# **Space Weather**

# **RESEARCH ARTICLE**

10.1029/2019SW002190

#### **Key Points:**

- A new method of capturing atmospheric radiation data from ground-level enhancements (GLEs)
  Demonstrates the use of a citizen
- Demonstrates the use of a citizen science data gathering system, using handheld silicon radiation detectors as carry-on luggage items on commercial aircraft
- The system operates via USB-connected smartphones, running a new application on Android OS, to record and upload data to a centralized server

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# A Citizen Science Network for Measurements of Atmospheric Ionizing Radiation Levels

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**Abstract** Historically, gathering data on atmospheric radiation levels during solar particle events has been difficult, as there is little or no time warning of events. Being able to accurately quantify radiation levels within the atmosphere during solar events is of significance to the aviation industry, as described in the International Civil Aviation Organization's (ICAO) Space Weather manual. Particularly during a large ground-level enhancement (GLE) where the ionizing dose to passengers and crew can exceed the recommended general public annual dose limits, set by the International Commission for Radiological Protection (Barlett, Beck, Bilski, Bottollier-Depois, & Lindborg, 2004, https://doi.org/10.1093/rpd/nch232), in a single flight. The Smart Atmospheric Ionizing RAdiation (SAIRA) Monitoring Network is a new system of handheld radiation detectors that can be carried on aircraft to monitor and record atmospheric radiation levels. The system operates via citizen science volunteers, who record radiation data as they travel for normal purposes. Over 30 flights have been conducted with volunteers to demonstrate that a citizen science network is possible. Volunteers have used a new Android application to record and upload data to a central server to form a database of flight measurements. The demonstration has shown that there is a willingness in public volunteers to use radiation detectors and engage in science outreach. A fully developed system will ideally provide the capability to quantify radiation levels during a solar particle event or ground-level enhancement and the data can be used by relevant organizations to minimize potential risks.

## 1. Introduction

Space weather can create enhanced radiation environments within the Earth's atmosphere that pose a significant risk to the aviation industry (Royal Academy of Engineering, 2013). In quiet solar periods, atmospheric radiation primarily consists of flux generated from galactic cosmic ray interactions with upper atmospheric nucleii (Figure 1). These interactions generate showers of secondary radiation, including neutrons, which are the dominant contributor to dose (Hands et al., 2016), with the peak neutron intensity seen at 60,000 ft (18,000 metres), known as the Pfotzer-Regener maximum (Carlson & Watson, 2014). At commercial aviation altitudes, the flux level is typically 300 times that of sea level but this can be significantly heightened during a solar particle event (SPE) (Royal Academy of Engineering, 2013), where the flux can increase in a few minutes and last for several hours or even days. The solar energetic particles (SEPs) that arrive with these events pose an increased risk due to the ionizing radiation dose received both by the crew and passengers onboard. There are SPE occurrences that have significant flux of particles greater than 300 MeV, allowing the secondary neutrons to penetrate further into the atmosphere and increase of the flux at sea level. These events are called ground-level enhancements (GLE) and happen, on average, once a year; it is during a GLE that the greatest radiation it is during a GLE that the greatest radiation dose rates can be received.

It is widely known that exposure to ionizing radiation is hazardous to human health throughout the lifespan. The effects can be drawn into three categories: stochastic, which are probable long-term effects based upon biological effectiveness, deterministic, which are effects caused after a particular dose threshold has been received, such as cell death and tissue reactions, and hereditary effects passed on to children (Wakeford, 2015). Along with the biological dose risk, SEPs also pose a risk of inducing single event effects into electronic systems of aircraft, leading to potentially critical implications in avionic and safety systems onboard. Airlines in the EU are required to manage their crews according to the ionizing dose they receive, in order to prevent them from exceeding the annual limitations set in directive 2013/59/EURATOM (Euro-







**Figure 1.** Graphic displaying the creation of the secondary interaction radiation shower within the atmosphere. At commercial aviation altitudes, the radiation flux level is typically 300 times that of sea level and can be significantly heightened during a solar particle event (Royal Academy of Engineering, 2013). Image courtesy of National Aeronautics and Space Administration.

pean Parliament, 2014). However, and unusually for an environment where both workers and members of the public are exposed, there is no compulsory requirement for physical measurements. Exposure is calculated using generic dose models designed for normal galactic cosmic ray background dose conditions and up until recently did not factor in the enhanced radiation environment from the arrival of a SPE (Eurados, 2004). Models such as CARI (Copeland, 2017) and WASAVIES (Kubo et al., 2018) have now included SPE conditions; however, they are awaiting validation against physical measurements.

While the majority of commercial airlines have limited awareness to the risks posed by increased levels of radiation during a SPE or GLE, some airlines, such as Delta Airlines, take action, by rerouting or reducing altitude (Delta Airlines, 2010), when the National Oceanic and Atmospheric Administration issues an S3 proton flux warning (defined as >  $10^3$  protons cm<sup>-2</sup>·s<sup>-1</sup>·sr<sup>-1</sup> [>10 MeV] measured in geostationary orbit). However the "S" proton flux warning levels do not necessarily correlate with the flux of secondary particles in the atmosphere and can lead to false alarms as well as risking the lack of an alarm for relevant events (Royal Academy of Engineering, 2013; Meier & Matthiä, 2018).

