The disappearance of the pfotzer-regener maximum in dose equivalent measurements in the stratosphere

A. D. P. Hands¹, K. A. Ryden¹, and C. J. Mertens²

¹Surrey Space Centre, University of Surrey, Guildford, UK, ²NASA Langley Research Center, Hampton, Virginia, USA

Abstract The NASA Radiation Dosimetry Experiment (RaD-X) successfully deployed four radiation detectors on a high-altitude balloon for a period of approximately 20 h. One of these detectors was the RaySure in-flight monitor, which is a solid-state instrument designed to measure ionizing dose rates to aircrew and passengers. Data from RaySure on RaD-X show absorbed dose rates rising steadily as a function of altitude up to a peak at approximately 60,000 feet, known as the Pfotzer-Regener maximum. Above this altitude absorbed dose rates level off before showing a small decline as the RaD-X balloon approaches its maximum altitude of around 125,000 feet. The picture for biological dose equivalent, however, is very different. At high altitudes the fraction of dose from highly ionizing particles increases significantly. Dose from these particles causes a disproportionate amount of biological damage compared to dose from more lightly ionizing particles, and this is reflected in the quality factors used to calculate the dose equivalent quantity. By calculating dose equivalent from RaySure data, using coefficients derived from previous calibrations, we show that there is no peak in the dose equivalent rate at the Pfotzer-Regener maximum. Instead, the dose equivalent rate keeps increasing with altitude as the influence of dose from primary cosmic rays becomes increasingly important. This result has implications for high altitude aviation, space tourism and, due to its thinner atmosphere, the surface radiation environment on Mars.

1. Introduction

The atmospheric radiation environment is a complex mix of various primary and secondary particle species. Galactic cosmic rays (GCR) provide a continuous source of highly energetic protons, alpha particles, and heavy ions that interact with molecules in the upper terrestrial atmosphere, creating cascades of secondary particles including neutrons, pions, electrons, and muons. The intensity of these secondary particles gradually builds up as atmospheric density increases, creating a peak in ionization rate at an altitude of around 60,000 feet (~18 km). Below this peak, known as the Pfotzer maximum (or more appropriately as the Pfotzer-Regener maximum [Carlson and Watson, 2014]), the secondary particle flux decreases steadily toward ground level, where it is approximately 3 orders of magnitude lower than the peak (though this is somewhat dependent on energy and particle species [Lei et al., 2004]). The intensity of the primary GCR flux, and hence also the secondary radiation environment, varies inversely with the solar cycle due to modulation by the heliospheric potential [Badhwar and O'Neill, 1996]. In addition, sporadic solar particle events (SPEs) cause short term (hours to days) increases in the flux of primary particles incident on the atmosphere, leading to enhancements in the atmospheric radiation environment that can be up to several orders of magnitude in scale [Lantos and Fuller, 2003].

