Advances in atmospheric radiation measurements and modeling needed to improve international air safety

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Abstract. Air safety is tied to the phenomenon of ionizing radiation from space weather, primarily from galactic cosmic rays but also from solar energetic particles. A global framework for addressing radiation issues in this environment has been constructed but more must be done at international and national levels. Health consequences from atmospheric radiation exposure are likely to exist. In addition, severe solar radiation events may cause economic consequences in the international aviation community due to exposure limits being reached by some crewmembers. Impacts from a radiation environment upon avionics from high-energy particles and low-energy, thermalized neutrons are now recognized as an area of active interest. A broad community recognizes that there are a number of mitigation paths that can be taken relative to the human tissue and avionics exposure risks. These include developing active monitoring and measurement programs as well as improving scientific modeling capabilities that can eventually be turned into operations. A number of roadblocks to risk mitigation still exist, such as effective pilot training programs as well as monitoring, measuring, and regulatory measures. An active international effort towards observing the weather of atmospheric radiation must occur to make progress in mitigating radiation exposure risks. Stakeholders in this process include standards-making bodies, scientific organizations, regulatory organizations, air traffic management systems, aircraft owners and operators, pilots and crew, and even the public.

Aviation radiation is an unavoidable space weather phenomenon. Air safety has improved significantly in many meteorological areas over the past decades with the exception of space weather, which includes ionizing radiation. While a framework for addressing radiation issues has been constructed, we believe more can and must be done at international and national levels. In particular, measurement programs must be expanded and linked with models to provide current epoch and, eventually, forecast information for the aviation ionizing radiation environment. A diverse radiation measurement and modeling community exists with a strong interest in improving international air safety.

There are two challenges in our ever more mobile, technologically dependent global society. First, pilots, crew, and passengers, which include fetuses between their first and second trimesters, might face additional radiation hazards in terms of dose equivalent rate (rate of absorbed dose multiplied by the quality factor), particularly when flying at commercial aviation altitudes above 26,000 ft. (8 km) (see Figure 1). Second, avionics can experience single event effects (SEE) from both the ambient high-energy and thermal neutron environment. The source of this radiation in either case is two-fold – from the continuous bombardment by primary background galactic cosmic rays (GCRs) and also from solar energetic particles (SEPs) emitted during occasional solar flare events lasting up to a few days.

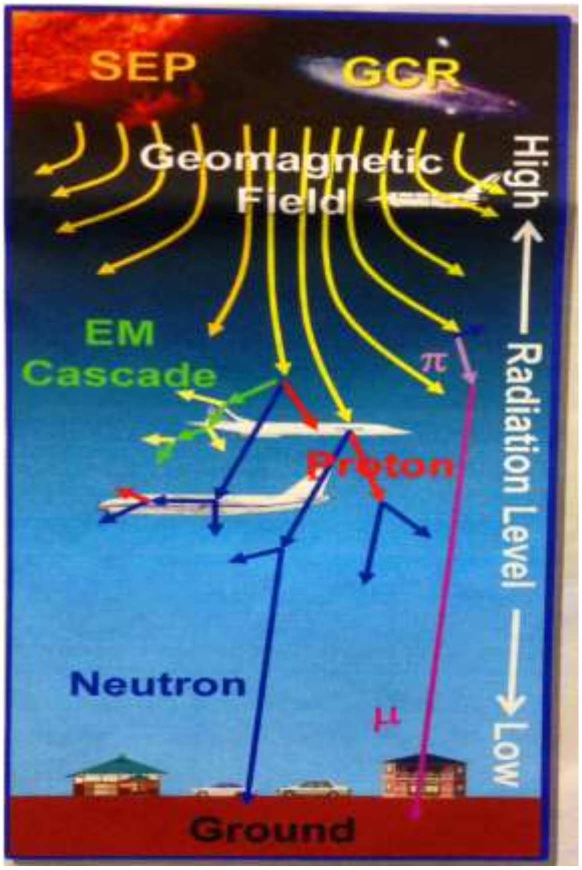

Fig. 1. All passengers in commercial aircraft flying above 26,000 feet will typically experience some exposure from atmospheric radiation [Credit J. Hwang].