Using detectors onboard aircraft to monitor the atmospheric radiation environment is an alternative approach. Detectors have been flown onboard aircraft previously, such as the Cosmic Ray Energetics and Mass detector on Concorde (Dyer et al., 1989), the Liulin detector with Czech Airlines (Dachev et al., 2015), and the Automated Radiation Measurements for Aerospace Safety detector units from National Aeronautics and Space Administration (Tobiska et al., 2016). However, flight measurements are sporadic in their nature, often only fitted to a single aircraft operating a specific route over a limited period. The unpredictability of SEPs and GLEs, along with this sporadic nature of in-flight monitoring to date, has resulted in very few data sets from GLEs recorded by monitors at aviation altitudes. The most notable of these are from 1989, where measurements were recorded onboard Concorde during GLEs 42 to 45 (Dyer et al., 1990).

An ideal solution would be for all aircraft to have radiation detectors fitted as standard; however, airlines are reluctant to install onboard monitors without an obvious financial incentive or compulsory regulation. Operating adetector requires time from the crew and detectors are thought to be cumbersome and heavy, such as theTissue Equivalent Proportional Counter, a propane-filled dose equivalent detector that weighs 10 kg withits carry case (Far West Technologies Inc, 2010) and is thought to be cumbersome and heavy. This, in turn, means aircrew are not provided with accurate measured dose reports for their specific flights, especially if a space weather event occurs. The almost instantaneous increases in radiation flux during a GLE (Dyer et al., 2017) does not provide a suitable warning timeframe to ready and launch any research aircraft to capture flux data. Hence, some efforts have been made for rapid response launches using weather balloons Dyer et al. (2018). However, the aim of the Smart Atmospheric Ionizing RAdiation (SAIRA) network is to create a new system that can constantly measure the radiation flux at aviation altitudes around the Earth on a 24-hr basis and therefore be able to provide new airborne datasets for GLEs.

## 2. SAIRA Network System Outline

#### 2.1. Citizen Science Data Gathering Approach

The Smart Atmospheric Ionizing RAdiation (SAIRA) Monitoring Network is the first system that proposes to use a citizen science model of data collection to vastly increase the amount of atmospheric radiation data that can be gathered. Citizen science research programs involve the use of public volunteers to help assist in either data gathering or basic data analysis. The public volunteers are treated as "field assistants," and by effectively utilizing them, periods of data gathering can be greatly extended or more widespread than a small team of dedicated researchers can achieve and at significantly less cost (Cohn 2008). This project is looking at the feasibility of using public "field assistants" to carry the SAIRA detectors on flights around the Earth. The core proposal is for these volunteers to carry a detector, as part of their carry-on luggage items into the aircraft cabin, which will be connected to their personal smartphone or tablet to operate it. Collected data are then uploaded to a central web-based server. A number of factors have changed in recent times to enable a citizen science approach to now be considered as an effective system. The first of which is the widespread use of smartphones and tablets by the general public and associated internet connectivity opportunities. People now view communicating with other electronic devices, such as TVs, and controlling data via their phones as a common feature and are more willing to accept using their phones as a host remote. Additionally, the reduced expense and increased speed of WiFi networks make internet hosted servers more accessible without the need to draw on a user's mobile data allowance. This is now extending to more widespread fitting of free high-speed WiFi onboard aircraft, an example of which is Inmarsat's European Aviation Network (Inmarsat Aviation, 2019). Lastly, recent relaxations of in-flight regulations around personal electronic devices (PEDs) present the opportunity to utilize the connectivity of smartphones and tablets while in the air (Portable Electronic Devices Aviation Rulemaking Committee, 2013).

The use of citizen scientists could vastly increase the amount of data about the atmospheric environment that can be gathered and released, with the added benefit that data can be recorded and released into the public domain without the restrictions that could be imposed on other approaches. The effectiveness of citizen science projects usually depends on how well the project and the science objectives are communicated to the public volunteers, along with how easy the research task is for volunteers to conduct. The simpler and quicker a task is to complete, the more the project is to get a larger number of active volunteers. The communication of the benefits of conducting the research, as well as the outcomes, is also key to the success of a citizen science project. Two important quotes taken from volunteers in a study on citizen science involvement are "What is exciting is knowing how scientists will use the data" and "We need to know how things are going" (Cohn, 2008). These demonstrate how the volunteers need to feel involved in the project by being





**Figure 2.** Range of responses to the survey question "Would you volunteer to carry a small handheld radiation monitor with you on your personal flights as part of a program that would contribute to scientific radiation research?" Over 60% of respondents were willing to volunteer provided they were given assurances about transporting the detector through airport security.

clearly able to see how it is progressing or what the research outcomes were that they directly contributed to, all of which leads to a feeling of reward for their effort. The European Citizen Science Association provides some useful information about citizen science engagement, including a guide outlining "10 principles of citizen science," highlighting points about volunteer engagement and how to keep them interested (European Citizen Science Institution, 2015).

