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Results of the space weather and aviation impact assessment survey

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Abstract
Space weather phenomena, which impact navigation and communication systems of our modern technological infrastructure, can influence flight operations affecting safety or efficiency of aviation. This study investigates these impacts with a comprehensive survey of industry professionals including 13 pilots. The results indicate that a significant amount of participants is familiar with space weather, but that specific impacts and potential risks are less understood. The results also show that communication between aviation stakeholders and space weather service providers in particular is perceived as lacking. This in turn has a negative impact on other issues, such as finding and using appropriate space weather services already in operation. The implications are discussed, highlighting a need for better communication between space weather service providers and aviation stakeholders, better space weather risk awareness, more in-depth space weather training and protocols as well as application-oriented space weather services. Thus, actionable instructions are provided to strengthen aviation's resilience to space weather events and to ensure dependable systems.

Keywords Space weather · Aviation · Air traffic management · User survey

1 Introduction

Space weather, driven by various processes of the Sun, constantly changes the conditions of Earth's near-space environment and can significantly impact key technologies of our modern infrastructure [20]. Especially space weather events, including coronal mass ejections (CME) and solar flares, can cause rapid, strong changes, that pose a threat to crucial systems in communication and navigation [9, 13]. Coronal mass ejections, on the one hand, release large amounts of plasma, that can disturb Earth's magnetic field, which in turn can cause geomagnetic and ionospheric storms, that effect the propagation of satellites signals including those of the Global Navigation Satellite System (GNSS). Solar flares, on the other hand, emit intense bursts throughout the solar spectrum, that directly interfere with high-frequency (HF) radio communication or that rapidly ionize Earth's upper atmosphere impacting the propagation of satellites signals as well [7].

These disruptions to communication and navigation systems [1, 16] have further implications for various applications, particularly transportation systems, which rely strongly on GNSS [26, 33]. The different modes of transportation, including aviation, maritime, rail, and road, are impacted each in their own way by space weather and therefore separate research and dedicated services or strategies are required to mitigate the negative effects [15]. Additionally, political and economic changes in recent years as well as ongoing development of new technologies (e.g. sector of unmanned aerial vehicle) increase the need of uninterrupted availability of key technologies like GNSS [10].

An additional space weather threat to aviation operations is the increased exposure to cosmic and solar radiation at high latitudes and in polar regions [2, 11, 19], which poses a risk to both, human health [5] and avionics [8]. Stronger fluxes of energetic particles penetrate the atmosphere in these regions along the magnetic field lines of the magnetosphere [21]. This can lead to elevated radiation doses for aircrews,

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particularly during solar particle events, or interrupt avionics and HF radio communications. Therefore, radiation hazards in these regions are a crucial concern for aircrew and general aviation safety.

Aviation operations and especially air traffic management can be significantly disrupted by space weather events, which in turn may lead to flight plan adjustments, delays, increased economic costs as well as additional stress for personnel like pilots and air traffic controllers [31–33]. The following scenarios pose a particular challenge in this regard. (1) Polar flights may be canceled or rerouted to airspace at lower latitudes during HF communication blackouts to bypass times of communication disruption [33]. (2) Flight distances may increase during GNSS disruptions, since aircraft cannot follow waypoints via GNSS and rely on ground-based navigation aids instead. The lack of precision approach capabilities during GNSS disruptions may also necessitate step-down descent procedures (instead of continuous descent) causing higher fuel consumption and lower operational efficiency. These impacts further may lead to decreased airspace or runway capacity [33]. (3) Anomalies in air traffic management systems like Automatic Dependent Surveillance–Broadcast (ADS-B) may occur [29] reducing the visibility and awareness of participants in shared airspace. Additionally, these anomalies complicate tracking and managing aircraft, which could compromise flight safety [33]. (4) Increased radiation levels during space weather events pose a health risks to both, aircraft crews and passengers. Therefore, flights may be canceled or rerouted to airspace at lower latitudes during such events [31, 33].

These challenges due to space weather impacts in aviation are focus of continuous research to increase our understanding of the interactions with technologies and to provide solutions that improve the resilience of these systems [15]. For example, the impact of radiation that poses a health risks to aircraft crews and passengers is investigated and modeled to predict times when rerouting to airspace at lower latitudes is required [3, 4, 12]. Anomalies in aircraft surveillance are analyzed within a broad context [25], but also with particular emphasis on human-made interference [17, 18] and space weather-driven processes [28, 29]. The impact of GNSS errors on air traffic management are also investigated [30] and improvements of Ground- and Satellite-Based Augmentation Systems (GBAS, SBAS) are developed to increase the reliability of GNSS navigation during precision approaches [6, 27].

As important as the research itself, is an understanding of the gap between the scientific knowledge of space weather and the awareness of non-expert users, such as pilots, and whether space weather alerts and forecast services are practical and meaningful for these end users. For that reason, an online-survey was conducted from 13 March to 28 April 2025 to gather insights and feedback from the public, industry professionals, or relevant stakeholders about their awareness, perceptions, and concerns regarding the impacts of space weather on aviation. By collecting these information, research priorities and specific needs for space weather products are identified. The survey also provides valuable feedback to support the development of policies, training material, safety protocols, and technologies aimed at mitigating the risks posed by space weather in aviation.

The present study summarizes the relevant results of this survey, defines the key findings and concludes recommendations. The aim is to provide actionable guidelines for space weather services. For that purpose, the survey and the reported results attempt to answer the following major research questions: (1) How do pilots and flight operators perceive the impact of space weather events on flight safety and operations? (2) What are the operational challenges or disruptions of aviation systems during space weather events? (3) What mitigation strategies and services are currently used in aviation to manage the risk of space weather, and how effective are they?

2 Method

The survey was conducted online using LimeSurvey via the Helmholtz Digital Services for Science with the aim of reaching as many users as possible while gathering relevant feedback about space weather impacts in aviation.

2.1 Survey participants

The survey was shared with various stakeholders in aviation: personal contacts including pilots, but also scientists with their own contacts in aviation, aviation organizations, pilot associations, other research institutes, aircraft industry, airlines, as well as aviation communities. Personal social media accounts (LinkedIn and ResearchGate), news blogs, the German Aerospace Center (DLR) Ionosphere Monitoring and Prediction Center (IMPC) website and the DLR website were also used to promote the survey. It should be noted that these outreach methods introduce a bias toward participants who are more familiar with space weather topics. To mitigate this, pilots (personal contacts) were encouraged to share the survey within their social networks, aiming to reach users with little or no prior interest in the topic. In general, it became apparent that requests to the industry remained unanswered. Personal contacts led to individual responses. The most successful were the posts on social media, which generally led to a variety of feedback. This broader outreach also ensured that the results are not biased towards pilots who are already more familiar than average with space weather and that different experiences are covered.