Galactic cosmic rays from outside the solar system consist mostly of energetic protons but also contain heavy ions such as iron. Solar energetic particles are commonly associated with solar flaring events and are dominated by protons. Regardless of their source, and depending upon their energy, these charged particles enter the Earth’s atmosphere at different magnetic latitudes and collide with atmospheric molecules. Below the top of the atmosphere (~100 km), the primary radiation decreases as a result of atmospheric absorption while a secondary radiation component increases. This occurs because many low-energy particles are created by the initial impacts (Reitz *et al.,* 1993). These competing processes produce an ionizing maximum that occurs between 20 and 25 km (65,000 – 82,000 ft.) called the Pfotzer maximum, although observational evidence may point to lower, or variable, altitudes of this maximum. Below the Pfotzer maximum, down to the Earth’s surface, the particle fluxes decrease. The secondary radiation, including protons, neutrons, pions, electrons, and gamma rays, have varying energies and are emitted in all directions. The primary and secondary energetic particles collide with atmospheric molecules, the aircraft structure, and interior materials (including passengers) to cause a further alteration of the radiation spectrum.

This resulting, complex spectrum of radiation environments may potentially cause an increase in cancer risk as the dose equivalent exposure increases. The atmospheric neutron component of this complex radiation field, in particular, holds special interest in the cancer research community. The energy spectrum of these neutrons extends over more than ten orders of magnitude. Both the high-energy neutrons (E > 10 MeV) and the very low-energy thermalized neutrons can also cause SEE errors in avionics (Normand *et al.,* 1994; Normand *et al.,* 2006). The high-energy neutrons have direct interactions with Silicon (Si) nuclei in electronics, producing excess charge carriers through nuclei recoils. The very low-energy neutrons are created by scattering from atmospheric constituents and aircraft materials (including fuel and passengers), which thermalizes them (creates neutrons in thermal equilibrium with their surroundings in an energy range of approximately 0.02 – 0.2 eV). These thermalized neutrons are then absorbed by Boron (particularly ^{10}B) found in Si-based aircraft electronics, for example. The net effect after absorption is the production of a gamma-ray (480 keV), an alpha particle (~4 MeV), and a lithium ion. The charged alpha particle may then interact with semiconductor structures and cause a SEE. Higher Z elements near the silicon layers (e.g. tungsten connectors) can exacerbate the SEE effect considerably.

Most of the time, the GCR radiation component dominates commercial aviation altitudes. It varies inversely with the approximate 11-year solar cycle. As an example, the outflowing plasma in the solar wind and the strength of the solar Interplanetary Magnetic Field (IMF) effectively screen lower energy GCR particles from reaching the Earth during high solar cycle activity. Thus, as the next solar minimum approaches (~2017–2021) the GCR radiation will become stronger as the solar wind and IMF become weaker. In addition, significant solar flaring events can produce radiation storms in which the SEP doses are additive with the GCRs. We note that Forbush decreases (a rapid decline in the observed GCR intensity following a solar coronal mass ejection, for example) can temporarily reduce the GCR component. The resulting GCR and SEP combined dose equivalent exposure level could possibly exceed safety thresholds established by the international radiation protection community.

