Zenith: A Radiosonde Detector for Rapid-Response Ionizing Atmospheric Radiation Measurements During Solar Particle Events

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Abstract Solar energetic particle events create radiation risks for aircraft, notably single-event effects in microelectronics along with increased dose to crew and passengers. In response to this, some airlines modify their flight routes after automatic alerts are issued. At present these alerts are based on proton flux measurements from instruments onboard satellites, so it is important that contemporary atmospheric radiation measurements are made and compared. This paper presents the development of a rapid-response system built around the use of radiosondes equipped with a radiation detector, Zenith, which can be launched from a Met Office weather station after significant solar proton level alerts are issued. Zenith is a compact, battery-powered solid-state radiation monitor designed to be connected to a Vaisala RS-92 radiosonde, which transmits all data to a ground station as it ascends to an altitude of ~33 km. Zenith can also be operated as a stand-alone detector when connected to a laptop, providing real-time count rates. It can also be adapted for use on unmanned aerial vehicles. Zenith has been flown on the Met Office Civil Contingency Aircraft, taken to the European Organization for Nuclear Research-EU high energy Reference Field facility for calibration and launched on a meteorological balloon at the Met Office’s weather station in Camborne, Cornwall, UK. During this sounding, Zenith measured the Pfotzer-Regener maximum to be at an altitude of 18–20 km where the count rate was measured to be 1.15 c s⁻¹ cm⁻² compared to 0.02 c s⁻¹ cm⁻² at ground level.

1. Introduction

The atmospheric radiation environment is generated by galactic cosmic rays (GCR) along with their interaction with the upper atmosphere. At high altitudes, the environment is dominated by high-energy primary GCR, consisting of protons, alpha particles, and heavy ions. As the GCR traverse down to lower altitudes they interact with the atmosphere producing secondary spallation products such as neutrons, protons, electrons, alpha particles, pions, muons, and photons. This combination results in a peak in the intensity of the radiation environment, known as the Pfotzer-Regener maximum (Carlson & Watson, 2014), at an altitude in the region of ~18 km (~60,000 ft). The flux of GCR seen by the Earth varies inversely with the solar cycle through the ebb and flow of the solar wind and the heliospheric field carried with it (Badhwar & O’Neill, 1996). However, solar energetic particles (SEPs) can also increase the intensity of the atmospheric radiation environment by orders of magnitude (Lantos & Fuller, 2004), where the increase in flux can occur in a matter of minutes and can persist on the order of hours to days. These SEPs are accelerated by rapidly changing magnetic fields close to the Sun and shock waves in the solar wind. This can pose a threat to aircraft avionics via single-event effects (SEE) and can also increase the radiation dose received by passengers and crew. Currently, all crew and passenger dose calculations are carried out retrospectively (Bottollier-Depois et al., 2009), leaving the possibility of legal dose limits being exceeded. A ground level enhancement (GLE) is considered to occur when the SEPs have sufficient energy and intensity to significantly enhance the secondary radiation environment at ground level (Bazilevskaya, 2005).

A number of radiation monitors have been developed, some are based on the use of gas-filled vessels such as the tissue equivalent proportional counter (TEPC) and others use solid-state sensitive volumes. Many solid-state detectors utilize PIN diodes, a diode consisting of the standard p- and n-type semiconductors but with an intrinsic semiconductor between these layers providing a far larger reverse biased depletion region than normal diodes. Solid-state-based instruments vary in complexity and sensitivity; the large surface area PIN-diode instrument RaySure (Dyer et al., 2009) has been modeled with Monte Carlo simulations and calibrated through ground testing, flights, and collateral measurements with TEPCs. In the past, the
instrument Cosmic Radiation Environment and Activation Monitor has been flown on Concorde (Dyer et al., 2003). Liulin is another PIN-diode-based instrument, where different variants have been extensively tested and flown. An overview of Liulin’s development can be found in Dachev et al. (2015). However, beyond calibration phases, few radiation monitors are routinely flown, and to date, the majority of the data collected represents GCR background conditions rather than space weather events (Tobiska et al., 2016).

