, but sometimes it is fast and reaches people and systems without prior preparation (ICAO, 2019a).

6 NEW INITIATIVES

Advances in the studies of space weather and its effects on technologies follow scientific and technical paths. NASA and ESA are agencies that delve into the scientific subject, providing greater theoretical knowledge, through MMS and LaGrange space missions. In Brazil, INPE cooperation with DECEA constitutes the main source of research. Based on such knowledge, advances in the technical area started to exist, such as the creation of the GNSS SBAS DFMC system.

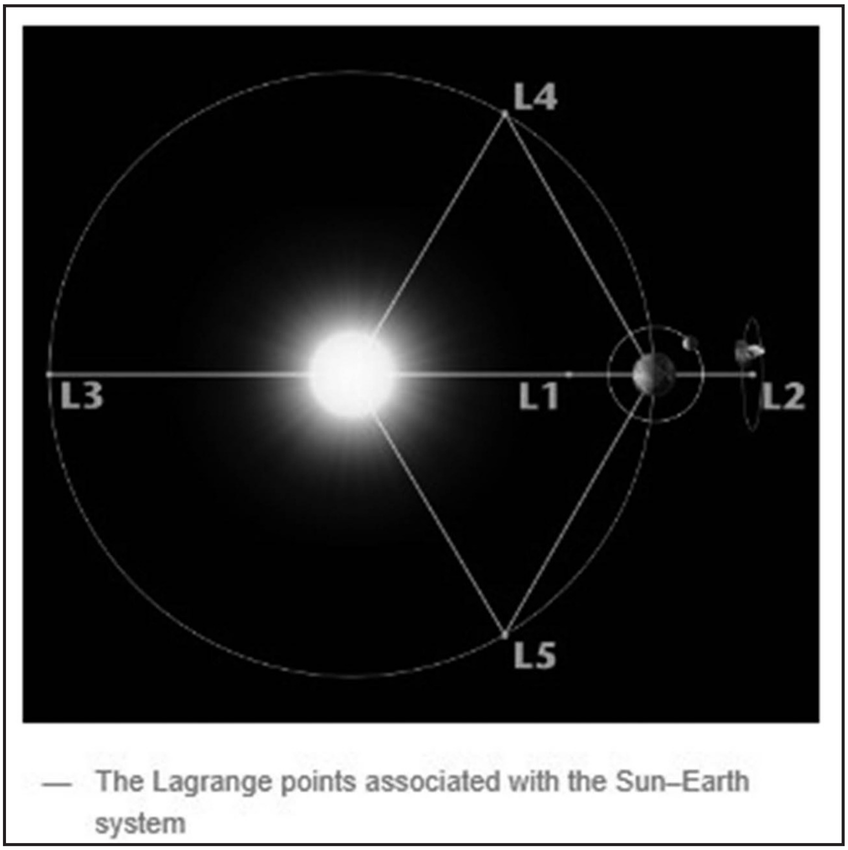
Currently, the positioning system used on an aircraft consists of a satellite constellation and a signal frequency. For GPS constellation, the frequency L1 (1575 MHz) is used, and there must be at least 4 satellites for three-dimensional gauging of the receiver position (ICAO, 2017). This system is used in PBN (Performance Based Navigation), ADS-B (Automatic Dependent Surveillance-Broadcast) and TAWS (Terrain Avoidance Warning System).

DFMC (Dual-Frequency Multi-Constellation) is a future system that aims to increase the robustness of the current SBAS of the GNSS. A frequency L5 (1176.45 MHz) will be added to the system. This will allow the integration between GPS, Galileo, GLONASS and BeiDou constellations. Through these implementations, this system will contribute to provide greater resistance against ionospheric scintillation and improve the geometry among satellites. DFMC is in certification process. The operation concept (CONOPS) for the system was developed by ICAO, in which it is described how it will be used in aviation in the coming years. The respective SARPs are expected to be validated in 2022 (ICAO, [s.d.]; RICARD, 2019).

In the scientific subject, NASA MMS space mission is composed of 4 aircraft that navigate in formation through the magnetosphere, a region where the Earth's magnetic field is present. It was launched in March 2015 aiming to study the phenomenon of magnetic reconnection. The 4 aircraft form a pyramid scheme, which allows the three-dimensional visualization of the magnetic phenomenon. From the success of the visualization, it is studied more clearly what it happens, with the aim of evaluating and develop the predictive knowledge about magnetic reconnection (NASA, [s.d.]).