Examples of events. An example of a severe tissue-relevant radiation environment occurred during the major SEP event on 23 February 1956 (only ground level measurements were available). For that event, Dyer *et al.* (2007) calculated a significant increase over background at high latitudes and at 12 km altitude with correspondingly higher dose rates for aircraft flight paths of several mSv hr^{-1}. The derived SI unit of ionizing radiation dose is the sievert (Sv). It incorporates the stochastic health risk of low levels of ionizing radiation on the human body, where radiation dose assessment is defined as the probability of cancer and genetic damage. On 23 February 1956 this radiation increase could have caused some aircrew members to exceed their currently recommended annual occupational flight limits in just one flight (Wilson, *et al.,* 2002; Dyer *et al.,* 2007). It also could have caused upsets every 3 seconds in a Gbyte of a typical memory device (Dyer *et al.,* 2003). An extreme event such as the 1859 Carrington Event could be considerably worse than this event. Here we use the terms "extreme" or "severe" to indicate a NOAA S5 radiation storm, possibly comparable to the 1859 Carrington Event. We also note that the NOAA scales themselves are a poor indicator for the aviation radiation environment; the GOES fluxes are a good indicator of when a Solar Proton Event (SPE) is occurring but only small subsets of these have significant fluxes of protons with sufficient energy to affect the atmosphere, even at polar latitudes.

A possible example of a severe neutron-induced avionics effect occurred on 07 October 2008 in Qantas flight 72 Airbus A330-303 from Singapore to Perth, Western Australia. While the aircraft was in cruise at 37,000 ft. one of the aircraft's three air data inertial reference units (ADIRUs) started outputting intermittent, incorrect values (spikes) on flight parameters to other aircraft systems. Two minutes later, in response to spikes in angle of attack (AOA) data, the aircraft's flight control primary computers (FCPCs) commanded the aircraft to pitch down. At least 110 of the 303 passengers and 9 of 12 aircrew members were injured; 12 were serious injuries and another 39 required hospital medical treatment. The potential triggering event that was not ruled out was a single event effect (SEE) resulting from a high-energy atmospheric neutron interacting with one of the integrated circuits (ICs) within the CPU module. While there was insufficient evidence to determine that a SEE was the conclusive cause, the investigation identified SEE as an ongoing risk for airborne equipment. All other known causes were eliminated. The aircraft manufacturer subsequently redesigned the AOA algorithm to prevent the same type of accident from occurring again (ATSB Transport Safety Report, 2011). We note that the GOES >10 MeV proton fluence was nominal on this date, i.e., there were no solar flare events.

Radiation exposure consequences. While the most significant, but highly unlikely, health consequences to atmospheric radiation exposure may include death from cancer due to long-term exposure, there are many lifestyle degrading and career impacting cancer forms that can also occur (Wilson, *et al.,* 2002). A cancer diagnosis can have significant career impact for a commercial pilot. The FAA requires each pilot to hold a medical certificate in order to exercise the privileges of his or her pilot's license. A cancer diagnosis can ground a pilot for some time, perhaps permanently given the diagnosis and time remaining in his or her career. International guidelines from the International Commission on Radiological Protection (ICRP) have been developed to mitigate this statistical risk (ICRP 1991, 2005, 2008). The ICRP recommends effective dose limits of a 5-year average of 20 mSv yr^{-1} with no more than 50 mSv in a single year for non-pregnant, occupationally exposed persons, and 1 mSv yr^{-1} for the general public. Radiation dose limits can be misunderstood. Pilots are trained in the use of engineering limits; however, radiation limits are not engineering limits. In the U.S., for example, they are treated as an upper limit of acceptability and *not* the design limit (NCRP Report 116).

Thus, to understand these consequences, the European Commission initiated and supported research projects on cosmic radiation in the 1990s, which included numerous on-board measurements (e.g., O'Sullivan *et al.,* 1999; Beck *et al.,* 1999; O'Sullivan *et al.,* 2004; EC Radiation Protection Report No. 140, 2004). Based on that experience, international institutes developed calculation codes for the assessment of galactic cosmic radiation exposure on-board aircraft. For example, the EURADOS (European Dosimetry Group) working group WG11, which focuses its activity on High Energy Radiation Fields, carried out international comparison of these calculation codes and confirmed good agreement (Bottollier-Depois *et al.*, 2009). Further, the international radiation protection community working on cosmic radiation effects to aircrew developed International Standards Organization (ISO) standards describing the conceptual basis for cosmic radiation measurements (ISO 20785-1:2006), including characterization of these instruments (ISO 20785-2:2011). The third part of this standard is still in progress related to measurements at aviation altitudes. In 2010, the International Commission on Radiation Units (ICRU) and ICRP jointly published Report 84 on this topic (ICRU, 2010). Recently during the 2014 European Space Weather Week at Liege, the EURADOS WG11 presented comparison of calculation codes, which estimate exposure due to solar energetic particle events on-board aircraft (Beck *et al.,* 2014).