As the SAIRA Monitoring Network is being designed as a potential tool for the scientific community, aviation authorities, airlines, and individuals to use, having the data publicly available held on a website would assist the engagement of volunteers and other enthusiasts to see how the data gathering and research outcomes are progressing. Further to this, using citizen science also provides an excellent science outreach possibility where the volunteers can be educated in the science of space weather and atmospheric radiation. The word "radiation" often generates concern in the general public and any opportunity to provide some simple education and context should be exploited.

#### 2.1.1. Volunteer Willingness and Concerns

We carried out an online questionnaire, via social media platforms, regarding perceptions of space weather and atmospheric radiation. Respondents were asked how willing they would be to take a detector with them on their personal flights. The majority of responses were positive with over 60% of the 50 respondents saying they would, though most would need some assurances about passing through airport security. The range of responses can be seen in Figure 2. Comments made by those that responded "No" were typically because they thought that they did not fly regularly enough to be of benefit to the system. Of all the potential volunteers that have been approached to carry out a flight test, only one person has declined to carry a detector. This was due to a fellow family member's security concerns and they did not want to upset that individual. At the time of writing, 17 different "ordinary traveler" volunteers have already carried a detector on at least one trip as part of their hand luggage.

#### Security

The main concern people have is whether it is acceptable to carry what, in their eyes, is an unconventional electronic device on an aircraft and whether they will be stopped at security. This is a legitimate concern as people fear that, with current anti-terrorism procedures, they will be stopped and asked questions about the detectors and, with limited knowledge to reply sufficiently, they might incur delays in their travel.

People are often unsure what regulations regarding electronic devices apply on an aircraft and what is restricted. The SAIRA detectors are classified as a passenger's PED, which according to the Federal Aviation Authority is "any piece of lightweight, electrically powered equipment. PEDs are typically consumer electronic devices capable of communications, data processing, and/or utility" (Portable Electronic Devices





**Figure 3.** Photos taken of early prototype Smart Atmospheric Ionizing Radiation detectors being operated by citizen scientist volunteers on flights BA776 on 14 September 18 and SN2096 on 4 November 18. Following these flights, feedback from volunteers requested a reduction in the size of the detectors, with the most recent prototype versions being reduced to  $130 \times 65 \times 40$  mm.

Aviation Rulemaking Committee, 2013). A requirement of electronic devices is that their operations must be demonstrated to security if requested. Typically, this is not needed; however, if asked, the volunteer can show the security staff simply enough using a connected smartphone.

Every volunteer in our work is provided with a signed letter from the research team, which details the research project, the organizations involved, and the contact details of the lead researchers in the event of concern. So far, no one has been stopped by security and the detectors have passed through 15 countries on three different continents. The detectors do not need to be removed from bags and simply pass through with everything else the volunteer is carrying. One volunteer deliberately notified security staff about the detector; the staff member replied to say they were interested in the project but had no concerns. Another volunteer was simply asked "Are you transporting a battery" to which the response was "yes" and no further questions were raised.

#### **Detector User Friendliness**

As mentioned above, the size of the SAIRA detector and ease of operation will be fundamental to the feasibility of this citizen science proposal. The detector must be handheld and not be a hindrance or inconvenience to a volunteer on their travels. Having a small device alleviates most of the potential inconvenience problems, and hence, this is a key design driver. Development has already seen the size of the detectors reduce from  $160 \times 90 \times 80$  to  $130 \times 65 \times 40$  mm, and feedback from the initial volunteer flight trials has indicated that it will need to be reduced in size further before production is scaled up. Development is continuing in order to reduce the detector units so that they can fit into a trouser pocket or handbag. Currently, the detectors are able to easily fit into a front seat pocket, and during flight trials, units have been operated in the lap of volunteers, in the seat pocket, on the tray table, and on the cabin floor. The device needs a stable platform in order to minimize potential shock vibrations, although an accelerometer is fitted to monitor shock forces so that erroneous data induced will be ignored.

#### 2.2. Detector Design

The SAIRA detectors, shown in Figure 3, use a silicon detector, which has been well established as a suitable technology for aviation dosimetry in previous work (Dyer et al., 2009). They are based upon the design of the Zenith Radiosonde detectors, also produced at the Surrey Space Centre (SSC) (Dyer et al., 2018) and therefore follow a similar design and specification. The detectors use a 18 mm ×18 mm ×300-um P-type Intrinsic N-type (PIN) diode coupled with a high sensitivity charge amplifier and four quad comparators that operate as a pulse height analyzer. When a particle interaction occurs within the PIN diode, a pulse of charge is created on the input of the charge amplifier (Figure 4). An equivalent voltage output pulse is