The survey has received 28 completed responses from 13 March to 28 April 2025. The breakdown of participants by professions is presented in detail in Sect. 3 with the other results verifying that the survey successfully caught the attention of pilots, but also other professionals in aviation. It should be noted, that the sample size is too small for a representative space weather impact survey and this limits the ability to generalize findings and reduces statistical strength. However, the results remain valuable because pilots offer direct expert insights into operational challenges caused by space weather. Thus, this small sample still allows to explore important topics.

2.2 Survey topics

The survey covers various topics with a total of 44 questions designed to be answered in about 10 to 15 min. The survey questions include a mix of yes/no, 5 point choice, multiple choice and open-text responses to gather a comprehensive range of feedback. Answering all questions was optional, so that participants could limit themselves to those topics and interests that were relevant to their work and expertise. The survey is organized into a total of eight groups of questions (see Appendix A), whose purpose is described as follows:

1. The topic *Space weather and its impact on aviation* investigates how the participants rate their knowledge of space weather and the technologies involved. The responses are meant to be compared with the questions of the following groups to determine whether there is an underestimation or overestimation of knowledge in the self-assessments.
2. The topic *Awareness of risks* investigates where the participants expect space weather to have an impact on technologies that are crucial for them.
3. The topic *Source of information* investigates which services and data are used by the participants to incorporate space weather information in their work.
4. The topic *Personal experience* allows participants to describe personal experiences with space weather in more detail.
5. The topic *Operational impact* allows participants to describe general processes in aviation that are impacted by space weather.
6. The topic *Training and protocols* investigates how participants rate space weather training and existing protocols for handling space weather events.
7. The topic *Needs and expectations* is further divided in four groups, which investigate the following topics: information and alerts, decision support, communication and coordination, as well as data.
8. The topic *General feedback* allows participants to give any other comments and to rate the survey itself.

The presentation of the results in Sect. 3 also follows this structure.

3 Results

In total, 20 of the participants stated their profession including 17 participants working in aviation and 13 pilots. Two scientists also took part in the survey as they are concerned with space weather in their work with unmanned aerial vehicles (UAV). Figure 1 shows the professions and operated aircraft in detail.

More than three-quarters of the participants come from commercial aviation and fly airliners. The majority of responses therefore represent the target group of our research. The other groups such as flight operators, aviation weather forecasters and crew resource management (CRM) trainers also offer interesting perspectives that are likewise very relevant for dealing with space weather in aviation.

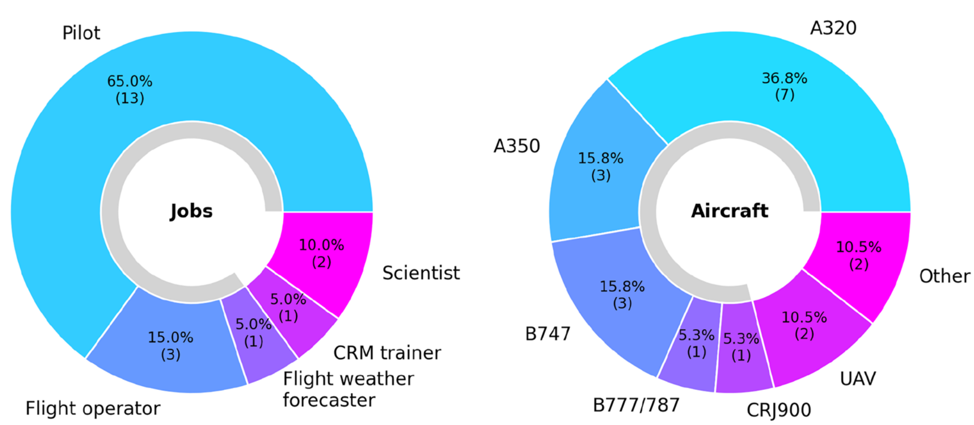


Fig. 1 Profession and operated aircraft of survey participants

3.1 Space weather and its impact on aviation

Figure 2 summarizes how participants rate their understanding of space weather and its impacts in flight operations.

The confidence of participants is generally very high, but slightly lower for the impacts of space weather on flight operations. However, the answers in the succeeding groups of questions show that these assessments do not necessarily reflect the actual level of understanding and that, for example, basic terms are mixed up or used incorrectly from a space weather perspective.

We noticed, for example, that space weather terms like solar flares and coronal mass ejections are mixed up by participants. From an expert space weather perspective, these are very different phenomena with different impacts. Such misunderstandings may not be relevant for dealing with space weather in flight operations, but it clearly indicates the need for a clear communication between both expert domains based on an agreed vocabulary. Another example of such miscommunication in the survey is noted by a participant, who asks which term, forecasted or observed, is correct, as "for [them] observed means observed on aircraft activity". In this case, the term was used in the survey from a space weather perspective and the corresponding questions were possibly understood differently by the participants than intended.

3.2 Awareness of risks

This group of questions summarizes how participants rate their understanding of space weather impacts on specific technologies applied in aviation.

The results of the five major questions shown in Fig. 3 vary with different tendencies. There are also participants who are not familiar with the impact on certain technologies at all, which conflicts with the generally high ratings in Fig. 2.

The highest rated category covers the impact of space weather on the Global Positioning System (GPS) with a strong tendency towards a complete understanding. The impacts of geomagnetic storms at high latitudes and the effects of solar bursts are also highly rated and assumed as well understood. The tendency for these two categories is less pronounced though. Thus, participants are generally confident about their understanding of impacts on communication and navigation in aviation. Nevertheless, one participant notes that "very precise navigation, i.e. [authorization required] approaches are a serious concern when a solar flare may disrupt GPS capabilities, and later on human response may not be completely trained or informed and up to dated to deal with an undesired event". Despite awareness of space weather and the availability of tools to mitigate its impact, the participant is unsure whether these are actually implemented or fully utilized during operations.

The lowest rated category covers the impact on GBAS and SBAS with a small positive trend. Three participants specifically mention that they would prefer to be better informed about space weather impacts on these and related systems (e.g. on-board internet access via satellite communication).

The potential risks of solar radiation is lower rated and has a strong tendency towards moderate ratings. One participant notes that "it may be that the radiation risks of higher solar activity are under-communicated and over-estimated compared to normal activity". This highlights a problem: pilots may lack the specialized background needed to accurately interpret the information provided on this topic.

Participants also ask for information on past events, "real impact" information in addition to International Civil Aviation Organization (ICAO) advisories and educational programs for pilots. These sentiments and wishes continue to appear throughout the follow-up groups of questions.

In general, the responses to the specific topics in Fig. 3 do not differ significantly from the overall assessment in Fig. 2a (especially considering the small sample size). Nonetheless, breaking down these topics is important to assess their relevance. Future surveys with larger sample size and thus more robust results may be able to directly identify priorities for focused research.