European Union (EU) member States have implemented regulations for aircrew members requiring exposure assessment when it is likely to be >1 mSv yr^{-1} and to take into account the assessed exposure when organizing working schedules to reduce the doses of highly exposed crew (EU Council Directive, 2013). In the U.S., there are no regulatory effective dose limits for aircrew members; the FAA (2014) accepts the most recent recommendations of the American Conference of Governmental Industrial Hygienists (ACGIH) and recommends ICRP limits for exposure to ionizing radiation for non-pregnant air carrier crewmembers. For pregnant crewmembers, the FAA recommends the ICRP limit of 1 mSv to the fetus/conceptus for the remainder of the pregnancy, once reported to management, and the National Council on Radiation Protection and Measurements (NCRP) recommends a limit of 0.5 mSv per month.

Modeled results (Mertens *et al.,* 2012) suggest that commercial aircrew flying at high latitudes will trigger the EU action level limiting annual flights if they fly more than 500-600 hours during solar minimum and more than 800-900 hours during solar maximum, based on typical GCR background radiation exposure. Modeling also suggests that the public/prenatal recommended limit (NCRP Report No. 174, 2013) can be exceeded in 100 hours of flight time and, for high-latitude or polar flights, the effective dose rate can be up to 10 μSv hr^{-1} (Mertens *et al.,* 2012). It is possible that a limit could be exceeded in a single flight during a severe solar particle event with a hard spectrum, i.e., a Ground Level Enhancement (GLE) (Dyer *et al.,* 2007; Copeland *et al.,* 2008). We note that these modeled hours are not the method that triggers an EU action level and there is a differentiation between limits (e.g., EU law) and recommendations (e.g., FAA and ICRP), where a recommendation can be exceeded even if no legal limit exists.

Impacts beyond health risks associated with exceeding limits have also been considered. The U.K. Royal Academy of Engineering (RAEng) determined that significant economic consequences might occur from fleet disruptions due to aircrew grounding because exposures can exceed monthly or annual limits during a single severe solar event (Cannon *et al.,* 2013). For example, at conventional cruising altitudes around 37,000 ft. across polar latitudes, a severe radiation storm could result in a worst-case dose to aircrew and passengers of >20 mSv. This single event dose would be 20 times the recommended exposure limit to the general public (not aviation-specific) and comparable to the entire annual occupational dose limit for aircrew. Again, we note that this is not applicable to U.S. crew as no actual limits have been promulgated, no regulatory limits exist, and no monitoring or tracking of exposure is performed. The RAEng study also concluded that pilot workload could increase during such periods to cope with any anomalous system behavior. This is because the complexity of modern aircraft computer interface/control and fly by wire avionics is such that prediction of an aircraft's response to increased radiation levels is necessarily subject to uncertainty, as seen in Qantas flight 72.

Risk mitigation paths exist. Because of added risk from severe radiation events, the radiation measurement and modeling communities have devoted considerable effort to understanding and characterizing this radiation field with mitigation strategies in mind. The community recognizes, as a starting point, that monitoring of the natural space environment for solar proton event occurrence is important. For example, with the start of an event, announcement levels are escalated. The NOAA Space Weather Prediction Center issues a *Watch* (long-lead-time geomagnetic activity prediction), a *Warning* (some condition is expected), or an *Alert* (event threshold is crossed). A Watch is provided only for geomagnetic storms and not SEP events. Additionally, the International Space Environment Service (ISES, http://www.spaceweather.org/) encompasses many Regional Warning Centers (RWCs) and these organizations also provide similar services of Watches, Warnings, and Alerts for their local users. It is important that the nature and severity of a SPE is quickly assessed to avoid false alarms occurring if automatic alerts are issued.