The relevance of the atmospheric radiation environment to aviation is twofold. The first aspect is the biological dose to aircrew and passengers due to the presence of ionizing radiation. This is the focus of the Radiation Dosimetry Experiment (RaD-X) experiment and of this paper. The second, no less important, aspect is the effect of the same radiation on avionics (aircraft electronics systems). High-energy particles, particularly neutrons, interact with electronic components, depositing charge in sensitive nodes that can potentially lead to process interruptions or even hard failures where a component fails permanently [Taber and Normand, 1993; Normand et al., 1997]. These phenomena, known as Single Event Effects (SEEs), are an important area of research, but we do not consider them directly in this paper. The RaD-X project was conceived to address the question of how the ionizing radiation environment changes as a function of altitude in the atmosphere. The environment at commercial aviation altitudes has been well studied because of the exposure of large numbers of passengers and aircrew [e.g., Tobiska et al., 2015; Ploc et al., 2013]. Regulations vary from country to country but it is a common practice, at least in Europe and the US, that dose to aircrew is taken into...
account by the relevant authorities and efforts are made to ensure that annual accumulated dose does not exceed safety thresholds [Dyer et al., 2009]. This is almost invariably achieved through the use of radiation environment models rather than calibrated in situ measurements [Bottollier-Depois et al., 2012]. One key aim of the RaD-X project is to generate data that will improve the radiation environment models used for these purposes by increasing the altitude range of validation measurements. At commercial aviation altitudes of 30,000–40,000 feet, dose rates are dominated by secondary particle radiation, especially neutrons [Hands and Dyer, 2009]. At the maximum altitude achieved by RaD-X (approximately 125,000 feet) there is a significant component of primary particle radiation, and it is important that this is accurately modeled during quiescent (GCR) conditions if models are also to be used for predicting environments under enhanced (SPE) conditions. Another reason, it is important to study the radiation environment at higher altitudes is the likely expansion of flight activity in this area in the future (e.g., http://worldview.space). Military jets, surveillance aircraft, and various other objects such as weather balloons already operate well above commercial aircraft altitudes (though vehicles other than rockets are seldom capable of flying above 70,000 feet). However, various sectors are predicted to exploit this territory in the near future, on both manned and unmanned platforms. The advent of high-altitude passenger balloon launches, and space tourism will increase the need to understand the potential risks associated with radiation in this environment. In parallel, the vulnerability of avionics on unmanned platforms, potentially operating for very long durations, will require knowledge of exactly the same environment. More exotically, potential future human explorations of the Martian surface will also benefit from an improved knowledge of the radiation environment in the upper terrestrial atmosphere. This is because the thinner Martian atmosphere provides an equivalent level of shielding from cosmic rays as the environment on Earth at around 80,000–100,000 feet (approximately 10–20 g/cm²) [see Townsend et al., 2011]. The RaD-X balloon is, in a radiation environment context, flying close to the surface of Mars.

The sections of this paper will be as follows. We describe the solid-state RaySure monitor, which is one of four radiation detectors carried on the RaD-X payload (data from the others are reported in accompanying papers). We will outline the measurements taken by RaySure and compare these with collateral tissue equivalent proportional counter (TEPC) measurements. We will then revisit the calibration of RaySure and analyze whether adjustments are required for the high-altitude environment. We then make conclusions on the implications our measurements have for our understanding of the environment and future requirements for developing our understanding further.

2. The RaySure Monitor

The need for a low-cost portable in-flight radiation monitor is becoming more and more apparent. The RaySure monitor was developed as an operational prototype in order to demonstrate how it is possible to meet this need with solid-state technology. The “gold standard” instrument for measuring biological dose equivalent is the tissue equivalent proportional counter (TEPC), which aims to recreate the micrometer scale of human cells via a large gas-filled sensitive volume. However, it is a sensitive scientific instrument that is not well suited to either mass production or miniaturization. At the other end of the scale, simple detectors, such as electronic personal dosimeters, can be made very small and portable; however, they are unable to distinguish between different types of radiation, and crucially, they have a very poor response to neutrons. RaySure was designed to plug this gap in capability. A picture of RaySure is shown in Figure 1. The unit is about the size of a house brick but weighs only a little over a kilogram. RaySure uses a large-area PIN diode

Figure 1. The RaySure monitor. The unit is usually powered with internal batteries. For RaD-X, however, power was supplied externally.
to count particle interactions using 15 logarithmically binned energy-deposition channels. The dynamic range allows for a variety of particle species to be detected in the mixed radiation field of the atmosphere, including direct ionization from protons, ions, and the electromagnetic cascade (electrons and gamma), as well as indirect ionization from neutron interactions. RaySure has been flown on many hundreds of flights, accumulating many thousands of flight hours on commercial and executive jet aircraft [Dyer et al., 2009; Federico et al., 2015; Getley et al., 2010]. Many of these flights have also carried a TEPC instrument, and these collateral data have been used to calibrate RaySure.