Meteorological balloon-borne space weather monitoring allows the measurement of the atmospheric radiation environment from ground level to high altitudes (~35 km) giving information of the environment’s evolution with altitude. These balloon-borne systems have a long heritage; for example, the Lebedev Physical Institute has been active in this area since the 1950s (Stozhkov et al., 2009). Recently, a collaborative meteorological balloon launch, called Radiation Dosimetry Experiment (RaD-X), has been carried out by NASA (Mertens, 2016), where several instruments were flown to an altitude of 38 km, with supporting measurement from various flight and ground test campaigns. A summary of the acquired data can be found in Mertens et al. (2016) and Hands, Ryden, and Mertens (2016). Other groups have taken atmospheric radiation environment recordings on meteorological balloons such as the “Earth to Sky Calculus” group (Phillips et al., 2016) using commercial X-ray and gamma-ray dosimeters. A scintillator-based detector has also been developed by University of Oxford and University of Reading (Aplin et al., 2017); however, their work is focused on determining any effect the radiation environment has on weather systems. By contrast the work presented in this paper concerns SEEs in avionics and crew/passenger biological dose. Instruments like Zenith and the others mentioned will assist in the international effort toward observing and understanding the atmospheric radiation environment with the aim of mitigating atmospheric radiation risks as discussed in Tobiska et al. (2015), Dyer et al. (2003), and Royal Academy of Engineering (2013). Collaboration with other groups such as Yaniv et al. (2016) and Makhmutov et al. (2015) will provide an understanding of space weather events at different geomagnetic rigidities, while measurements from aircraft flights will further enhance the data set by providing continuous data over a range of geomagnetic rigidities.

The aim of this work is to develop a rapid-response system, which is operated 24 h a day and capable of measuring the evolution and impact of GLEs from ground level up to an altitude of ~35 km. This approach has also been suggested by Nicoll and Harrison (2014). After the completion of initial work, it is hoped that Zenith will be stationed at different locations covering a range of geomagnetic rigidities, with the UK well-placed covering 50°–60° in latitude. Zenith has been specifically designed as a rapid launch system where instruments are ready to be launched in response to the detection of an event, giving local temporal information of its evolution. The use of a solid-state silicon-based PIN diode lends itself well to the calculation of SEEs in silicon-based components used in avionics. Ambient dose equivalent can be calculated from the energy deposition spectra recorded by Zenith through processes such as “millidosimetry” outlined in Hands and Dyer (2009).

Devices such as Zenith will assist the aviation industry in making informed decisions as to when action is needed in response to space weather. Currently, some airlines take action when the National Oceanic and Atmospheric Administration (NOAA) issue a S3 warning (defined as >10^3 protons cm^-2 s^-1 sr^-1 (>10 MeV) measured in geostationary orbit). However, these events do not necessarily increase aircraft dose (Royal Academy of Engineering, 2013) where the validity of this warning system can be further determined by our instrument. Zenith has been designed to be operated, in terms of connection, data transfer, and storage, in the same way as Vaisala’s own external instruments, this has been done for ease of use, allowing it to be launched by the Met Office as and when the appropriate alert is issued.

2. Instrument Description

Zenith’s main objective is to accurately record 120 keV–100 MeV energy depositions in silicon. The energy depositions are registered within a number of discrete energy bins so that an “energy deposition spectrum” can be plotted. During a GLE the particle flux could be orders of magnitude greater than the normal radiation environment. Under normal conditions the count rate seen at the Pfitzer-Regener maximum is expected to be on the order of 1 c s^-1 cm^-2, while during a GLE the count rate could potentially reach 1,000 c s^-1 cm^-2.

To reliably measure these events, Zenith has been designed and laboratory tested to accurately record count rates up to 1,500 c s^-1 cm^-2. Zenith’s observation window can also be varied depending on the environment.