A second recognition is that there is a need for dosimeters onboard aircraft. Because the radiation exposure of airline crew and passengers in the U.S. is unregulated, the responsibility for mitigation of exposure called for by the NCRP principle *As Low As Reasonably Achievable* (ALARA) is left up to the air carrier and/or the pilot. Either one usually has very limited information on which to base a decision and dispatcher/pilot training on this subject matter is virtually nonexistent. The FAA very recently added ALARA guidance to its reference material on in-flight radiation (FAA, 2014) as the basis for exposure management. In the event of a communication blackout or from air carrier policy, we note that any decision may be left solely to the pilot. The air traffic control (ATC) system is also not prepared for responding rapidly to major solar radiation storms, even though they may be rare. The International Civil Aviation Organization (ICAO) is just beginning to investigate the issue. Thus, much more work toward mitigation of radiation effects of large SEP events upon the airline industry is needed at the decision-making level.

While probabilistic SPE forecasting exists, current prediction methods typically rely on empirical formulations to estimate the decay to background from the peak of an event. Once an event has started, and for its duration, the exposure mitigation strategy for commercial aviation is relatively straightforward to implement. Any implementation is subject to maintaining safe airspace separation minima, avoiding terrestrial weather hazards, and retaining sufficient trip fuel but would include:

- fly at lower altitudes and/or latitudes for moderate or larger radiation events;
- avoid polar region flights during severe solar radiation events until they subside;
- issue a no takeoff alert if a large SPE is ongoing;
- enable ATC, operators, and aircrews with the real-time exposure information necessary to descend the enroute system to a less exposed altitude en masse; and
- enable ATC, operators, and aircrews with the real time information necessary to divert polar flights from polar flight paths when communications reliability is at risk.

ICAO and FAA communications requirements largely drive the avoidance of polar flight during increased solar activity. Due to reliance on High Frequency (HF) radio as the primary communication link between an aircraft and ATC during polar flight, and its susceptibility to disruption by a solar storm polar cap absorption (PCA), polar flight during significant solar radiation storms (NOAA S scale ≥ S3 for PCA) may be prohibited. However, the addition of INMARSAT satellite capability by some airlines may remove the human protection side benefit that occurs when ensuring continued communications. That is to say, because INMARSAT enables polar communications, a conscious decision would be required to avoid polar flight during a solar radiation storm. The FAA Solar Radiation Alert (SRA) system activates at a high proton flux level (i.e., when the estimated effective dose rate induced by solar protons at 70,000 ft. equals or exceeds 20 μSv h^{-1} for each of three consecutive 5-minute periods); it is not regulatory in its direction to pilots or dispatchers.

Mitigation of SEE in avionics, which is a probabilistic phenomenon, will mainly be achieved through improved engineering processes and, while key standards are now available, notably IEC-62396-1, it will take many years for such approaches to become universally adopted. There has been ongoing work for the International Electrotechnical Commission (IEC) SEE standard since 2000 but there are only recent signs that national bodies may mandate it. The existing certification is for quiet cosmic ray conditions only and extreme space weather is not yet considered. Furthermore, there will still be a limit to the radiation level that can be managed with confidence, depending on the design specification applied. In order to mitigate the risk of injuries during unexpected aircraft behavior such as a SEE (even though it is not yet possible to deterministically identify its higher probability), a simple but generally effective measure would be to ensure that passengers and aircrew have their seat belts fastened. While SEE are probabilistic and may occur at any altitude, even during non-SPE conditions (as may have been the case for Qantas), this mitigation path is helpful for other hazards as well such as clear air turbulence. Whatever the cause, a lesson from Qantas Flight 72 was that if seat belts had been fastened far fewer injuries would have occurred. Thus, radiation measurements and alerts may have a role to play in alerting pilots to switch on the seat belt sign (including directing passengers and crew to take their seats and ensuring their seat belts are fastened), which is a simple and low cost mitigation of any unexpected aircraft behavior risk. Built-in aircraft protections, monitors and dispatcher/pilot training are all needed as are improved engineering processes.