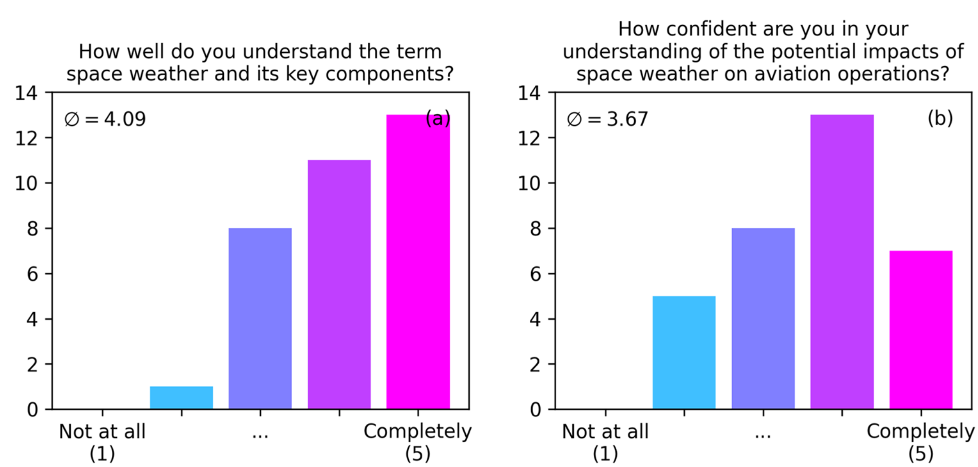


Fig. 2 Self-assessment of participants about space weather and its impacts in aviation

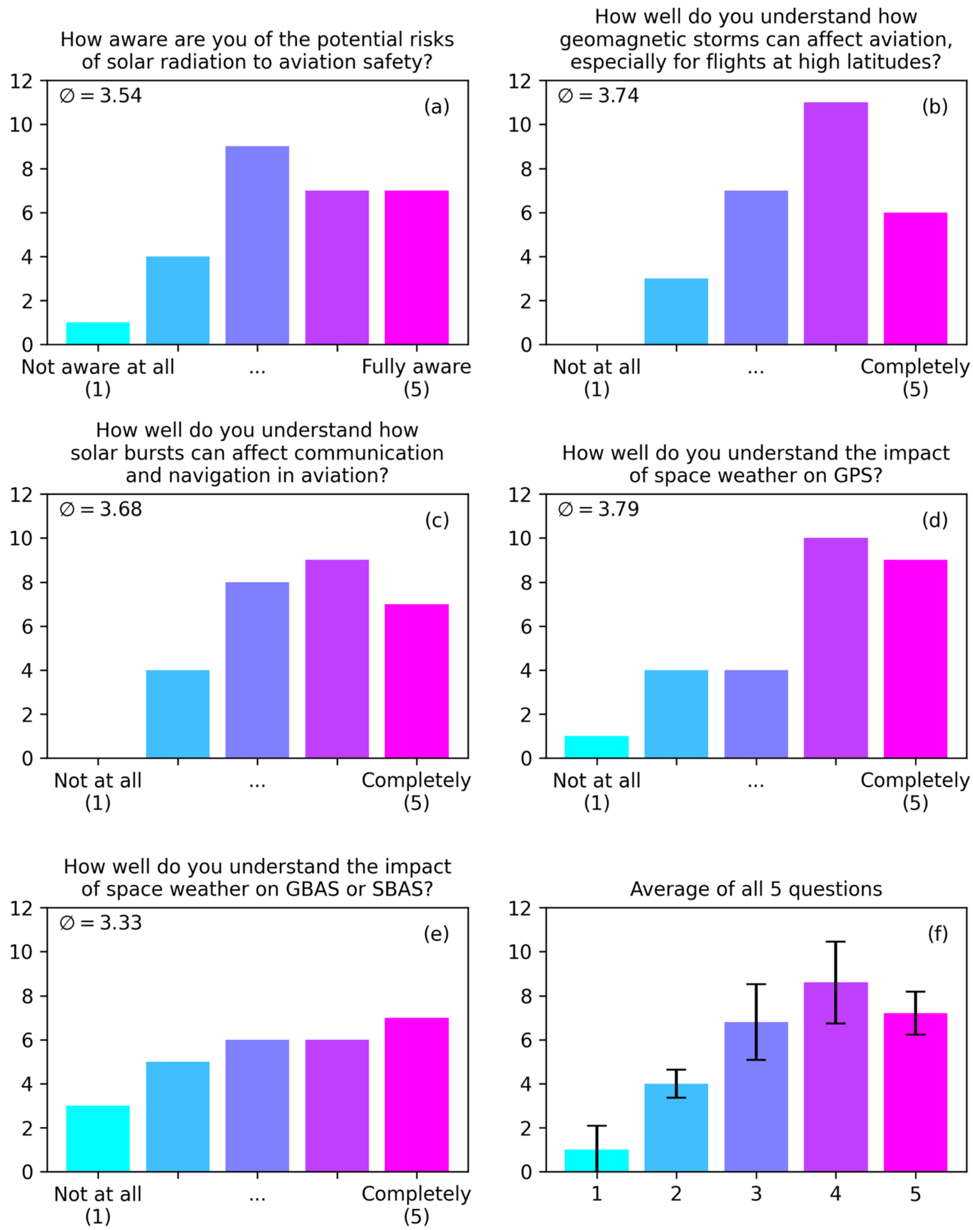


Fig. 3 Self-assessment of participants about specific space weather impacts

3.3 Source of information

This group of questions explores how space weather data are used in aviation-related tasks. As shown in Fig. 4, only a small number of participants currently incorporate space weather data and services into their work.

Consequently, space weather services – including some with aviation-specific dashboards – have not yet achieved meaningful engagement with these users.

Figure 5 shows the various space weather services used.

Around 15% percent of participants understand ICAO as their space weather information provider, which distributes data through a rotation among four global service providers: the Space Weather Prediction Center (SWPC), the Partnership of Excellence for Aviation Space weather User Service (PECASUS), the Australia-Canada-France-Japan (ACFJ) consortium, and the China-Russian Federation Consortium (CRC). Participants also highlighted SWPC and PECASUS as a source of information (approximately one-third) indicating that they are less familiar with the two other providers and possibly the rotation of the on-duty shifts. The European Geostationary Navigation Overlay Service (EGNOS) and Wide Area Augmentation System (WAAS) amount to approximately one-quarter. A bias in the responses for European and North American services is not surprising and in general SWPC is used more frequently by participants than other services. This may be due to its larger public presence. A smaller number of participants also accounted

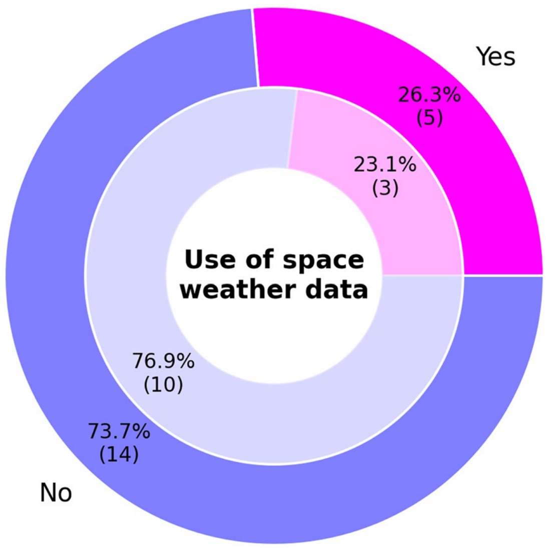


Fig. 4 Amount of participants using space weather data for their work. The inner circle shows the results for only pilots