2. Zenith
it is used in. Throughout this paper a 60 s window was used, where the dead time was measured to be 40–70 ms per window.

Zenith is light-weight (420 g with batteries/220 g without), small (220 × 145 × 80 mm), low-current (<50 mA), and has been designed to withstand the challenging physical environment it will experience on a typical meteorological balloon flight. On these soundings Zenith will reach an altitude of ~35 km, exposing it to turbulence, moisture, and temperatures down to −65°C. To mitigate this, Zenith has been encapsulated in an IP54 rated and radio frequency shielded enclosure, stopping water ingress and providing shielding from the radiosonde’s transmitter. Polystyrene has also been fitted as insulation, and to ensure normal operation, Zenith has been tested in a low-temperature environment, reaching −70°C through the use of dry ice.

The design of Zenith can be split into two top-level areas, the front-end and back-end; this can be seen in Figure 1. The front-end consists of a large surface area 3.24 cm² PIN diode, a charge amplifier, and a bank of 16 comparators operating as a pulse height analyzer. When the radiation environment impinges on the PIN diode a pulse of charge is generated, the charge amplifier then outputs an equivalent voltage pulse, where the amplitude is dependent on the amount of charge liberated by the event. The output of the charge amplifier is then assessed by the logarithmically scaled voltage comparators to determine if their threshold has been met. The resultant binary representation of the event pulse height is then passed on to the back-end circuitry.

The back-end consists of a microcontroller and its supporting circuitry, including a microSD and MicroWire communications interface. The microcontroller monitors the output of the comparators, bins each event, keeps the time for observation windows, and transfers the accrued bin data for internal or external storage.

Vaisala’s RS92-SGP radiosonde is used by the UK Met Office and offers a connector for external instruments, primarily for Vaisala’s ozone monitor. However, other third-party instruments, such as Zenith, can also be connected. The data from the instrument is transferred, in a similar fashion to Reading University’s RS92-SGP/instrument interconnector the PANDORA (Harrison, Nicoll, & Lomas, 2012), through the RS92’s serial peripheral called MicroWire using Vaisala’s propriety protocol. The RS92 then transmits these data down to Vaisala’s ground station software, DigiCORA, at a rate of 80 bits/s. A frame of Zenith’s data takes four consecutive transfers to complete with each transfer starting with a unique header allowing postprocessing to determine if any data has been lost. Depending on the wind conditions at different altitudes, the radiosonde can travel great distances, which means there is a high chance of Zenith landing at sea. However, as the data have been transmitted throughout the flight, it is not vital to retrieve Zenith or the radiosonde and the UK Met Office does not usually do so. To this end, Zenith has been designed to meet the UK Met Office’s requirements of disposability.
Zenith can also be operated as a stand-alone radiation detector onboard a plane or at a ground test facility, where the data can be stored either inside the microcontroller or on a microSD card; once the observation period has finished, the data can be extracted for analysis. Alternatively, Zenith can be controlled by LabView, via a personal computer, where live and accumulated count rates can be monitored through a graphical user interface as well as being stored in an accessible .csv file.

3. Calibration and Flight Data

Zenith (Figure 2) has been deployed in several environments; at 24,000 ft (7.3 km) in Met Office Civil Contingency Aircraft (MOCCA), at the accelerated radiation environment produced by European Organization for Nuclear Research (CERN)-EU high energy Reference Field (CERF), and on a meteorological balloon released from Camborne, UK, which ascended to an altitude of ~33 km. These observations will be explained in more detail below.