International stakeholders. Exposure mitigation implementation at altitude can only be accomplished by a combination of stakeholders, including but not limited to: *i)* international collaborations laying guideline foundations such as the International Standards Organization (ISO) space weather and aviation radiation standards (IS 15390, IS 21348, IS 17520, IS 20785), International Commission on Radiation Units (ICRU) Joint Report (84), International Electrotechnical Commission (IEC) SEE standard for avionics (IEC 62396), JEDEC Solid State Technology Association (JEDEC) SEE standard for avionics (JESD89A), World Meteorological Organization (WMO) observing requirements (#709, #738), and International Civil Aviation Organization (ICAO) regulatory guidelines (SARP 3.8.1); *ii)* national air traffic management (ATM) systems that are upgrading to NextGen and SESAR, for example; *iii)* commercial and corporate aircraft owners and their dispatchers using actionable information, often from third party weather providers; and *iv)* aircrew using actionable information and public education about potential risks.

Research data collection. A key condition for enabling all stakeholders to make their contributions in exposure mitigation is having quality dose measurements at altitude and emphasizing measurements at latitudes where the highest risks exist. Numerous measurements have been made and used for post-flight analysis (e.g., Dyer *et al.*, 1990; Beck *et al.*, 1999; Kyllönen *et al.*, 2001; EC Report 140, 2004; Getley *et al.*, 2005; Beck *et al.*, 2005; Latocha *et al.*, 2007; Meier *et al.*, 2009; Beck *et al.*, 2009; Dyer, *et al.,* 2009; Hands and Dyer, 2009; Getley *et al.*, 2010; Gersey *et al.*, 2012; Tobiska *et al.*, 2014), though the vast majority are for background conditions and not during major space weather events. Some of these have made neutron flux and dose equivalent measurements with solid-state detectors (e.g., Dyer, *et al.,* 2009; Hands and Dyer, 2009; Tobiska *et al.*, 2014). Together, these measurements have made important contributions to model validations of the radiation field at altitude, especially for human tissue issues. However, monitoring cannot be considered really effective until regular, validated, real-time, and global effective dose rate and neutron measurements (including the thermal component) are made. This capability does not yet exist and, because very few in-flight radiation measurements during significant solar particle events have occurred, it is critical that calibrated monitors are flown as widely and routinely as possible in order to maximize data capture that can both validate models and potentially be the basis of issuing alerts.

Future measurements. Total ionizing dose measurements such as those by Automated Radiation Measurements for Aerospace Safety (ARMAS) (Tobiska *et al.*, 2014) are an example of a surrogate index measurement that could be used in monitoring a real-time environment. Another example is the Space Weather D-index, based on dose rates at aviation altitudes produced by solar protons during solar radiation storms, as the relevant parameter for the assessment of corresponding radiation exposure (Meier and Matthiä, 2014). Recently, real-time assessment of radiation exposure due to solar energetic particle events have been presented at the 2014 European Space Weather Week (Liege, Nov. 2014) using the updated code AVIDOS 2.0 (Latocha *et al*., 2014; cf., European Space Agency's Space Weather Portal http://swe.ssa.esa.int). Two new instrument concepts include: *i)* the Dose Spectra from Energetic Particles and Neutrons (DoSEN) instrument (Schwadron *et al.,* 2013) for measuring not only the energy but also the charge distribution of energetic particles, including neutrons, that affect human and robotic health; and *ii)* the Thermalized Neutron Measurements (TiNMan) instrument for measuring thermal neutrons related to SEE in avionics (L. Dominic and S. Wender, private communication).