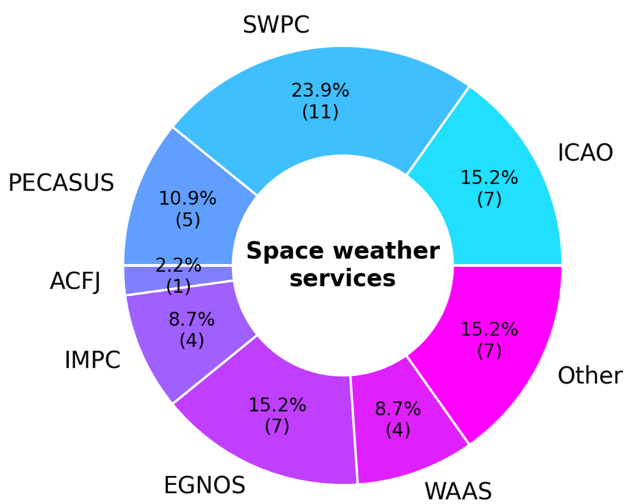


Fig. 5 Major global and local space weather services used by participants

regional services like the IMPC which integrates its services into PECASUS or ESA's Space Weather Service Network. The strong connection between the services is therefore confirmed by the fact that this study conducted by the IMPC had participants who use a large number of these services. Other services that are mentioned by participants include specific electronic flight bag (EFB) software, applications for other mobile devices and briefing documents provided by airlines.

Figure 6 summarizes how participants rate their familiarity with space weather services.

Interestingly, a significant amount of the participants state that they do not have good access to space weather information and four participants further state that they are unable to access them at all. Three of these participants are also pilots. This further confirms that users in aviation do not fully engage with the available services. Overall familiarity with space weather services is moderate, with three pilots reporting no familiarity with such services at all. For space weather services offering aviation-specific forecasts (e.g. aviation dashboard by ESA's Space Weather Service Network), a bimodal distribution is observed, with a larger amount of participants unfamiliar with these services compared to those who are familiar.

3.4 Personal experience

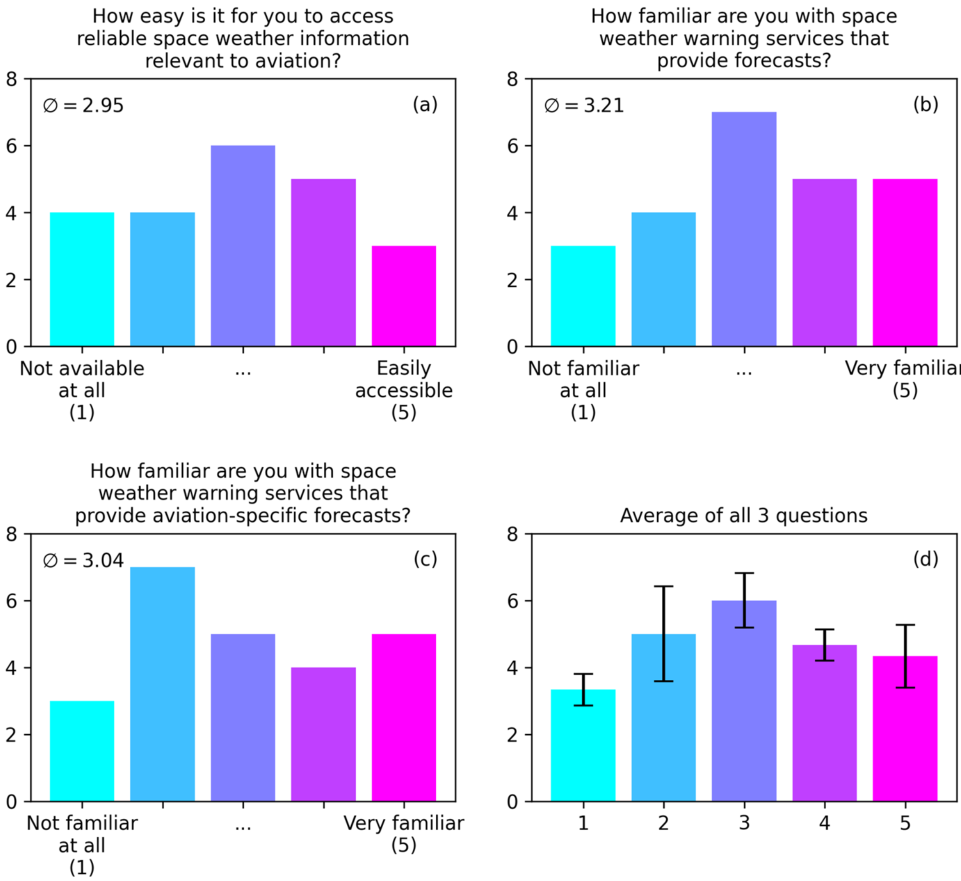
The following two groups of questions include a significant number of open-text responses, which participants generally tended to avoid. However, six participants took the time and effort to provide detailed descriptions of their experiences, offering valuable insights into how they perceive the impact of space weather during their work. Figure 7 shows how these six in-depth reports (magenta shading) are the major contribution to this group of questions.

Participants described a range of personal experiences related to space weather impacts, including four reports of HF communication failures, two reports of satellite communication (SATCOM) issues, and one report of momentary location-specific alarms triggered by space weather. Unfortunately, participants did not clarify how they became aware of these events, whether they received timely warnings, or how those warnings were communicated. These questions should be included in future surveys for a more comprehensive understanding.

Participants described further the procedures followed during these events, including three reports of flight level adjustments, two reports of avoiding high latitudes or specific regions, and one report of rerouting. One participant also describes that their airline has a dedicated team that responds to space weather events and provides pilots with appropriate instructions. This is the only instance of established and standardized procedures reported by a participant. Information used during these personally experienced space weather disturbances was received by two participants through ICAO, and one participant used information from SWPC. This corresponds well with the results in Fig. 5.

All six in-depth reports confirm that they were involved in decisions and procedures related to mitigating space weather risks during operations including instances where space weather led to changes in flight routes or flight level adjustments. Other participants, however, do not share such experiences. A comparison of these two groups, in relation to the previous questions, reveals that participants with personal experience are generally more familiar with space weather services and utilize a wider range of services (approximately 14% higher ratings).

