Space Weather Services for Aviation – Current Capabilities and Future Needs

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Introduction
Space weather originates on the sun and drives changes in the near-Earth environment. Space weather has been present since the Earth existed as it does today, but the dependence on and application of technologies affected by space weather has increased many fold in recent decades. Many of these technologies underpin aviation in how we navigate and how we communicate. Space weather can impact radio communications, satellite-based navigation, and even lead to increased radiation exposure for passengers and crew on rare occasion. Solar radio bursts can also affect satellite-based navigation as well as air traffic control radar. All of these have the potential to significantly impact aviation operations, particularly during the rare but extreme.

Space weather is a broad term used to characterize several distinct, but often related phenomena. Some space weather impacts are restricted to the daylight side of Earth, while other effects are focused in regions dictated only by latitude, such as polar or equatorial regions. Additionally, the different phenomena that comprise space weather have very different times scales, both with respect to ability to warn before onset and duration. Furthermore, space weather is characterized by physical parameters many are unfamiliar with. Unlike rain, sleet, snow, temperature, or wind, space weather cannot be felt or seen (visibility or the aurora excluded). These intangible qualities make it difficult to easily understand and interpret space weather information, the importance of the magnitude of a space weather event, or the likely effect. For this reason, the challenge for both space weather service providers and users alike is to translate this environmental information into likely impacts. This is challenging for many reasons, including the difficulty of predicting the underlying phenomena itself, to the difficulty in anticipating the impacts to systems given the wide variety of systems with the same intended function, but widely varying performance parameters and configurations.

To take the first steps in mapping space weather to likely impacts on commercial aviation, space weather services are progressing within ICAO, with a commencement of services likely in November 2018. The initial space weather services will provide this increased, impact-based situational awareness to the aviation community. While valuable, these services are still maturing and will not fully meet user requirements with respect to desired lead time, skill, and specificity. And while there are a number of existing space weather service providers, even some with fairly mature aviation capabilities, implementing a globally-harmonized service presents many challenges.
Space Weather and its Impact on Aviation

Space weather happens continuously, in some form or another, but truly significant space weather activity is fairly infrequent. Some elements of space weather trend with the roughly 11-year solar cycle, rising and falling with the overall appearance and disappearance of sunspots. These sunspots are the source of significant activity, and while these sunspots generally follow this 11-year overarching trend, significant activity can occur at any phase of the solar cycle and independent of solar cycle size.

The first observable of a space weather event is the enhancement in X-rays, the solar flare. These X-rays further ionize the D-layer of the ionosphere on the sunlit sit of Earth, the ionized part of Earth’s upper atmosphere, affecting High Frequency (HF) communication for minutes to hours. Although the lowest HF frequencies are affected most strongly, significant flares can “black out” use of all of HF. These HF blackouts can result in difficulty in reaching oceanic aircraft, although the use of satellite communications as a primary means of communication is commonplace and largely robust. Although not well-correlated with the intensity of the X-ray enhancement, these flares can also have associated radio bursts, or increases in the solar radio noise at certain frequencies. On rare occasion, these radio bursts can affect Global Navigation Satellite System (GNSS) performance and air traffic control radar systems. Both of these phenomena are difficult to forecast with any skill and are largely considered no-notice events; this is unlikely to change for the foreseeable future.

Additionally, increases in the energetic radiation near Earth can result from a solar eruption, dominantly created by the acceleration of a coronal mass ejection (CME). The sun’s outer atmosphere is called the corona, and as part of the eruptive sequence of events, part of the corona can be explosively blown into space. These radiation enhancements significantly increase the radiation impinging on Earth’s atmosphere, and can result in HF blackouts in the Polar Regions (for this effect, ~60 degrees magnetic latitude and poleward) as well as increases in radiation exposure for passengers and crew in the same geographic footprint. These enhancements can persists for hours to days, although the most intense periods of radiation are generally at event onset and short-lived. It should also be noted that significant events rarely occur in isolation, with the more typical sequence of events being comprised of several significant eruptions over a period of a week or more.

These CMEs transit the 150 million kilometers between sun and Earth, and little to no information about the particulars of the CME is obtained between initial observation at the sun and arrival at the L1 Lagrange point, roughly 1.5 million kilometers upstream of Earth on the sun-Earth line. At this point, the magnetic field strength and orientation, velocity, and density can be measured in situ by satellite. This information can then be used to drive short-term empirical and physics-based forecasting models, as well as automated or human-in-the-loop warnings of geomagnetic storm intensities. CMEs have been observed to affect Earth in as little as ~15 hours after eruption, but more typical transit times for significant events range from ~18-30 hours. The CME then interacts with Earth’s magnetosphere, the region of space affected by Earth’s own magnetic field, resulting in a geomagnetic storm.