3.1. Energy Bin Calibration

The energy thresholds of the comparator bins are determined by using the precision pulse generator Ortec 419, which emits pulses at a known frequency. It was used to produce pulses of negative polarity on one terminal of a measured 2.0 pF capacitor; the other terminal is connected to the charge amplifier that senses a charge proportional to the amplitude of the pulse. The calibration was achieved by varying pulse amplitude, while the outputs of the comparators are monitored and counted; when half of the pulses were counted in the lowest energy bin, this was determined to be Zenith’s lowest threshold. The pulse amplitude was then increased until the lowest and second lowest energy bins split the counts equally; this process was then repeated for the remaining bin boundaries. It should be noted that the highest energy bin does not have an upper boundary in terms of an event energy deposition. However, the charge amplifier is limited to a maximum amplification that is equivalent to 100 MeV, any greater energy deposition in the PIN diode is amplified to this upper limit, and the log resistor ladder has been designed to match this upper limit. Therefore, the analysis in this paper used an energy threshold of 100 MeV for the highest energy bin. The energy thresholds determined by this calibration approach are used throughout the analysis in this paper; however, they will be refined and validated at a particle accelerator facility in the future. In addition, further work is needed to determine how ambient dose equivalent can be calculated from Zenith’s binned energy deposition data. In this paper, all dose estimates relating to Zenith in this paper are derived from other instruments or through simulation.
3.2. UK Met Office MOCCA Flight

The UK Met Office charters a plane called MOCCA that is operated out of Bournemouth Airport in the UK. This presented an opportunity to test Zenith in a more intense radiation environment than that seen at ground level. Three separate flights were carried out where the pressure altitude FL240 (~24,000 ft/7.3 km) was maintained for extended periods allowing a total of 90 min of data to be recorded with Zenith’s observation window set to 60 s. For comparison, the calibrated RaySure monitor (Hands & Dyer, 2009) was also operated on these flights with the same duration observation window.

The data recorded by both Zenith and RaySure needed to be compared to each flight’s flight-log to determine when FL240 was attained and lost. Zenith uses a simple internal time stamp, which is referenced to the time at which it was turned on, while RaySure logs a coordinated universal time timestamp. A conservative approach was taken in determining which data to keep, whereby the first 2 min of data after the logged arrival at FL240 along with the last 2 min before MOCCA descended were discarded.

These data have been analyzed, and a count rate for each bin has been calculated by using each bin’s midpoint energy and each instrument’s PIN diode area resulting in the quantity counts per second per MeV per cm². The error for each bin has also been calculated using a 95% confidence level Poisson distribution; for further reading, the methodology is described here (European Space Components Coordination, 2014).

The response of both devices has also been simulated using the atmospheric radiation model MAIRE (Model for Atmospheric Ionising Radiation Effects) (RadMod, 2017) by RadMod Research Ltd and the radiation transport tool MULASSIS (Multi-Layered shielding simulation analysis), which is available in SPENVIS (Space Environments Information System) (Lei et al., 2002). MAIRE is used to model the primary and secondary atmospheric radiation environment for specific locations, dates, and altitudes, producing fluence outputs. This simulated environment is then used as an input for MULASSIS to calculate count rates based on the dimensions of each instrument’s PIN diode and bin threshold levels. These are shown in Figure 3.

Zenith and RaySure show reasonable agreement with each other across the range of deposition energies. At higher energies, a greater level of variability can be seen but this is believed to be due to the short observation period and stochastic nature of the atmospheric radiation environment. Zenith also appears to show an increased sensitivity at the lower energies when compared to the simulation. Further observations are needed to determine the nature of this over sensitivity, where initial investigations will

Figure 3. Zenith and RaySure MOCCA energy deposition profile and simulation at FL240, where Zenith and RaySure show reasonable agreement with their simulated response. The error for each bin has also been calculated using a 95% confidence level Poisson distribution.
determine whether microphonics is the source. The simulated response for RaySure is also lower than that recorded on the FL240 flights. These discrepancies between simulated and recorded count rates for both instruments need to be investigated. The change in rigidity cutoff over the flight path has also been investigated through MAIRE showing a variation of 0.1–0.2 GV for the flights, resulting in a change of <2% in the simulated atmospheric radiation environment. This variation cannot be assessed by either Zenith or RaySure as the statistical errors associated with the data collected is >10%. A far larger data set would need to be collected to observe any spatial dependence on a flight path of this length.