In addition to in-flight measurements, RaySure has been extensively calibrated at ground-based test facilities [Hands and Dyer, 2009], again alongside TEPCs and other detectors. These data have been used, in conjunction with simulations and particle transport calculations, to calculate coefficients with which to calculate dose equivalent from count rates. Dose equivalent is an alternative measure of dose, based on adjusting absorbed dose for equivalent tissue damage, using quality factors linked to the linear energy transfer (LET) value of incident radiation. For example, a unit of absorbed dose from a 1 MeV neutron has a quality factor of approximately 20 when calculating dose equivalent [ICRP, 2007]. In other words, a neutron of this energy is deemed to do 20 times as much damage to tissue (for a given unit of absorbed dose) compared to beta or gamma radiation. Unlike the TEPC instrument, RaySure is unable to directly measure the LET of particles depositing energy in its sensitive volume. This is because the track length of the ionizing particle is unknown. Therefore, in order to calculate the dose conversion coefficients it is necessary to make assumptions, both about the radiation environment in which the measurements are made and about the distribution of secondary particles in the detector. The RaySure calibration described in Hands and Dyer [2009] is based on the mixed radiation environment at commercial aviation altitudes. In a later section of this paper we explore whether these coefficients are suitable for a high-altitude environment where the mixture of particle species is subtly different.

3. RaySure Data

The RaD-X balloon was launched from the Columbia Scientific Balloon Facility (CSBF) in Fort Sumner on 25 September 2015. More details on the launch and wider project can be found in accompanying articles in this special issue. RaySure was configured to record counts in its energy deposition channels at a cadence of every 2 min. The total count rate in all channels is plotted in Figure 2, together with the altitude profile for the balloon flight.

Figure 2 shows that there are several stages to the RaD-X flight. Over the first few hours the balloon rises to its maximum altitude of ~125,000 feet (125 kft) before gradually descending to below 80 kft over the next 16 hours and finally ascending once again. The rapid ascents and slow descent mean that the data collection period is concentrated in the 75–125 kft altitude range, with other altitudes having limited data collection opportunity. After rising initially with the ascent, the RaySure count rate is observed to peak at just under 60 kft and then varies inversely with altitude for the remainder of the flight. This is a direct consequence of the Pfotzer-Regener maximum as the RaySure total count rate is proportional to the ionization rate in the
atmosphere. This can also be observed in terms of absorbed dose. In Figure 3 absorbed dose in silicon, as measured by RaySure, is plotted against barometric altitude. Here the data have been averaged over 10,000 feet bins (5–15 kft, 15–25 kft, etc.) for clarity. It is important to clarify that the measured value is absorbed dose in silicon, as the value for absorbed dose in other materials would not be the same because of how LET varies between materials for each particle species. The absorbed dose rate profile peaks at 70 kft rather than 60 kft, where we might have expected given the count rate profile. However, the relatively large error bar demonstrates that the data are not inconsistent with a peak closer to 60 kft. Counts recorded in the higher energy deposition channels contribute more to absorbed dose than counts recorded in lower energy channels. As there are relatively few counts in the higher energy channels, this makes the absorbed dose rate very sensitive to small number counting statistics. We then used the dose conversion coefficients calculated by Hands and Dyer [2009] to calculate a profile for dose equivalent in tissue. This is shown in Figure 4.

The dose equivalent profile is different from the absorbed dose profile in two ways. First, the dose equivalent rates are elevated compared to absorbed dose rates at all altitudes, reflecting the additional quality factors applied to higher energy deposition channels, based on the relatively high LET of particles responsible for those counts (assumed to be predominantly protons and alpha particles resulting from neutron interactions, and recoil Si nuclei). The enhancement effect relative to absorbed dose varies as a function of altitude, but is, on average, approximately two. The second noticeable effect is that the peak in the dose rate profile has disappeared. The fraction of counts in RaySure’s higher energy channels increases with altitude. Quality factors applied to counts in these channels effectively offset the diminution in overall count rate, causing the dose equivalent rate to plateau above 60 kft rather than decline. The errors on these dose equivalent values, shown in Figure 4 at the 1σ level, are significant and very sensitive to the stochastic appearance of infrequent counts in the higher energy channels. For example, in one 2 min data bin at around 70 kft, just three counts are responsible for more than 50% of the dose equivalent calculated for that bin, out of a total of over 600 counts across all channels (this is also, of course, a reflection of the greater amount of energy deposited, regardless of quality factor). Such random fluctuations are responsible for the large error bar at 70 kft in Figure 4 (above this altitude the much greater volume of data during the balloon’s long descent phase smooths out the statistical fluctuations). This observation rests upon the fidelity of RaySure’s calibration, and we must now test this with reference to measurements from another instrument.