Fig. 6 Role of space weather services for participants



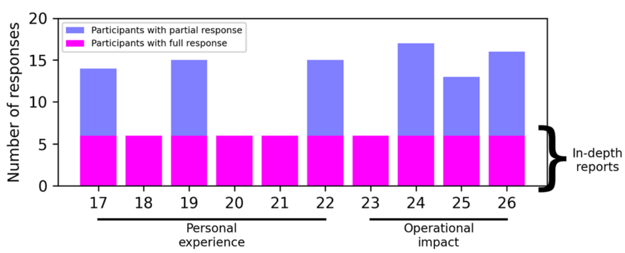


Fig. 7 In-depth reports throughout questions about personal experience and operational impact. Questions and two question groups are identified according to Appendix A

3.5 Operational impact

The trend observed in the preceding group of questions continues with the questions about operational impacts. While many participants submitted text responses, the majority could be summarized with one pilot's statement, "This has never happened", when asked about space weather-related disruptions during operations. However, a few responses offer more detailed insights into disruptions that had occurred.

For the frequency and severity of disruptions, participants note that HF failures occur between one to three times a year with durations up to two hours. Similar numbers are stated by several participants and some of them also mention specific regions (high latitudes, Atlantic and Europe) where they observed these disruptions. One participants specifies even further that "EGNOS seems to have problems in the northern parts of its coverage area during ionospheric scintillation".

One participant notes that "[it] is very difficult to quantify. Disruptions occur occasionally, but their root cause often is unknown". Another participants states that "if disruptions had the root cause of space weather, [they were] not aware of that". Not only is there a lack of information during the events, but even afterwards the cause of the disruptions remains unknown to these pilots.

Further, participants describe the following procedures to deal with disruptions: informing crew, basic navigation or radar vectors, navigation according to flight plan, actions according to operation manual or secondary protocols, paper maps and local knowledge, or "[working] with what's available". Several participants remark that they prepare for taking pictures of the upcoming auroras in case they actually notice space weather warnings. So at least in this respect, there is a shared enthusiasm for space weather.

3.6 Training and protocols

As demonstrated in the preceding groups of questions, understanding space weather is crucial for identifying its impact on

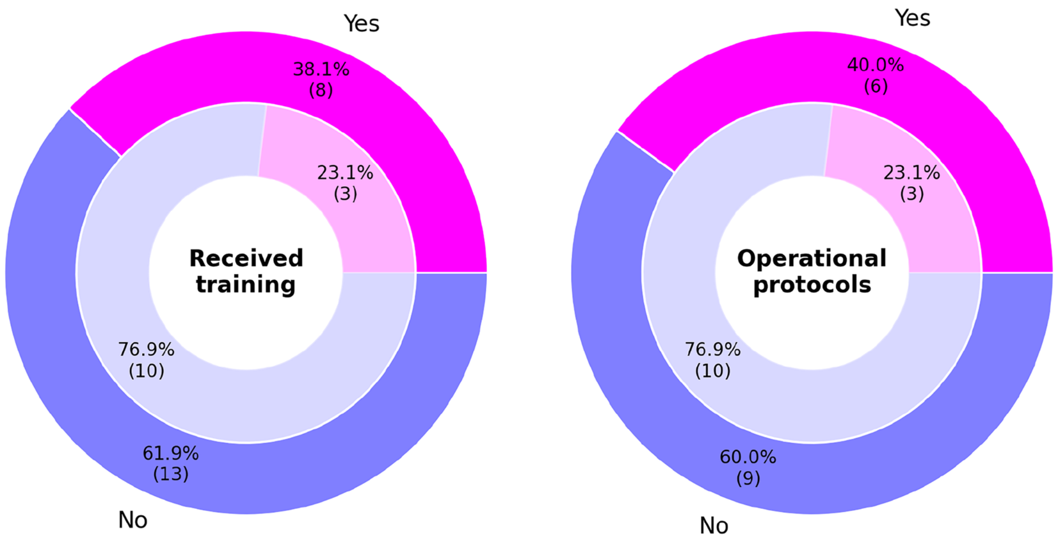


Fig. 8 Received space weather training and awareness of operational protocols. The inner circle shows the results for only pilots

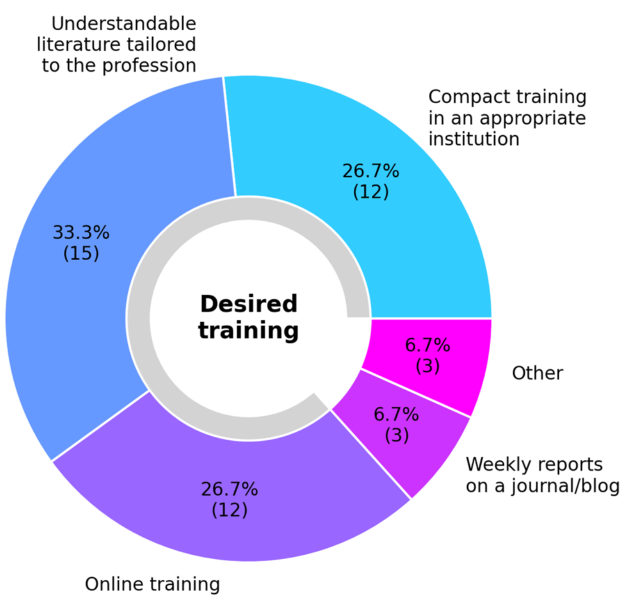


Fig. 9 Preferred training formats of participants for further space weather education

systems used in aviation. For this reason, this group of questions examines how many of the participants have received formal space weather training, what protocols are in place to support them in their work, and how they themselves would like to see training improved.

Figure 8 shows that just over one-third of participants have received training on space weather.

Among pilots, this amount drops to less than one-quarter. A similar trend is observed in the availability of protocols for managing space weather events. Given the limited formal training and available protocols, it may be inferred that the majority of knowledge about space weather is likely acquired through self-education. As summarized in Fig. 9, participants wish for different possibilities to develop or improve their understanding of space weather.

Understandable literature, online training and training in an appropriate institution are all similarly preferred education formats of participants. And to a certain extent, these offers already exist [e.g. the extensive guidance material including fact sheets and videos, 23]. There is a wide range of literature on space weather, from specific publications to dedicated user guides for services. However, with regard to the preceding groups of questions, it can be expected that these are not easy for users to find or do not address the specific problems in aviation. One participant confirms this by stating that "training received is very superficial," and they "wonder if a deeper approach shoud be given". Another participants wishes for "more training by manufacturers of technologies used in aviation [...] for more comprehensive understanding on the [extreme space weather] impacts".

Three participants also see a benefit in regular journal or blog posts about space weather impacts in aviation, which could be published weekly, monthly or quarterly. These could, for example, summarize current space weather events in order to raise awareness of space weather as a possible source of disruption.

The responses to the question regarding which space weather-related topics participants would prefer to be informed about (see Sect. 3.2) provide insight into potential priority topics for training. Three participants asked for more information on GBAS, SBAS, and SATCOM. This could suggest a broader need for training focused on the specific impacts of space weather on these technologies and is further supported by participants who seek better understanding (and thus training) on "real impacts", referring to disruptions in their flight operations.