From an aviation impacts perspective, geomagnetic storms disturb the ionosphere, affecting GNSS performance, HF radio propagation, and satellite communication performance. Strong geomagnetic storms can also cause the areas affected by the aforementioned radiation enhancement to expand equatorward on the order of 10 degrees in latitude or more.
Scientific Challenges and Development Needs
Models to describe the radiation environment at aviation altitudes are available, both to describe the background radiation environment from the ever-present Galactic Cosmic Ray (GCR) background as well as the solar event-driven enhancements. It is important to consider both, as significant solar activity can suppress the background radiation (a Forbush decrease). There are fairly extensive measurements during quiet times (GCR-only) to validate these models, but measurements during event-driven enhancements are limited. One example of the much needed verification and validation data is shown in Figure 1, below, radiation exposure measurements taken regularly on a Munich to Chicago route (Beck, et al., 2005). These measurements show the fairly steady background rates as well as an enhancement during the intense space weather activity of late October 2003 (top panel). These measurements show the increase in radiation during the event as well as evidence of suppression of the background term; both must be accounted for to give an accurate assessment of the change in exposure related to an event. As significant events are fairly rare, extensive verification and validation data is generally lacking, and the field could benefit from continued and targeted measurement campaigns.

In general, there are many uncertainties associated with the modeling of the radiation environment at aviation altitudes, particularly during times of event-driven, elevated exposures. These models could benefit by better characterization of the radiation environment at the top of the atmosphere both by direct satellite measurement and inference of the impinging radiation field through the interpretation of globally-distributed neutron monitor measurements. These models could also benefit from improvements in and better application of radiation transport codes to describe the changes in this mixed-field radiation environment as it penetrates and cascades to flight level altitudes within the atmosphere.

Nowcasting of the radiation environment, while still fraught with uncertainty, is mature enough to add value to aviation operations. The ability to differentiate a quiet environment from an enhanced one is sufficient to support the first generation of space weather services within ICAO. However, skill in the multi-hour or pre-event forecasting domain remains challenging. As the driving eruptions at the sun themselves cannot be predicted with any skill prior to their occurrence, longer-term forecasting with a high level of skill will remain out of reach for the foreseeable future. Significant advancements in understanding the sun and its eruptive nature are needed to affect change in this domain. That said, there is some skill in predicting the decay of an event once in progress, barring subsequent eruptions.
Ionospheric modeling underpins describing the impacts to HF communications and GNSS performance. Many HF needs are served today by empirical models that can describe the impacts of space weather on HF propagation (i.e. solar flare-driven HF blackout and radiation-driven absorption in the polar cap). More sophisticated empirical or physics-based models are in early use or development today to fully describe the dynamics of the ionosphere. The current cutting edge in the ionospheric modeling domain is the expansion of and coupling of physics-based terrestrial weather models with physics-based ionospheric and upper atmospheric models. Since the ionosphere is forced both from below by tropospheric weather and from above by solar or geomagnetic storm inputs, accounting for both is critical in fully reproducing the behavior of the ionosphere. It should be noted that space weather forcing from above will dominate during significant geomagnetic storms. An example from the U.S.‘s Space Weather Prediction Center is shown in Figure 2, below.
These models need solar wind conditions as one of their most important inputs capturing the forcing from above, and as noted previously, those conditions are only measured 1.5 million km upstream of Earth. Given nominal solar wind velocities of ~400 km/s, with velocities several times that during significant space weather, the predictive timescales of these models is limited by the ballistic propagation of the solar wind from measurement at L1 to Earth. For this reason, these models can only provide skill over short-term predictive timescales during geomagnetic storm conditions (10’s of minutes).

Any skill in true multi-hour or multi-day forecasting under geomagnetic storm conditions will only come with advancements in the ability to observe or predict the characteristics of the driving solar wind, or the CME, with longer lead times. On the long range horizon, basic research may eventually enable greater, pre-eruption characterization of the CME, but that remains rather unlikely for the foreseeable future.

Furthermore, even with perfect characterization of the solar wind forcing, many elements of accurately predicting the complex physical processes of the ionosphere remain very much in the basic research realm. This is a focus area of many basic and applied research programs, and ionospheric modeling should progress substantially in the coming years. And just as terrestrial weather modeling has matured and skill has improved with data assimilation, the same will be true in the ionospheric domain. The improved skill, resulting from both data assimilation and model development, will lead to a greater ability to describe the forecasted impacts on HF as well as the conditions affecting the accuracy and availability of GNSS.
Overall, when compared to terrestrial weather modeling, ionospheric modeling remains immature, but it is progressing.

Fundamentally, while progress has been made in the short-term forecasting and nowcasting domain, multi-hour or multi-day forecasting of space weather remains in the hands of the space weather forecasters. Improved tools and observations, both empirical and physics-based, can add value in improving the skill in this often chaotic, event-driven paradigm. Forecasting at longer timescales will remain dependent on anticipating the commencement of an event, and describing the likely degradation in performance that will result. In many cases, these will be limited to broad generalizations, not only spatially and temporally, but also with respect to intensity in what may result.

**Conclusion**
While the introduction of space weather services is a positive step forward, space weather services are still immature with respect to the specificity and skill truly needed in this domain. Our understanding of the sun and the eruptive processes that drive space weather are still maturing. Our understanding of how the Earth system responds to space weather is maturing as well. As the science and modeling improves, so will space weather services for aviation. Curiosity-driven research will always remain important, but the targeted, applied research to transform these advances in our understanding to actionable products for aviation users must be a focus. Clear user needs and an understanding of the application of technologies affected by space weather will be key to guiding and facilitating that progress.

**References**