3.3. CERN-EU High Energy Reference Field (CERF) Facility

CERF is a well-documented reference facility for aviation dosimetry, closely replicating the neutron environment produced by cosmic rays at commercial aviation altitudes but at higher fluxes. This allows accelerated tests to be carried out to confirm Zenith’s capability of accurately monitoring the radiation environment during extreme space weather events, i.e., at high flux. The operation of CERF is briefly described here to highlight its differences to the neutron environment at aviation altitudes as well as the limitations of the results presented in this paper. A full description of CERF can be found in Mitaroff and Silari (2002), which also includes Monte Carlo, specifically FLUKA, simulations of the environment.

An axonometric representation of CERF’s layout can be seen in Figure 4, showing the position of the Top Concrete location relative to the copper target, which is irradiated by 120 GeV c⁻¹ positive particles (35% protons, 61% pions, and 4% kaons) to produce spallation products. These secondary particles are then attenuated as they propagate through 80 cm of concrete to generate the desired radiation environment. Throughout the two experiment runs, Zenith was located in 1 of the 16 designated “Top Concrete” positions shown in Figure 5.

The CERF facility quantifies the intensity of the beam with the precision ionization chamber (PIC) instrument placed in the beam just upstream of the copper target. One PIC-count corresponds to $2.2 \times 10^4 \pm 10\%$ particles impinging on the target. CERF operates in a cyclic fashion where particles impinge on the target for 5.1 s of each 18.6 s cycle. The beam intensities quoted in this work are the measured PIC counts per cycle averaged over the experimental run. Typical values of ambient dose equivalent rates (for the entire linear energy transfer (LET) spectrum) are 0.3 nSv per PIC-count at Top Concrete. For positions T4 and T6, the FLUKA simulated reference values are 185 and 270 pSv per PIC-count, respectively (Mitaroff & Silari, 2002).

![Figure 4. Axonometric view of the CERF facility (Mitaroff & Silari, 2002) showing location of Top Concrete with respect to the copper target.](image)

![Figure 5. a) Image showing Zenith (circled, in position T6, LabView USB SPI transceiver and USB extension cable. b) Diagram of the 16 positions for Top Concrete; the arrow indicates the path of the beam and the grey box represents the copper target (Mitaroff & Silari, 2002).](image)
Zenith was placed in position T6, on top of a yellow block to elevate the sensitive volume (PIN diode) to the height (25 cm) at which all reference measurements are made. Zenith is connected to a USB SPI transceiver, which is then connected to a laptop running LabView in the control room. Zenith was oriented with its sensitive volume facing the radiation source and irradiated with the full range of intensities available at CERF. The PIC instrument measured this to range from 399 to 4578 PIC counts per cycle. To estimate the dose rate at T6, the rates measured by the Long Interval Neutron Survey Meter (LINUS) instrument at T4 were converted via the ratios found in Mitaroff and Silari (2002) to a dose rate of 20.6 to 212.5 μSv h⁻¹. Zenith was started and stopped in line with each experiment run, with the irradiation runs intended intensity logged. The actual PIC count and dose observed at T4 by LINUS for each experiment were logged by the CERF team and subsequently used in this analysis. These values can be seen in Table 1.

The first run lasted 60 min and was setup to deliver the maximum flux permitted, ~4,500 PIC counts per cycle, after which runs of roughly 15 min were carried out with decreasing fluxes, down to ~375 PIC counts per cycle. Afterward, a run was carried out with the collimators closed to obtain the downstream (from the Super Proton Synchrotron (SPS)) background radiation profile. Once this was completed the SPS experienced a fault and ceased operating; Zenith was left running for a further 30 min to observe the true background radiation. These results have been plotted in the graph shown in Figure 6, along with the data from the averaged FL240 flights on MOCCA and ground observations at Surrey Space Centre, Guildford, UK.