International scientific modeling using measurements. There are many modeling systems into which these types of data could be integrated, e.g., LUIN (O'Brien *et al.,* 1996), CARI6PM (Friedberg *et al.,* 1999; Friedberg and Copeland, 2003; Friedberg and Copeland, 2011), FLUKA (Zuccon *et al.,* 2001), QARM (Lei *et al.,* 2006), AIR (Johnston, 2008), PARMA (Sato *et al.,* 2008), AVIDOS (Latocha *et al*., 2009; Latocha *et al*., 2014), NAIRAS (Mertens *et al.,* 2013), PANDOCA (Matthiä *et al.,* 2014), and KREAM (Hwang *et al.,* 2014). Recent work by Joyce *et al.* (2014) utilized CRaTER measurements (Spence *et al.,* 2010; Schwadron *et al.,* 2012) in deep space to estimate dose rates through the Earth's atmosphere at a range of different altitudes down to aviation heights.

Further, different kinds of measurements are also needed including the SEE response of ICs used in avionics to high-energy neutrons; testing can be done in ground-based laboratories with simulated neutron beams. Per current guidelines (IEC 62396-1) the SEE response data would be combined with the output from in-flight neutron detectors to obtain SEE rates. ICs are constantly evolving with greater capability and ever-smaller feature size and, since these are being chosen for use in upgraded avionics systems, it is necessary to continue testing the newer electronics for their susceptibility to SEE from high-energy neutrons. For example, electronics parts testing at the Los Alamos Neutron Science Center (LANSCE) is an ongoing activity by many IC and avionic manufacturers. This facility is capable of closely simulating the high-energy atmospheric neutron energy spectrum at a neutron flux such that an hour of exposure at LANSCE is equivalent to 300,000 hours at 40,000 ft. Similar testing is also done in laboratories with thermal neutron sources. In addition, all ICs within a subsystem should be analyzed for their SEE rates using measured SEE cross sections. If the rates are combined for all ICs and protection factors built into the system (e.g., error correcting code), then an overall effective SEE rate can be obtained.

Action is needed at all levels. We recognize the value of stakeholders' efforts to mitigate potential exposure risks to humans and avionics from events that affect the aviation radiation environment. We also recognize that additional near-term action is needed to:

- expand international scientific research in the aviation radiation environment;
- develop reliable, new measurement systems that can provide calibrated real-time dose equivalence data for a highly mixed and changeable radiation field;
- obtain in-flight measurements during solar particle events in order to calibrate instruments and validate models;
- test semiconductor devices at a wide energy neutron source as part of certifying their use in avionics;
- continue and expand ground level neutron monitor measurements to record GLEs as a subset of SPEs;

- create new modeling systems that can assimilate real-time radiation data;
- discover and validate new forecasting capabilities;
- combine data and modeling for improved monitoring in an operational context;
- provide current condition information to decision makers (pilots and dispatchers);
- train decision makers on the information available;
- educate airline personnel, managers, dispatchers, and pilots on the exposures, measurements, risks, as well as mitigation techniques available;
- provide feedback to the scientific community on the adequacy of the information provided to the decision maker; and
- provide the public with scientific-based, but easily understood, information on the aviation radiation environment.

We conclude that, in order to improve aviation safety in a radiation environment, one must begin observing the weather of atmospheric radiation. Our current state-of-art technology only reports the data-driven climatology. The combination of low-cost, quality dosimetry measurements, integrated with modeling systems, does not yet exist. Using calibrated sensors at multiple, simultaneous altitudes from the surface to space, whose data can be used to validate algorithms and for assimilation into physics-based, global climatological models, is an important path toward producing a dose equivalent rate in tissue and a SEE error rate in avionics. With support for the above activities at an international level, air safety can and should be further improved in the arena of atmospheric radiation exposure risk mitigation for aircrew, the public, and avionics, particularly during severe radiation events. The need for these activities will only increase with time as air travel expands and as aircraft avionics technology advances toward greater miniaturization.

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