3.7 Needs and expectations

This group of questions is divided into four topics in order to define more precisely what improvements could look like. The focus is on information and warnings, decision support, communication and coordination, as well as data provision.

3.7.1 Information and warnings

Participants clarify once again in this group of questions, that they need specific information for impacts on aircraft operations and severity to make informed decision. General space weather warnings do not fulfill the needs in aviation and instead participants ask for reliable prediction about a specific effect (e.g. loss of communication or GPS navigation) during space weather events. One participant also clarifies again, that "[they] need an alert and a corresponding protocol to follow" to act on space weather information. Participants also expect information about the "availability of HF, SATCOM, GNSS on the planned route" or a "warning if radiation levels on polar routes are elevated". In other words, the participants imagine a user-specific monitoring and prediction service that communicates possible impacts directly to them. The advisories analyzed during flight planning and preparation already fulfill this task, but this does not seem to meet their expectations.

Figure 10 summarizes the preferred format and required lead time for space weather information.

The lead times given by participants vary depending on their use cases and the expected impacts. One participants gives an in-depth explanation, how these values "depend on the effects and the operational adjustment. For ad hoc altitude or routing changes, fuel is required. This is decided 1 h prior to take-off, so 7–9 h before leaving the polar area again. In case of GPS-effects impacting the approach up to 12 h lead time may be desirable. But special alternate planning procedures may apply and mitigate this risk". Thus, the responses allow deriving lead times for different applications. Furthermore, there is no indication of concerns with the existing services in this regard (i.e., overly long lead times). This contradicts the results of a preceding survey [14], where insufficient lead times of space weather services were a major concern for participants. It should be noted, that implementation of space weather products with the suggested lead times, also requires to consider which accuracy is achievable for different space weather predictions. Therefore, a follow-up to this survey should identify the needs for this as well.

Figure 10 also shows that participants prefer visual maps for information, but text, notifications and graphs are useful as well. This way of compiling information is already commonly used in space weather services and therefore only requires adaptation to aviation-specific needs.

3.7.2 Decision support

What has already been shown in preceding groups of questions is that decisions and instructions for action should be provided together with the space weather information. For this reason, the participants did not propose any new or improved tools for decision support and instead reiterated the importance of comprehensible information that is integrated into existing briefings or software. One participant summarizes how "[they] get most of [their] information from the airline Dispatch organisation which [prepares] a pre-flight briefing package. [They] expect that Dispatch [has] the tools and access to relevant information in order to assemble a briefing package and flight plan advise". They further note that the "easiest way to communicate information would be through charts indicating areas where space weather can affect services".

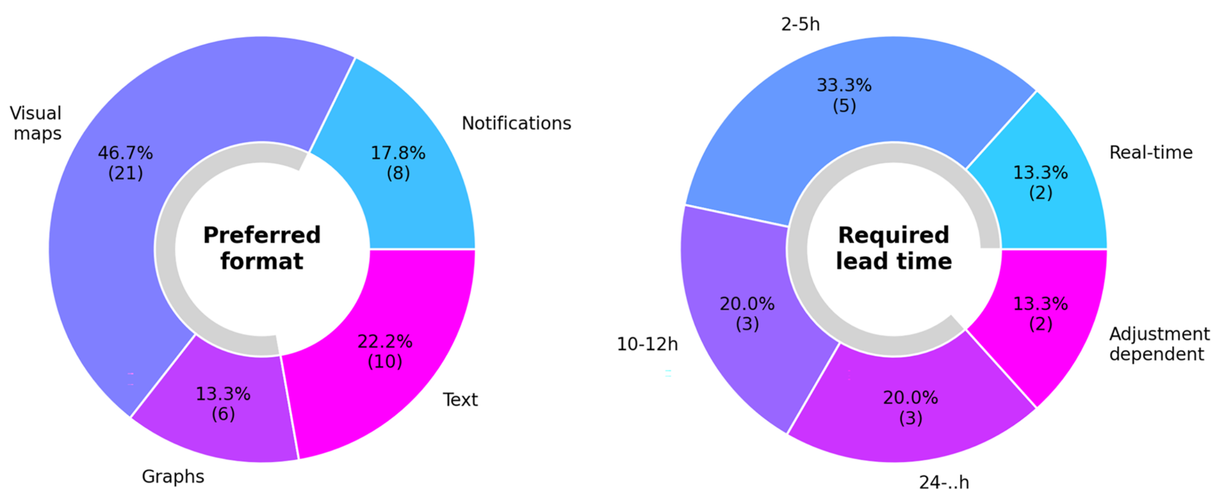


Fig. 10 Preferred format and required lead time for space weather information

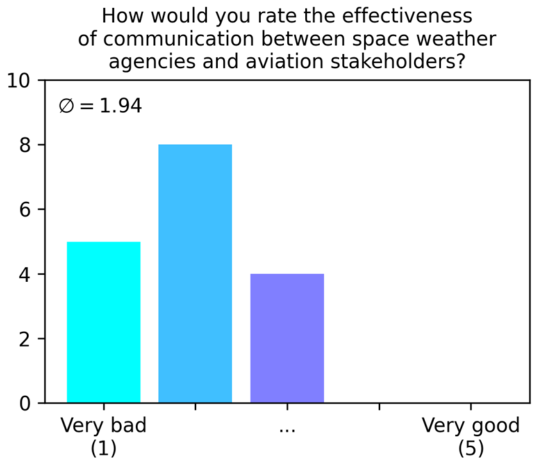


Fig. 11 Communication between space weather service providers and aviation stakeholders

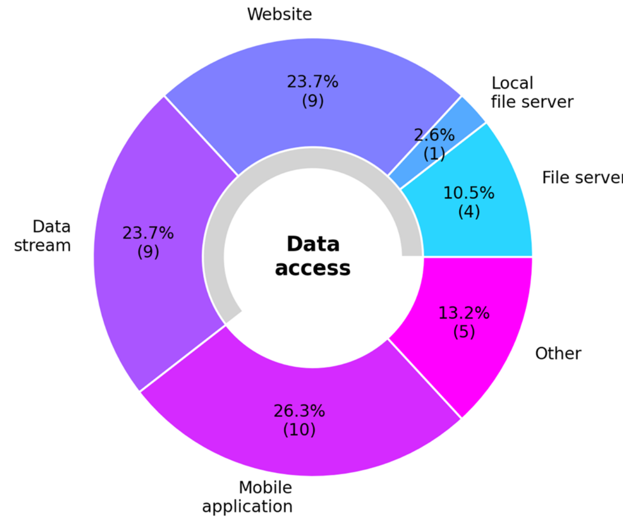


Fig. 12 Preferred data access for space weather information

3.7.3 Communication and coordination

The results for this group of questions highlight that communication (e.g. of requirements or applicability) is insufficient between space weather service providers and aviation stakeholders. In addition, several of the participants report that they are unable to assess the state of coordination, since no insights are provided to them. Figure 11 shows that not a single participant rates the communication with a positive response and the tendency is towards a very bad effectiveness. One participant states that "those that emit [extreme space weather] alerts should look at how it's used" and another that "current severity scales do not accurately reflect threats" as there are "too many levels that do not have impacts and just create noise". Similar discussions are presented in the findings by [24], that suggest revisions to NOAA's space weather scales for aviation and other applications. Their results highlight the need for unified, simplified, and more application-specific space weather scales that meet the unique requirements of flight operations. They also highlight a solar radio burst event in December 2023, which caused unexpectedly severe disruptions to aviation communication systems — impacts that were not predicted by space weather services. This supports the participants' concerns that the current scales may not be applicable for all space weather disruptions.