Table 1



Channel	Absorbed dose (Gy)
0	1.22E-10 to 1.47E-10
1	1.47E-10 to 1.86E-10
2	1.86E-10 to 2.49E-10
3	2.49E-10 to 3.48E-10
4	3.48E-10 to 5.05E-10
5	5.05E-10 to 7.52E-10
6	7.52E-10 to 1.15E-9
7	1.15E-9 to 1.83E-9
8	1.83E-9 to 2.82E-9
9	2.82E-9 to 4.39E-9
10	4.39E-9 to 6.86E-9
11	6.86E-9 to 1.09E-8
12	1.09E-8 to 1.72E-8
13	1.72E-8 to 2.71E-8
14	2.71E-8 to 4.28E-8
15	4.28E-8 to 6.75E-8

*Note.* The absorbed dose rating for each channel is listed in (Gy).

then generated, the voltage of which is dependent on the initial charge deposited in the PIN diode. The four quad comparators are used to assess and assign the equivalent voltage pulses into 16 channel bins, with the thresholds set in a logarithmic scale to cover input charge depositions of 200 keV to 100 MeV. Table 1 displays the energy deposition ranges for each of the channel outputs from pulse analyzer. The binary representation of each of the bin counts is then passed to a microcontroller for processing.

The microcontroller continuously analyzes the binary levels of the comparator outputs and collates the individual pulse channel counts. The count rates are then output via the Universal Serial Bus (USB) connection once a second. To minimize the risk of missing a pulse, the microcontroller is capable of running at 96 MHz, though this can be scaled back if longer battery life is required. For portability and recharging purposes, the device is powered by an external USB power source, such as a Li-Ion power pack.

#### 2.3. Smartphone Application

Together with the hardware, a smartphone application has been developed, and released onto the Google Play Store, to enable the sensor to be operated via a smartphone or tablet running Android 5.0.1 or later (Clewer, 2018). The application processes the incoming count rate data, via a USB On-the-Go cable and records this as a .csv file. As the intended operators of the sensor are public, citizen science volunteers, the application has a series of graphical displays that allow them to observe and interpret the incoming data while the detector is operating. The main screen shows the current radiation estimated absorbed dose rate, along with the total dose recorded and the hourly average for the duration of the flight so far. In order to give the users an approximation of the equivalent dose rates, the application displays an equivalent dose that is derived from the MAIRE model (RadMod Research Ltd) using channel weighting factors and the absorbed dose; however, this has not been fully calibrated yet. Also included are a series of the graphs that show the charge deposition rates throughout the flight, as well as showing the count rates and totals of the individual comparator channels; see Figure 5 for screenshots.

To give the user some form of associated risk level in the event of a GLE, the SAIRA system presents the level of radiation flux in similar terms to that of the D-Scale system created by the German Aerospace Center (Deutsche Zentrum fr Luft und Raumfahrt) (Meier & Matthiae, 2014). The D-Scale uses a series of linear increasing dose levels, given as an integer starting from 0 upward that correspond to an enhanced dose rate, given in micro sieverts per hour, above a specified background rate, which has been set at 6  $\mu$ Sv/hr in the application. This will allow the SAIRA Network to be incorporated as part of a space weather service as it





**Figure 4.** Block diagram of smart atmospheric ionizing radiation detector. The detectors use a Silicon P-type Intrinsic N-type (PIN) Diode as the radiation sensor, coupled with a charge amplifier and pulse analyzer in the form of four quad comparators. The data are then processed via an internal microcontroller that interfaces with the smartphone via a Universal Serial Bus (USB) On-the-Go (OTG) output.

will be providing warnings using a recognized system. The thresholds for the different D-Scale warnings can be found in Meier and Matthiae (2014).

The application is able to use the smartphone's inbuilt GPS receiver to record the GPS track over the duration of the flight in the same .csv file, if it is available. GPS reception inside an aircraft is variable at best and thus cannot be relied upon. From experience, it typically relies upon seat location and being in a window seat is often essential. Therefore, the SAIRA Network uses another service, detailed in section 2.4, to obtain the flight route navigation data. Acquiring the accurate location data of the recorded radiation data from SAIRA is a key aspect of enabling the system to be used as a global scientific service.

The Android application provides an excellent platform to be used as an educational tool as well as a data gathering system. As detailed earlier, citizen science programmes have the best engagement and results when the volunteers learn about the area of science involved, why the research is needed and how it could affect them. To assist with this, the application includes a variety of educational information about Space Weather, its interaction with the Earth and its effects, as well as information about radiation, explaining the units of measurement and providing an appropriate context as to how flights could be affected.

#### 2.4. Server Database and Website

When data are uploaded from the Android application, it is sent to a server running at the University of Surrey. The server processes the uploads in order to attach navigational data and organizes the recorded results into a database. The SAIRA flight radiation data need to be linked with the flight path by the server as radiation flux levels vary around the Earth and further so in SPEs. Historically, ad hoc monitors, such as Cosmic Ray Energetics and Mass, needed the navigational flight path to be recorded manually by pilots on paper, or, more recently, acquired from the logs in the aircraft's flight computers. The SAIRA system utilizes data from FlightRadar24.com, a live flight tracker web company, as the primary flight location data source. FlightRadar24 offer unlimited and unrestricted access to all the flight logs stored on their servers to anyone that is able to forward on Automatic Dependent Surveillance-Broadcast (ADS-B) transponder signal receptions from local aircraft. The flight log history is stored for 2 years, and any flight that has been tracked on the FlightRadar24 site has a log available to download. Each log has location data for the entire





**Figure 5.** Screenshots, taken from varying devices, of our Android application "SAIRA Network" that is available to download from the Google Play Store (Clewer, 2018). The SAIRA detectors connect to a phone or tablet, running Android 5.0.1 or later via USB OTG. The application then records and processes the data throughout the flight, before uploading the data to a server at the University of Surrey upon landing. The screenshots display the various graphics that the user can view to observe the data they are recording. As part of the citizen science concept, the application includes educational information about Space Weather.