![Figure 6. CERF and MOCCA FL240 energy deposition profiles compared, where Zenith accurately recorded an environment orders of magnitude stronger than that normally seen at aviation altitudes. There is also a clear count rate enhancement in the 1–5 MeV energy deposition range; this is partially due to the background low-LET muons present at CERF. The error for each bin has also been calculated using a 95% confidence level Poisson distribution.](image)

Table 1
Describing the Desired PIC Count, Duration, Actual PIC Count, and Ambient Dose Equivalent Measured by the LINUS Instrument at T4 for Each of the Irradiation Runs Carried Out at CERF With Zenith Located at T6

| CERF PIC setting | Duration (s) | Measured PIC count per cycle | Dose at T4 (nSv s⁻¹) | Dose estimate at T6 (nSv s⁻¹) | Dose estimate at T6 (μSv h⁻¹) |
|------------------|--------------|-------------------------------|----------------------|-----------------------------|-------------------------------|
| 4,500            | 3,540        | 4,537                         | 40.0                 | 58.4                        | 210.1                        |
| 4,400            | 960          | 4,578                         | 40.4                 | 59.0                        | 212.5                        |
| 3,900            | 900          | 4,000                         | 35.2                 | 51.4                        | 184.9                        |
| 3,000            | 1,020        | 3,157                         | 27.6                 | 40.3                        | 145.0                        |
| 2,600            | 1,080        | 2,722                         | 23.8                 | 34.7                        | 125.0                        |
| 2,000            | 1,500        | 2,046                         | 18.0                 | 26.3                        | 94.5                         |
| 900              | 1,020        | 896                           | 8.0                  | 11.7                        | 42.1                         |
| 375              | 1,200        | 399                           | 3.9                  | 5.7                         | 20.6                         |

Zenith was placed in position T6, on top of a yellow block to elevate the sensitive volume (PIN diode) to the height (25 cm) at which all reference measurements are made. Zenith is connected to a USB SPI transceiver, which is then connected to a laptop running LabView in the control room. Zenith was oriented with its sensitive volume facing the radiation source and irradiated with the full range of intensities available at CERF. The PIC instrument measured this to range from 399 to 4578 PIC counts per cycle. To estimate the dose rate at T6, the rates measured by the Long Interval Neutron Survey Meter (LINUS) instrument at T4 were converted via the ratios found in Mitaroff and Silari (2002) to a dose rate of 20.6 to 212.5 μSv h⁻¹. Zenith was started and stopped in line with each experiment run, with the irradiation runs intended intensity logged. The actual PIC count and dose observed at T4 by LINUS for each experiment were logged by the CERF team and subsequently used in this analysis. These values can be seen in Table 1.

The first run lasted 60 min and was setup to deliver the maximum flux permitted, ~4,500 PIC counts per cycle, after which runs of roughly 15 min were carried out with decreasing fluxes, down to ~375 PIC counts per cycle. Afterward, a run was carried out with the collimators closed to obtain the downstream (from the Super Proton Synchrotron (SPS)) background radiation profile. Once this was completed the SPS experienced a fault and ceased operating; Zenith was left running for a further 30 min to observe the true background radiation. These results have been plotted in the graph shown in Figure 6, along with the data from the averaged FL240 flights on MOCCA and ground observations at Surrey Space Centre, Guildford, UK.
Zenith shows a fairly consistent energy deposition spectrum over the full range of intensities; however, there is an enhancement in the 1–5 MeV range, which is not seen in Zenith data from other environments. From the work carried out in Mitaroff and Silari (2002) it is known that there is a significant low-LET background radiation field at Top Concrete, which is mostly independent of the hadron beam’s intensity. The source of this is mainly high-energy muons from pion decay in the beam line or hadron beam losses from upstream or neighboring beam lines. While Mitaroff and Silari (2002) offers no specific muon energy ranges due to the environments variability, the enhancement observed by Zenith looks to be consistent with that described in the paper. In Figure 7, this background muon environment has been subtracted from each experiment run reducing the enhancement; however, it is still prominent for the lower intensity runs; this needs to be investigated further during future campaigns at CERF. As can be seen from the graph the radiation environment at the lowest CERF intensity is still an order of magnitude greater than that seen during the FL240 flights. For the 399 PIC irradiation a rate of 20.6 μSv h⁻¹ was estimated by LINUS; for comparison, the MAIRE simulated ambient dose equivalent at FL240 was found to be 1.5 μSv h⁻¹.