From a scientific point of view and as the operator of a space weather service, communication does not look any better and it is a challenge to organize effective exchange of experiences, knowledge and data. Further, a participant's comment about "this survey [being] too long for most pilots" and similar responses to mails or social media post sharing the survey show that overcoming these communication barriers is not straightforward.

3.7.4 Data

This group of questions focuses on the technical provision of data and therefore also depends heavily on the preferred formats for space weather information.

Figure 12 shows that those data sources that are crucial for real-time monitoring and forecasting are preferred. Data streams and websites are commonly used to provide space weather information and cover the expectations of most participants. However, mobile applications (for smartphones or EFB) are also highly demanded. From the participants' point of view, there is a lot of catching up to do for the established space weather services with regard to these applications. One participant notes that they need space weather information "via the normal aviation weather services [and] on the EFB, flight planning documentation or [Aircraft Communications Addressing and Reporting System (ACARS)]". Therefore, existing communication channels should be leveraged instead of creating new ones. This would, for instance, involve cooperation between space weather services and manufacturers to integrate the necessary forecasts and warnings into EFB.

3.8 General feedback

Several participants used the final group of questions to reiterate the most important points for them. Some of these comments repeat that "space weather could be an underestimated issue" and that "aviation has changed dramatically and people involved need to be better prepared". Participants note the missing awareness and one participants notes in detail the "lack of knowledge, lack of formal protocol from the regulator, governing body (FAA/ICAO/etc.), lack of standard response from users/operators". Nevertheless, participants also state that commercial trade-off and potential risks must be equally considered to approach the topic in an appropriate manner.

Generally, participants engaged the most with questions that offer yes/no, 5 point choice or multiple choice responses (see varying engagement in Fig. 13), which confirms the need for brief and concise information exchange.

Especially text responses have a significantly lower engagement, which limits the amount of in-depth reports. Furthermore, the amount of responses decreases towards later questions, as the survey likely took too long for several participants (average completion time of 16 min).

Nevertheless, several of the participants have agreed to participate in follow-up interviews. These will be held at a later date if required. Furthermore, the survey is still publicly accessible so that users can leave feedback at any time.

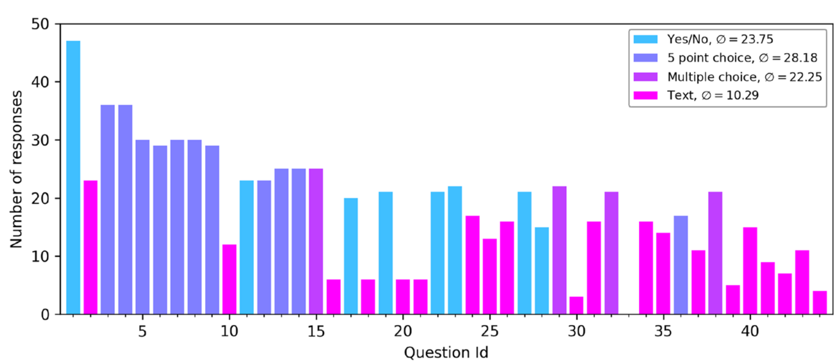
4 Discussion

The survey is likely influenced by two key limitations. Firstly, the overall number of participants is very low, with the subset of pilots being even smaller at only 13. For this reason, no definitive statistical or general conclusions can be drawn for the entire aviation sector. Secondly, the number of non-European participants is very limited, despite efforts to recruit an international sample. This may, for example, explain the bias towards certain services (see Fig. 5). Attempts to mitigate this by distributing the survey through non-scientific media with an international audience were unfortunately unsuccessful. Furthermore, the sample is likely biased toward participants with above-average familiarity with space weather, since such users are more likely to notice and engage with a survey on this topic. Despite these limitations, the results are in good agreement with several findings of similar surveys [14, 22] and provide valuable insights that could inform new approaches in space weather research.

The following points outline the key findings of the survey, presented in order of importance, reflecting the topics of greatest concern among participants:

1. *Lack of communication:* Participants strongly emphasized a lack of communication between space weather service providers and aviation stakeholders, expressing concerns that crucial information about events and impacts is not effectively shared (i.e. actionable warnings or detailed post-event reports). Additionally, participants reported to be excluded from discussions and decision-making processes, suggesting that their expectations and needs are not adequately considered. This sense of exclusion impacts the willingness to actively participate in efforts to resolve the issues (i.e. investing time in efforts like the survey), as they expect that their needs and therefore their efforts will not be considered.
2. *Lack of space weather risk awareness:* Several participants are left uncertain about when disruptions due to space weather occur. This and the lack of communication undermines the ability to effectively prepare for these events. Further, this uncertainty causes a resistance to engage with the topic and may lead to inadequate mitigation strategies during impacted operations.
3. *Insufficient training and protocols:* Participants reported insufficient space weather training and protocols, which are crucial to effectively respond to provided space weather warnings. All participants would welcome further training in various formats, which would also initiate continuous communication and improve the awareness of space weather risks. Participants also expect space weather services to provide their products in an application-oriented manner combined with instructions for action.
4. *Insufficient use of space weather services:* Only a small group of the participants integrate space weather information in their tasks, while the majority is unfamiliar with products appropriate for their use case. In the context of a follow-up survey or study, it would be particularly interesting to investigate which mobile applications are used, how they are utilized, and from where they source their data.
5. *Lack of specialized services:* Professional space weather services are to date not equipped to address the aviation-specific expectations and do not provide their services

Fig. 13 Engagement with survey questions



through the expected interfaces (e.g. mobile applications). Participants require monitoring and forecast with user-specific information (e.g. according to their flight plan), visual maps with probable impacts and warnings with actionable recommendations. Parameters, that are useful to space weather experts (e.g. the commonly used total electron content), cannot adequately fulfill these expectations and have to be refined into suitable products. Appropriate lead times for forecasts are also crucial so that changes to flight plans can be realized at all.