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**Figure 6.** An example of a test website that has been created to demonstrate a method of communicating the collected data to the scientific community and citizen science volunteers. The web page shown provides an example of volunteer accessing their individual flight data. Citizen science research states that projects involving volunteers are most effective when they actively engage those volunteers with the ongoing research progress and completed outcomes (Citizen Science Association). Allowing them access to the gathered data through a website will assist in this commitment.

flight, usually updated in 15 second intervals, provided a feeder ADS-B receiver is in range of the aircraft. As the SSC can provide the ADS-B data needed, this provides an accurate, flight route history source to use if the smartphone is unable to record the location. FlightRadar24's global coverage rate, including noncommercial aircraft, makes it a highly reliable service that can effectively guarantee the exact flight route of any commercial flight used by this research.

In order to make the SAIRA Network usable as a dosimetry service, a publicly accessible website is currently being created to display the collected data, an internal developmental example of which is shown in Figure 6. The website would allow all of the recorded data to be publicly available for anyone to view and use as they need. The idea is that this will include individuals, airlines, and even aviation authorities, should the data be made available within a sufficient timeframe.

As explained earlier, in order to keep citizen science volunteers engaged in a project, they need to see how they have contributed to the overall outcome or data set. The SAIRA website would allow the volunteers to view the data they have recorded and submitted, thus enabling them to track their personal dose as well as see how they are contributing to the SAIRA project.

# 3. Flight Trials

Flight trials for the SAIRA Network began with a limited number of volunteers, flying for both business and short holiday trips, in the period June–August 2018. The first few flights were kept to within Europe with short return timeframes, with destinations such Corfu and Helsinki. The volunteers for these flights were



Table 2							
European Flight Routes Conducted as SAIRA Test Flights							
Flight			Aircraft	Cruising	Time	Absorbed	
number	Route	Date	type	altitude (ft)	recorded (hr)	dose (µGy)	
AY1332	LHR-HEL	27/06/18	A350	43,000	1.83	3.40	
AY1337	HEL-LHR	29/06/18	A320	34,000	2.43	2.21	
BA776	LHR-ARL	14/09/18	A320	39,000	2.27	1.81	
BA776	LHR-ARL	13/12/18	A320	37,000	0.93	1.28	
BA783	ARL-LHR	18/09/18	A320	37,000	2.3	2.34	
BA783	ARL-LHR	18/12/18	A320	34,000	2.62	2.75	
D89474	LGW-CFU	20/08/18	B737	37,000	3.13	2.20	
D89475	CFU-LGW	27/08/18	B737	38,000	2.13	1.91	
EZY8550	MJV-LGW	22/07/18	A320	37,000	2.7	2.62	
FR1546	FRA-STN	18/12/18	B737	3,000	1.3	0.62	
FR1687	STN-FRA	13/12/18	B737	35,000	1.13	0.59	
OK886	PRG-LED	05/01/19	A310	39,000	2.02	4.13	
SN2096	LHR-BRU	04/11/18	A310	23,000	1.28	0.25	
SN2095	BRU-LHR	08/11/18	A310	24,000	1.0	0.28	

given detailed instructions on how to operate the first prototype, as well as the flux readings they would expect to see. The unit used on these flights used power from four 9-V interal batteries for the analogue sensor circuit and power from the smartphone's USB connection for the digital section.

Upon completing the first few European flights, opportunities arose for some willing volunteers to carry the SAIRA detectors over to the United States. After starting long haul flights, there was a concern for battery life from the internal 9-V batteries. In order to allow the longer flight times and easy recharge by the volunteers, an upgrade was made to replace the internal batteries with an external power pack, explained in section 3.1.2. After this, the units were handed out for longer periods where volunteers were able to fly them on four or more flights in one trip, such as the domestic U.S. flights in October and November 2018, listed in Table 3.