LaGrange mission is a future scientific exploration concept by the European Space Agency (ESA). On the presentation website (EUROPEAN SPACE AGENCY, [s.d.]), it is stated by the agency that: "Providing timely and accurate space weather information, nowcasts and forecasts is possible only if sufficient observation data are continuously available"[9]. The mission aims at the LaGrange points of space, as shown in Figure 6. These are points where the Sun and the Earth's gravity forces interact on the points, in order to provide stability, that is, the objects do not orbit in these positions. There are five points with this feature on the heliosphere, identified as L1, L2, L3, L4 and L5. The mission is to place aircraft at points L1 and L5. The purpose of the first position is to improve interplanetary observations to assess the speed, densities, temperature and dynamic pressure of the solar winds.The objective of the aircraft in L5 position is to complement the aircraft observations in L1 and notice the plasma cloud propagation emitted by the Sun at a better angle, as well as observe the face of the preceding Sun before it faces the Earth.

Figure 6 - Scheme of LaGrange positions.



Source: (EUROPEAN SPACE AGENCY, [s.d.]).

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[9] Translation of: "Providing timely and accurate space weather information, nowcasts and forecasts is possible only if sufficient observation data are continuously available."

7 CONCLUSION

GNSS navigation system is projected to be the main feature of PBN (Performance Based Navigation) by 2030 (EUROCONTROL, 2020). Future plans for the system are defined at ICAO meetings, which include continuously increase of availability, forecasting and positioning integrity (SMAOUI, 2017). These improvements are necessary since the airspace, in non-contingency conditions, is increasingly dense and requires greater reliability.

One of the main threats to GNSS accuracy has a complex origin and is difficult to predict. The damage that can be caused in the most diverse technological networks is immeasurable, as there was no event like the one occurred in 1859. However, it is known among researchers that the material damages would be serious, deeply affecting the financial situation of the countries (BAKER et al., 2013; BERDERMANN et al., 2018; NATIONAL RESEARCH COUNCIL, 2008).

Current predictive systems are still not reliable, as there are solar phenomena that are not predictable (ICAO, 2019a). During the 2017 events, for example, the aviation community was not aware, and only received the alert that such service was unavailable (HF and LPV) (REDMON et al., 2018). It has been required by the European Union, in the coming years, that Air Navigation Service Provider (ANSP) creates contingency procedures if the only common global means of navigation (GNSS) fails. These procedures were extensively discussed in EUROCONTROL (2020) and reversal actions to conventional means were detailed, such as VOR/DME, besides procedures under ATC responsibility. The document will guide the creation of a second document in the future, which will be regulatory.

The new space missions led by NASA and ESA could convey a theoretical breakthrough on the topic, improvingpredictive capabilities. However, the studies are recent and others are still being analyzed, such as MMS and LaGrange, respectively.

In order to increase security, as well as to reduce the damage that can be caused by space weather, it is necessary to have greater awareness of thisphenomenon by the main users of threatened technologies, mainly by aviators. This topic is so relevant that some authors, such as BERDERMANN et al.(2018), REDMON et al., (2018) and HAPGOOD, (2017, p. 3), discuss the need for continuous improvement in learning and predictive knowledge on the subject.

Brazil does not have a reduction system for ionospheric effects similar to SBAS and GBAS for aviation. However, there are several researches and projects, such as the ones performed at INPE and INCT, which may bring new positioning methods to Brazil in the future.

In 2017, there was a meeting between DECEA and representatives of FAA, Boston College, companies like Mirus, Honeywell, Boeing and airline companies to discuss and design the GBAS certification at Galeão International Airport in Rio de Janeiro (GALEMBECK, 2017). In SURCO ESPEJO's work et al., (2020) the precision of the approach and landing phase of an aircraft was simulated at Galeão airport, in Rio de Janeiro. It was concluded that the GBAS augmentation system installed at the airportcannot be certified for use, due to the equatorial ionospheric effects,which reduce the instrument accuracy.

The Brazilian geomagnetic location is a contributor to greater negative effects if space weather events occur (SPOGLI et al., 2013). Therefore, weather space awareness in Brazil should be equal or greater in rigor.There is lack of knowledge on the subject in Brazil, as well as throughout society, including users of susceptible technologies. For HAPGOOD, (2017), this is a great challenge to be faced.

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