4. Comparison with TEPC data

The RaD-X payload included a HAWK version 3.0 TEPC, manufactured by
Far West Technologies. Detailed results from this instrument are presented in an accompanying paper by Mertens et al. [2016]. Here we reproduce only the processed dose equivalent rate, as measured by the TEPC, to compare to the same quantity as estimated by RaySure. For both instruments we use aggregated data for the whole flight period, rather than just the ascent phase.

Figure 5 shows a comparison of the two instruments as a function of altitude. We see that there is good agreement between them up to approximately 60 kft, albeit with relatively poor statistics due to the rapid ascent through this region of the atmosphere. Immediately above the nominal Pfotzer-Regener peak altitude (~60 kft), RaySure dose equivalent exceeds TEPC dose equivalent by approximately 20–25% (similar to the standard deviations, which are, respectively, 23% and 30%), before coming into close agreement again above 100 kft. The qualitative difference between the two appears to be that TEPC dose equivalent rises steadily above 60 kft, whereas RaySure dose equivalent exhibits the plateau that was discussed in the previous section. It is possible that this difference is an artifact. Errors plotted in Figure 5 are 1σ standard errors on the mean of all dose equivalent values calculated in the given altitude range (one value per 2 min bin). Standard deviations of the ranges of dose equivalent values are significantly larger, reflecting the sensitivity to counting statistics on the low count rates of the higher energy deposition channels. For example, the full range of RaySure dose equivalent values (in 2 min counting bins) for the altitude range 75–85 kft is 4–22 μSv/h, with a mean and standard deviation of 9.7 ± 3.4 μSv/h. The equivalent range for TEPC dose equivalent (in 1 min bins) is 3–20 μSv/h, with mean and standard deviation of 7.8 ± 3.0 μSv/h. Hence, we can see that there is considerable overlap between the two measured dose rate distributions at this altitude, even though the mean dose equivalent values are not in good agreement with each other. It is interesting that the difference is only significant in this narrow altitude range. Again, this could be an artifact, a statistical anomaly due to relatively low numbers of counts that strongly influence the calculation of dose equivalent for RaySure. Without additional measurements in a similar environment we cannot rule out this possibility. However, it is also the case that unlike at lower altitudes, in this region of the atmosphere, there is a significant presence of primary protons from cosmic rays. Whether or not these could distort or even invalidate the RaySure’s calibrated dose conversion coefficients is explored in section 5.

There is one other factor to consider when making the comparison with TEPC data. The original calibration for RaySure employed a scale factor for converting absorbed dose in silicon to a tissue equivalent absorbed dose. This factor was set at 1.4, though as can be seen in Hands and Dyer [2009] there was considerable scatter around this value from both ground-based and in-flight data comparisons. The average ratio of absorbed dose between TEPC and RaySure over the RaD-X flight is approximately 1.05 (61.3 and 58.6 μGy dose to tissue and silicon, respectively). This is lower than assumed by the original calibration and at the very lower end of the spread observed in previous comparisons. The explanation for this may be systematic. In pre-flight calibrations, using a Co-60 gamma source, the TEPC was observed to underestimate absorbed dose by approximately 16% [Straume et al., 2016]. During the same experiments the ratio between a facility reference value of absorbed dose in tissue, and the value measured by RaySure in silicon, was 1.21. In the section 5 we explore the consequences of varying the silicon-to-tissue dose conversion factor used in our calculation of dose equivalent.