3.4. Meteorological Balloon Flight

At the UK Met Office’s weather station in Camborne, Cornwall, UK, Zenith was setup with a RS92-SGP radiosonde and the ground station software DigiCORa. After verifying that DigiCORa’s manual flight mode was working and all data were being received and recorded, both Zenith and an RS92 were launched on a helium filled meteorological balloon as shown in Figure 8.

Zenith ascended for 100 min to an altitude of ~33,500 m at which point the balloon burst, Zenith then descended for a further 55 min until radio contact was lost at an altitude of ~1 km. During the flight, the radiosonde reported wind speeds of up to 20 m s⁻¹ and temperatures as low as −61°C with Zenith functioning continuously throughout. After contact was lost, the manual flight mode in DigiCORa was concluded and the data were exported for analysis.
The raw count rate from Zenith varies from minute to minute by up to a factor of 3; this is partly due to the stochastic nature of the radiation environment, but there are also other factors such as turbulence, which may affect the count rate through microphonics in the unsupported PIN diode. Figure 9 shows the ascent data after it has been smoothed by a 10 min rolling average; a clear peak in the count rate at ~18–20 km (~60,000–65,000 ft) can be seen corresponding to the Pfotzer-Regener maximum. The ascent profile starts at ~2 km due to the 10 min rolling average, with the raw data starting from an altitude of 700 m.

For Figure 10, the data have been split into 5 km groups; from this, it can be seen that there is an increase in count rate for all channels; however, there is a high level of uncertainty in this data set due to the short
duration of the flight and low-intensity environment. The error bars have not been plotted on this graph as their inclusion leads to considerable clutter.

Figure 11 shows fewer high-altitude regions, highlighting the difference in count rate and giving an indication of the results error. The average FL240 data, the lowest intensity CERF data (corrected for the muon background), and the ground environment at SSC have also been plotted with their respective errors. It is interesting to note that the MOCCA FL240 (7.3 km) count rate is significantly lower than the 5–10 km count rate reported from the balloon flight 5 months later. There is also an increase in the high-energy count rate above the Pfotzer-Regener maximum; however, this could be a product of the small data set recorded during a single launch. These results from altitudes of 15 km and above are consistent with that recorded by RaySure on the RaD-X flight launched from Fort Sumner, New Mexico, USA, on the 26th September 2015 (Hands et al., 2016). From here we can make a simple comparison between the estimated dose during CERF’s lowest intensity run and the MAIRE simulated dose at the Pfotzer-Regener maximum. This gives an estimated ambient dose equivalent of 20.6 μSv h⁻¹ and 9.3 μSv h⁻¹, respectively. This factor of ~2 difference is similar to the difference seen between the two energy deposition spectrums plotted in Figure 11.