#### 3.1. User Experience Feedback 3.1.1. Initial Prototype Flights

During the initial flight trials conducted in June/July 2018, the SAIRA device was known to have a potential hardware problem. This was due to the microcontroller digital circuitry being powered via the USB bus provided by the smartphone. The initial idea behind this was a test to see if the smartphone would be capable

Table 3           North American Flight Routes Conducted as SAIRA Test Flights								
Flight			Aircraft	Cruising	Time	Absorbed		
number	Route	Date	type	altitude (ft)	recorded (hr)	dose (µGy)		
AA2291	JFK-CLT	20/10/28	B737	24,000	2.23	0.70		
AA378	MIA-GCM	24/08/18	A319	34,000	0.92	0.44		
AA5040	JFK-RDU	04/11/18	CRJ7	30,000	1.63	0.76		
AA5073	CID-CLT	28/10/28	CRJ7	36,000	1.78	1.64		
AA574	CLT-JFK	28/10/18	A319	30,000	1.52	0.94		



of powering the whole detector. Inducing vibrations, and on some phones, operating the touchscreen caused erroneous readings to be recorded. The volunteers were made aware of this prior to the flight, and feedback was provided that they were overcareful when handling the detector and were worried they might be causing erroneous readings. This lead to them constantly checking the detector rather than leaving it alone and enjoying their flight.

The first volunteers to take a SAIRA detector transatlantic left both the detector and their phones alone for the majority of the flight, only checking them every few hours to make sure it was still running ok. This produced a more stable set of results and confirmed it was the interaction with the phone that was causing the reading problems.

While this digital hardware issues have since been resolved, the early volunteers who flew this prototype expressed a key point in their feedback that the release version of the detector must be able to be left alone and not be constantly monitored. Feedback has also indicated that the release version of the detectors needs to be further reduced in size, as this would enable them to easily stored away somewhere secure and be left to run without it preventing the volunteer from enjoying their flight.

#### 3.1.2. Li-Ion Power Bank Hardware Update

In addition to the digital USB power problem, a limiting factor to the initial volunteer runs was the battery life. The system was initially running off four 9-V batteries based upon the design of Zenith (Dyer et al., 2018). This lead to a limited operation time of approximately 24–30 hr. The internal arrangement of the detector meant that it needed to be dismantled in order to change the batteries. As it was not feasible for the volunteers to replace the batteries themselves, to prevent the risk of damaging the circuits, the volunteers were required to return the units after only a couple of flights. The use of batteries also meant that a switch was needed on the outside of the box, so the volunteers had to ensure the detector not switched on by accident in their hand luggage.

In order to increase the battery life and improve the user friendliness, the internal 9-V batteries were replaced by a power system that takes an external 5-V USB input, mainly Li-Ion power banks. By having the power source external, it enables the unit to be very light and thus improve the portability in hand luggage. The ability to use Li-Ion power banks also vastly increases the battery life as it can be extended by simply using a larger power bank, though 20,000 mAh is the typical limit imposed by airlines. A Li-ion bank of this size will power the detector for 100+ hr. Li-Ion power banks are also extremely simple to recharge and therefore volunteers can take detector units for extended periods of time. Adding this feature removed the need of a power draw from the smartphone USB bus for the digital circuitry, as a power bank has enough capacity to power both sections of the circuit for an extended period of time (30+ hr).

#### 3.1.3. Main Flight Trials

After the Li-Ion upgrade, four detectors were produced and used in circulation by different volunteers. Positive comments were made by volunteers who had flown the previous prototype about the weight decrease and the risk of no longer having the detector switch on in their bag. The extended battery life meant one volunteer was able to take the detector across to the United States for 2 weeks and record seven flights worth of data, two transatlantic and five domestic. There were some issues where the detectors would fail due to internal wiring connection problems; however, a new hardware iteration has solved this issue. Another upgrade had to be made, after two specific flight tests; the accelerometer thresholds were readjusted and as a precaution, the ability for trained users to change the sensitivity of the accelerometer in the SAIRA detector via the Android application was added. This was because after reducing the preprogrammed sensitivity of the accelerometer, to counter the effects of small vibrations, placing the detector on the cabin floor could cause the accelerometer to constantly flag a warning from the vibrations passing through the airframe of the aircraft. This lead to a loss of data on two flights from London to Japan and from London to Geneva. After the upgrade, the users reported they were now able to rectify this problem by reducing the sensitivity setting during the flight via the Android application. Users have since been able to record results for the full flight duration and successfully upload the data to the server over internet after landing.

Flight trials are expected to continue throughout 2019. There are opportunities to fly the detector alongside others on the Facility for Airborne Atmospheric Measurements 146 and the Met Office Civil Contingency Aircraft operated by the Met Office. There is also the target to prove the ability to stream real-time radiation data via free in-flight Wi-Fi by mid-2019.





BA207 23-08-2018

**Figure 7.** Plot of Smart Atmospheric Ionizing Radiation data from flight British Airways flight BA207 from London-Heathrow to Miami (MIA). The plot displays the recorded altitude, absorbed dose in  $\mu$ Gy/hr and the total counts recorded per minute for the duration of the flight based upon 1-min sample windows. The scatter of the absorbed dose compared to the total counts recorded in the differing energy bins. The effects on an increase in altitude are demonstrated when the aircraft increased altitude from 28,000 to 34,000 ft (8,530 to 10,360 m) near the Azores, with count rates going from an average of 30 per minute to 50 and absorbed dose increasing from approximately 1.4 to 2.5  $\mu$ Gy/hr.