5. Discussion

In order to interpret the RaySure measurements, especially in the context of the comparison with TEPC data, we need to understand the compositional changes of the detector count rate as a function of altitude. Figure 6 shows RaySure energy deposition spectra for three different altitude ranges: below 60 kft, 60–100 kft,
and above 100 kft. Due to the balloon’s rapid ascent, the amount of data contributing to the <60 kft segment is limited and statistical fluctuations are more severe. Hence, we have also included a representative energy deposition spectrum from a measurement taken on board a flight from San Francisco (SFO) to London Heathrow (LHR) in 2013. The cruising altitude for this flight was predominantly in the range 33–36 kft. This, effectively, is a more statistically robust representation of the sub-Pfotzer environment, albeit at a lower average cutoff rigidity than the ~4 GV cutoff at Fort Sumner.

The most significant difference in the spectra presented in Figure 6 is the higher count rate in high energy deposition channels at high altitude. This is what we expect given the increasing influence of primary cosmic ray protons above the Pfotzer-Regener maximum. However, we also note that the spectrum above 100 kft is, within statistical uncertainties, very consistent with the spectrum in the 60–100 kft range. This is the case even for the highest energy deposition channels where any counts caused by direct ionization from heavy ions would be expected to be recorded. This implies that we are not seeing a significant presence of primary cosmic ray heavy ions even at the highest altitudes reached by the RaD-X balloon. However, even small differences in deposition spectra can translate to observable differences in relative contribution to the dose equivalent rate. Figure 7 shows the relative contributions of each energy deposition channel to absorbed dose and dose equivalent, as calculated with RaySure conversion coefficients. For this comparison the altitude binning is slightly finer with 20 kft width bins above a 40 kft threshold. These plots also demonstrate a split between the sub-Pfotzer region and the super-Pfotzer region. Even for absorbed dose, the contribution of the higher energy deposition channels is significantly greater for the >60 kft regions than the <60 kft regions. The change appears to be quite rapid, as the 60–80 kft curve is closer in shape to the >100 kft curve than it is to its “neighboring” 40–60 kft curve. The same effect is apparent in the dose equivalent plot too. Here, in all cases, the contribution of higher energy channels is considerably greater than for absorbed dose. Nevertheless, we again observe a polarization of the distributions between the two lower altitude curves and the three higher altitude curves.

In both cases this is the result of the quality factors applied to the higher energy channels in the dose equivalent calculation. These quality factors (referred to as Q*) are from the original calibration of RaySure and are shown in Hands and Dyer [2009] (Figure 10). The factors were calculated by breaking down simulated nuclear-induced energy deposition tracks in the RaySure diode into 2 μm steps and are thus directly analogous to the quality factor (Q) concept in microdosimetry. Initially, factors applicable to counts from indirect nuclear

Figure 6. Energy deposition spectra for RaySure in three altitude ranges. The spectrum measured during a commercial flight is also shown, demonstrating a clear division between the radiation environments below and above the Pfotzer-Regener maximum.

Figure 7. Relative contributions to absorbed dose (LHS) and dose equivalent (RHS) from RaySure energy deposition channels. The five curves from different altitude ranges reveal a qualitative split between the regions above and below the Pfotzer-Regener maximum.
interactions (induced primarily by neutrons and protons) are calculated. The quality factor for direct ionizing counts is unity. To account for this a so-called “constraining function” \( F \), i.e., the estimated fraction of nuclear-induced counts relative to the total (this is very low at low energy, rising steadily to unity at high energy) is used to produce net quality factors \( Q^* \) that are applied to the counts in each channel. These quality factors were calculated for a commercial aviation radiation environment, at approximately 40,000 feet (~12 km) altitude. We now consider what the qualitative effect of a higher altitude radiation environment should be on these factors, and thus, how this might affect the dose equivalent calculation.

Our results indicate that up to the Pfotzer-Regener maximum we should not expect a significant change in the energy deposition spectrum, hence, no requirement to amend the applied quality factors. In the stratospheric region immediately above the Pfotzer-Regener maximum, however, we do observe an increase in high energy deposition counts (Figure 6). If these counts are primarily due to indirect ionization (nuclear interactions) between silicon nuclei and neutrons, protons, or ions, then, to a first approximation, the established quality factors remain appropriate. If, however, the additional high energy deposition counts are due to direct ionization from primary cosmic ray ions, then the assumptions underlying the previous derivation of quality factors are invalid. To investigate this we calculated LET spectra and alpha particle fluxes at 40 kft and 125 kft using the Model of Atmospheric Ionising Radiation Effects (MAIRE) (www.radmod.co.uk/maire) at the geographical coordinates of Fort Sumner.