The count rates observed during the decent have also been analyzed and found to have similar profiles and count rates at higher altitudes; however, at lower altitudes (<5 km) the descent count rates are significantly lower than the ascent. After considering the various possible causes of this discrepancy, it is believed that it is likely due to microphonics causing an increase in counts during the ascent. This is thought to be due to the meteorological balloon (during ascent) experienced more turbulence than the parachute (during descent) as the balloon has a larger frontal area. To examine the effect of microphonics, a future launch is required where two Zeniths are launched in a similar fashion as discussed in Edwards et al. (2014): one Zenith with the current design and another having its PIN-diode affixed to the printed circuit board (PCB). We also assessed whether the difference could have been explained by any spatial variation in the radiation environment seen at the launch and landing site. An analysis using the model MAIRE produced a difference in rigidity cutoff of 0.1 GV resulting in an increase of <3% in the simulated radiation environment at the landing site. This is the opposite of what was observed; in addition, the data’s statistical errors are in the region of 10–30%, which means that an environmental difference of <3% would not be detected.
4. Future Work

Zenith has been shown to be a capable atmospheric radiation detector, providing reliable data throughout the meteorological balloons ascent and descent; however, there is scope for improvement. On the design side, the volume of the instrument can be reduced as can the power consumption. Another alteration would be to firmly attach the PiN diode to the PCB with adhesive, reducing the possibility of charge being liberated through microphonic, i.e., vibrations caused by atmospheric turbulence. This could be confirmed by ground testing via vibration testing methods often used for satellites. Zenith will also need to be updated to work with Vaisala’s RS41 radiosonde, which is now routinely used by the UK Met Office. The RS41 uses a much faster data protocol for communication with an attached instrument, which means more data can be transferred during a balloon flight, along with reduced dead time between observation windows. Zenith will also need to undergo a further phase of calibration and characterization; this can be achieved via the use of multiple radiation sources or a particle accelerator. Afterward, Zenith will be assessed via either the “millidosimetry” method outlined in Hands and Dyer (2009) or through the calibration approach used in Wissmann et al. (2014) to determine ambient dose equivalent estimates based on Zenith’s energy deposition spectrum. With these modifications, Zenith can progress from a prototype to a more developed instrument capable of being launched multiple times to amass good statistics for the normal reference radiation environment, which is vital for the accurate assessment of space weather events. Once completed, Zenith can be used as a 24 h rapid-response system in multiple locations to accurately monitor the radiation environment during solar particle events and GLEs. As some airlines currently use level S3 on the NOAA space weather scale as their trigger point for taking action, this will also be used as the threshold for the initial studies in order to test its validity.

5. Conclusions

Zenith is a compact battery-operated instrument capable of detecting events that deposit energy in the range 120 keV–100 MeV in a large PiN diode. It has been shown to consistently observe the radiation environment in different conditions. Zenith was deployed on a meteorological balloon from the UK Met Office’s Camborne Weather Station on 15 December 2016, where the data from Zenith were recorded by the ground station throughout the entirety of the ascent and descent until the radiosonde dropped below the ground station’s line of sight horizon at an altitude of 1 km. The results of this test flight have been discussed in this report, where Zenith shows a clear count rate peak, 1.15 c s$^{-1}$ cm$^{-2}$, at the Pfozter-Regener maximum at ~18–20 km (~60,000–65,000 ft), which agrees with measurements taken at similar latitudes by other teams and instruments.

Zenith has been flown at FL240 on the UK Met Office’s MOCCA showing comparable results to that produced by RaySure. However, both instruments showed a higher count rate than the simulated results produced with the use of RadMod’s MAIRE model and the radiation transfer tool, MULASSIS, within SPENVIS.

The CERF facility provides a radiation environment spectrum that is comparable to the aviation altitude’s but at fluxes orders of magnitude greater. This provides an opportunity to determine Zenith’s capability of accurately observing the radiation environment during a space weather event where the flux may be elevated to these levels. During this testing, Zenith showed a consistent profile at different beam intensities with a muon modified background radiation profile.

This work paves the way for producing a larger number of updated instruments to gather statistically significant data of the reference/normal atmospheric radiation environment up to ~100,000 ft (~30 km). Zenith can then be utilized as a quick response radiation monitor for observing the effects of space weather events on the atmospheric radiation environment.

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Acknowledgments

We gratefully acknowledge funding support from UK Met Office under P.O. PI00007. The data used in this paper can be found at: https://doi.org/10.5281/zenodo.1144097.