#### 3.2. Flight Results

During the test flights conducted so far, SAIRA detectors have been flown on a variety of different routes with a range of latitudes and altitudes, ranging to 15 different countries on three different continents. Figures 7 and 8 show data sets from two of the flight tests conducted. The flight data shown are from BA207, from London-Heathrow (LHR) to Miami (MIA), and VS401, from Dubai (DXB) to London-Heathrow(LHR), respectively. Each of the figures shows the recorded total counts and absorbed dose rate, in µGy/hr, per minute, along with the navigational altitude for the duration of the flight. The absorbed dose rate is calculated by totalling up the counts recorded in each channel and multiplying by the median value in each of the channel weightings, specified earlier in Table 1. We will be calibrating the system to read Dose Equivalent in µSv/hr in due course according to Hands, A and Dyer, C (Hands & Dyer, 2009). Both graphs show a strong correlation between count rates and the altitude, as is expected. Figure 7 demonstrates the change in radiation received when an aircraft climbs between flight levels. The flight began the first part of its route at 28,000 ft (8,530 m) on the way toward the Azores; once past, it increased its altitude to 34,000 ft (10,360 m). Both the count and absorbed dose rates show a relative increase after this altitude change, with count rates going from an average of 30 per minute to 50 and absorbed dose increasing from approximately 1.4 to 2.5  $\mu$ Gy/hr, taken from 1-min sample windows. As well as the effects of altitude, Figure 8 shows the effects of latitude on the rates recorded by the SAIRA detectors. VS401 is a flight by Virgin Atlantic from Dubai (DXB) to London-Heathrow (LHR). As the flight progresses, and heads north, the rigidity reduces and, as expected, the recorded rates of both counts and micro grays per hour increase progressively even at the similar altitudes.

Tables 2–4 provide a list of the successful flight tests completed to date. Note that the data provided here are prior to the calibration of the SAIRA detectors, and the absorbed dose recorded is subject to a maximum of 20% uncertainty at the time of publishing. Flights have tended to be based out of London, typically from London-Heathrow and have flown to Continental Europe, Asia, and the United States. The flights are ongoing at the time of writing, having started in June 2018, and are expected to run into mid-2019. A plot of the





VS401 16-01-2019

**Figure 8.** Plot of smart atmospheric ionizing radiation data from Virgin Atlantic flight VS401 from Dubai (DXB) to London-Heathrow. (LHR). The effect of latitude, as the flight progressed north, can clearly be seen, with both total counts and absorbed dose per minute linearly increasing despite only a small change in altitude. The navigational flight path can be seen in Figure 10.

navigation routes of the successful flight tests is shown in Figure 9. SAIRA detectors have been flown by 17 volunteers using a variety of Android devices. Since an Android application update in September 2018, each flight recording by the SAIRA application asks the user to log their seat location after the server will obtain the aircraft type and identification from Flightradar24. This is accumulating data in order to accurately determine if there are any potential effects from the aircraft type and internal location on the recorded doses.

Figure 10 displays the recorded energy deposition spectrum from a select group of flights that highlight the effects on the radiation dose from both altitude and latitude. The graph displays the spectrum in terms of

Table 4           Long Haul Flight Routes Conducted as SAIRA Test Flights								
Flight			Aircraft	Cruising	Time	Absorbed		
number	Route	Date	type	altitude(ft)	recorded (hrs)	Dose (µGy)		
AA141	LHR-JFK	19/10/18	B777	36,000	7.67	11.7		
AA174	RDU-LHR	04/11/18	B777	37,000	5.35	8.82		
BA206	MIA-LHR	02/09/18	B747	35,000	8.52	10.5		
BA207	LHR-MIA	23/08/18	B747	32,000	8.9	7.46		
BA282	LAX-LHR	09/09/18	B747	35,000	10.18	8.26		
BA283	LHR-LAX	29/08/18	B747	36,000	11.13	10.2		
LH736	FRA-NGO	16/11/18	A340	35,000	9.83	16.0		
NH211	HND-LHR	13/10/18	B777	34,000	7.62	14.9		
VS401	DXB-LHR	16/01/19	A330	37,000	6.13	7.61		
Note SAIRA = smart atmospheric ionizing radiation								





**Figure 9.** Google Earth plot of the flight routes flown as part of smart atmospheric ionizing radiation network trials. Routes have been flown to 15 different countries on three different continents. The effects of latitude on atmospheric radiation levels are demonstrated by the flight routes between the United Kingdom and Japan and the United Kingdom and Dubai. Flight trials began in June 2018 and are expected to continue through 2019.