The different findings are connected and require a coordinated strategy to address them. In the following, recommendations are provided for such a strategy that could be considered by space weather service providers for implementations in the near future:

1. *Outreach activities:* A better interaction with users in aviation is necessary to raise awareness of space weather impacts. This includes the preparation of scientifically sound and easy-to-understand material that emphasizes the benefits of taking space weather into account. It is crucial that these are not fundamental physics lessons on space weather phenomena, but rather training focused on the desired understanding of "real impacts", specifically relating to flight operations. Further, the topic must be present at aviation conferences, in aviation blogs and journals as well as on other public platforms. In the long term, continuous cooperation between space weather service providers and aviation stakeholders should be established.
2. *Implementation of aviation specific services:* The collection of existing space weather products and the associated presentation of solar, geomagnetic or ionospheric parameters requires expert knowledge for a useful interpretation and is not sufficiently integrated into workflows. The existing products of space weather services should therefore be refined for specific technical systems and, in the best case, provide user-specific monitoring and forecasting. It is also crucial that these products can be integrated into existing software and work flows. Finally, proposed revisions to space weather scales by aviation professionals should be implemented to better address the specific needs of the aviation sector.
3. *Implementation of training material/courses:* Space weather products and services are at best provided with how-to guides, but these cannot replace more comprehensive literature and training. The approach by space weather service providers, that combines the release of new products with educational programs, should therefore be intensified and supported by broader outreach activities. These efforts have to consider both the scientific and technical point of view equally.
4. *Continuous feedback:* Users must be able to give feedback easily and at any time. If this does not work, space weather service providers must obtain this feedback through surveys or public outreach activities specifically targeted at aviation users. Space weather products and services can only remain up-to-date and relevant if they follow trends in aviation promptly.
5. *Research of space weather impacts on aviation technologies:* The benefits of taking space weather into account must be supported by sound scientific studies and the sectors in which the provision of products and services is appropriate must be defined. For this purpose, it is important that research identifies how space weather events translate into disruptions of specific technical systems or affect air traffic management on a large scale. Cooperation from aviation stakeholders is crucial for this, as they have the data required for this research.

After reviewing the responses to the survey and identifying the key findings and recommendations, IMPC will take the first steps to integrate the suggestions into further work and, in particular, maintain the communication with aviation stakeholders (particularly by more application centered research, the development of tailored services for aviation and by providing more effective user guidance).

5 Conclusion

The survey allowed to gather insights from aviation professionals and stakeholders to understand (1) the perception of the impact of space weather events on flight safety and operations, (2) operational challenges or disruptions of aviation systems during space weather events as well as (3) mitigation strategies and currently used services to manage the risk of space weather. The survey report finds a lack of communication between space weather service providers and aviation stakeholders, a lack of space weather risk awareness, insufficient space weather training and protocols, insufficient use of space weather services and a lack of specialized services. For that reason, the survey report concludes with recommendations including more effective outreach activities, development of aviation specific services, development of training material/courses, providing platforms for continuous feedback and application-oriented scientific studies.

Appendix A: Survey questions

This section presents the various question groups and questions in Tables 1, 2, 3, 4, 5, 6, 7 and 8. The question index is continued across question groups.

Table 1 Question group: Space Weather and Its Impact on Aviation

	Question	Question type
User information		
1	Do you work in aviation?	Yes/No
	What is your role or job?	Text
2	If applicable, which kind of aircraft do you operate?	Text
General Understanding of Space Weather		
3	How well do you understand the term space weather and its key components (e.g., solar flares and geomagnetic storms)?	5 point choice
4	How confident are you in your understanding of the potential impacts of space weather on aviation operations (e.g., navigation, communications, aircraft systems)?	5 point choice

Table 2 Question group: Awareness of Risks

	Question	Question type
5	How aware are you of the potential risks of solar radiation to aviation safety?	5 point choice
6	How well do you understand how geomagnetic storms can affect aviation, especially for flights at high latitudes?	5 point choice
7	How well do you understand how solar bursts can affect communication and navigation in aviation?	5 point choice
8	How well do you understand the impact of space weather on GPS?	5 point choice
9	How well do you understand the impact of space weather on GBAS or SBAS?	5 point choice
10	Which of these and other space weather related topics would you prefer to be better informed about?	Text

Table 3 Question group: Source of Information

	Question	Question type
11	Do you use space weather information during the preparation or execution of aviation related tasks?	Yes/No
12	How easy is it for you to access reliable space weather information relevant to aviation?	5 point choice
13	How familiar are you with space weather warning services that provide forecasts?	5 point choice
14	How familiar are you with space weather warning services that provide aviation-specific forecasts?	5 point choice
15	Which services do you use for space weather information?	Multiple choice
16	If applicable, which other space weather services do you use?	Text

Table 4 Question group: Personal Experience

	Question	Question type
17	Have you ever experienced any disruptions in aviation operations due to space weather events?	Yes/No
18	Can you describe a specific experience and the observed impacts?	Text
19	Have you been involved in any decisions or procedures related to mitigating space weather risks during operations?	Yes/No
20	Can you describe the decisions and procedures?	Text
21	Which space weather information have you used in these situations?	Text
22	If applicable, can you recall any instances where space weather led to changes in flight routes or altitude adjustments?	Yes/No

Table 5 Question group: Operational Impact

	Question	Question type
23	Have you encountered issues with GPS or communication systems due to space weather?	Yes/No
24	In your experience, how often do space weather-related disruptions occur, and how severe are they?	Text
25	How do you handle or respond to space weather-related disruptions?	Text
26	How do you handle or respond to space weather alerts?	Text

Table 6 Question group: Training and Protocols

	Question	Question type
27	Have you received any training specific to space weather and its impact on aviation?	Yes/No
28	Are there operational protocols in place for responding to space weather-related threats that apply to your work?	Yes/No
29	How do you think current space weather training could be improved?	Multiple choice
30	What other training would be helpful?	Text

Table 7 Question group: Needs and expectations

	Question	Question type
Information and alerts		
	Question	Question type
31	What specific information do you need about space weather to make informed decisions in aviation operations?	Text
32	What format or method of space weather alerts do you find most useful?	Multiple choice
33	What other format would be helpful?	Text
34	How much lead time would you need in advance of a space weather event to make operational adjustments?	Text
Decision support		
	Question	Question type
35	What tools or resources would make it easier to assess the impact of space weather on your aviation operations?	Text
Communication and coordination		
	Question	Question type
36	How would you rate the effectiveness of communication between space weather agencies and aviation stakeholders (e.g., air traffic controllers, pilots, airline operations)?	5 point choice
37	Are there any specific gaps in communication you've noticed during space weather events?	Text
Data		
	Question	Question type
38	How would you like to access or receive space weather products and data?	Multiple choice
39	Which other data access would you prefer?	Text
40	How quickly must data be available (e.g. within a few seconds, minutes, hours or days)?	Text
41	Which data currently covered by space services are particular helpful?	Text
42	Which data currently not covered by space weather services should be available?	Text

Table 8 Question group: General Feedback

	Question	Question type
43	What are the main challenges you face when trying to integrate space weather information into your decision-making?	Text
44	Do you have anything else to share?	Text

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