Counts MeV<sup>-1</sup>s<sup>-1</sup> with a data point for each channel. The background flux levels recorded at the SSC in Guildford, UK (51.24°N, 0.57° W, 150 ft above sea level) can be used as a comparison. The majority of the flight tests recorded follow as similar pattern to the results shown by flights BA207, AY1337, and BA282, with typical cruise altitudes of 34,000–36,000 ft (10,360-10,970 m). The effects of altitude can be seen by the lines drawn for flights AA2291 and AY1332, dark blue and light blue, respectively. AA2291 was a domestic U.S. flight that flew from New York (JFK) to Charlotte (CLT) with a cruise altitude of only 24,000 ft (7,315 m). The count rates are approximately half the typical flight profiles shown by BA207, AY1337, and BA282, with the medium to high linear energy transfer more equivalent to background levels. The opposite is the case for flight AY1332, recorded onboard an Airbus A350 aircraft from London-Heathrow (LHR) to Helsinki (HEL), with a cruise altitude of 43,000 ft where the recorded count rates are clearly higher than those of the other typical flights. Flights over the polar region have a higher energy deposition spectrum, shown by NH211, Tokyo-Haneda (HND) to London-Heathrow (LHR), and LH736, Frankfurt (FRA) to Nagoya (NGO), in channels 4–15. The spectrum for LH736, marked in light green, matches that of the high-altitude flight of AY1332, despite cruising 7,000–8,000 ft (2,130-2,440 m) lower, and the spectrum for NH211, in purple, exceeds this further still with a cruise altitude of 24000ft (7,315 m).

The reduced count on some flights in channel 0, compared to channel 1, is currently being investigated and is being attributed to results from one specific detector, which is an older prototype. This is not a major concern as channel 0 has the smallest weighting factor when converting to equivalent dose.

# 4. Future Work

The SAIRA Monitoring Network is proving that the concept of using citizen science to monitor atmospheric radiation levels is feasible, given that it is otherwise difficult to obtain routine, long-term in-flight measurements. Over 30 flights have been successfully completed by 17 volunteers traveling to 15 different countries

Flight Counts per Channel



**Figure 10.** Comparison of the average counts  $MeV^{-1}s^{-1}$  from flights of smart atmospheric ionizing radiation detectors. The legend has a note for each flight to its corresponding data table. The plots from flights AY1332, at 43,000ft (13,100 m), and AA2291, at 24,000ft (7,315 m), highlight the difference in energy spectrum while flying at differing altitudes. In addition, two polar flight routes between London and Japan are included to show the increase in counts in bins 4–15 when flying at high latitudes compared to flights at lower latitudes but similar cruise altitudes.

on three continents. Volunteers have carried the SAIRA detectors as part of their carry-on hand luggage and have used a newly created Android application, available on the Google Play Store Clewer (2018), to record and process data. An internal developmental website has been constructed that allows flight data to be uploaded upon landing directly to a server at the University of Surrey. Flight results have been obtained from domestic and international flights, and trials will continue through 2019 in order to gather further feedback from volunteers, before evaluating larger-scale production. Volunteer feedback has driven both the development of the Android application, with new features or bug fixes implemented in response to feedback, and the hardware design of the detectors themselves. A key detector design modification, driven by users, was to allow the detectors to power of an external USB source, such as an LI-Ion power bank, so that the detectors were easy to recharge and keep powered off while being transported in hand luggage. Development is continuing to reduce the size of the detectors further still, having already produced a smaller version since the initial flight trials.

Flight trails need to be continued on repeating routes to prove the reliability of the system, and additional flights to cross calibrate SAIRA against other detectors are essential to accurately report equivalent dose levels. The devices are uncalibrated at the time of publishing; however, equivalent dose calibration analysis is currently under way, using cross calibration with other instruments, including Tissue Equivalent Proportional Counter and RaySure units, the results of which are expected to be produced in later 2019. Volunteers have expressed a wish in being able to assist in demonstrating a real-time data stream direct from an aircraft. The completion of a reliable WiFi data stream will enable the SAIRA Monitoring Network to demonstrate the ability to actively report the arrival of SPE and GLE events to the aviation authorities, airlines, and scientific community in real time. An investigation into the potential societal impacts of providing the general public the capability to record radiation also needs to be completed, as well as the response of the airlines of publicly available measured dose data. The SAIRA system will be especially beneficial during the next GLE to gain a much wider range of in-flight measurements. It is hoped that this project will help persuade



airlines to engage in-flight dosimetry and raise awareness with their crews and passengers about radiation from space weather events and its potential effects.

#### Acronyms

- **ADS-B** Automatic Dependent Surveillance-Broadcast
- ARMAS Automated Radiation Measurements for Aerospace Safety
- CREAM Cosmic Ray Energetics and Mass
  - DLR Deutsche Zentrum fr Luft und Raumfahrt (German Aerospace Center)
  - FAA Federal Aviation Authority
  - FAAM Facility for Airborne Atmospheric Measurements
    - GCR Galactic Cosmic Rays
    - GLE Ground-Level Enhancement
  - ICAO International Civil Aviation Organization
  - ICRP International Commission on Radiological Protection
  - LET Linear Energy Transfer
- **MOCCA** Met Office Civil Contingency Aircraft
  - NASA National Aeronautics and Space Administration
  - NOAA The National Oceanic and Atmospheric Administration
    - OTG On-The-Go
    - **PED** Personal Electronic Device
    - PIN P-type Intrinsic N-type
  - SAIRA Smart Atmospheric Ionizing Radiation
    - SEE Single Event Effect
    - SEPs Solar Energetic Particles
    - SPE Solar Particle Event
    - SSC Surrey Space Centre
  - TEPC Tissue Equivalent Proportional Counter
  - USB Universal Serial Bus

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