Our calculations shows that there is a significant increase in alpha particle flux at energies of a few GeV or higher. However, as shown by the LET curve in Figure 8, this energy range corresponds to minimum ionizing particles that would be measured in the lower LET channels of RaySure and for which a quality factor of unity would apply. Figure 8 (left) shows that in spite of a nearly 3 orders of magnitude increase in primary alpha particle flux at these energies, the increase in integral flux for particles with the same LET is only a factor of 3. This is because the low LET environment is dominated by primary protons and various species of secondary particles. From these calculations we infer that primary cosmic ray light ions are only able to deposit dose in the high energy deposition channels of RaySure via nuclear interactions (producing high LET low energy protons, alpha particles, and Si recoil nuclei). Heavier (higher Z) ions at minimum ionizing energies may contribute to the count rates in the higher channels via direct ionization. However, due to absorption and low initial abundance, these ions are only present at low fluxes, even at the peak altitude for RaD-X. Also, the LET range required for direct ionization counts is of the order of tens of keV/\( \mu \)m for channels 10 to 12, corresponding to quality factors in the range ~ 3–10, which is similar to the aggregate \( Q^* \) factors used by RaySure. Only in the top two or three RaySure channels is there significant divergence between the existing \( Q^* \) factors and the alternative quality factor applicable to direct ionization counts in those channels. As these channels make only a small contribution to dose, this is likely to be a very subtle effect and far too small to be perceptible from our data.

Therefore, we believe that the changes in energy deposition distributions visible in Figures 6 and 7 are primarily the result of an increase in indirect ionization from primary cosmic ray particles at higher altitudes. A change in balance between directly and indirectly ionizing particles could justify a subtle adjustment to the constraining function used to calculate \( Q^* \) coefficients, as discussed above. However, the impact of such changes is overwhelmed by other systematic uncertainties, especially the issue of converting dose in silicon to dose in tissue. The limited data from RaD-X are insufficient to validate a complete remodeling of the

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**Figure 8.** (left) Atmospheric alpha particle spectra at 40 kft and 125 kft. The LET of alpha particles is also plotted on the right hand scale. (right) Integral ion LET spectra at 40 kft and 125 kft. The presence of few GeV alpha particles has a clear effect below 0.007 MeV.cm\(^2\)/mg.
calibration of RaySure in the subtly different radiation environment at high altitudes. However, we aim to revisit this issue in the future with additional data from follow-on experiments.

We discussed in a previous section the evidence for a smaller scale factor for tissue equivalence than is assumed in the original RaySure calibration (1.05 cf. 1.4). This is the value that is used to convert absorbed dose in silicon to absorbed dose in tissue (reflecting the higher LET of ionizing particles in tissue). As mentioned previously, the fidelity of absorbed dose values measured by TEPC is uncertain. Ground calibration measurements in a Co-60 facility showed an underestimate of dose by the TEPC; however, similar measurements at a Cf-252 facility resulted in much better agreement with the facility reference values [Straume et al., 2016]. Therefore, we choose not to renormalize the TEPC data ourselves. Instead, we examine the impact of using alternative silicon-to-tissue dose conversion factors on the comparison between RaySure and TEPC. We select three values for comparison: 1.4 (based on the original calibration and used in Figure 5), 1.21 (the measured ratio based on the Co-60 facility reference), and 1.05 (the average ratio between TEPC and RaySure over the RaD-X flight). The alternative RaySure dose equivalent rates are plotted in Figure 9. To avoid clutter, standard error bars on RaySure data have not been plotted. However, Figure 5 provides a guide to their magnitude. Standard deviations are considerably larger.

We can see that the uncertainty over the correct dose conversion factor fully encompasses any absolute discrepancy between TEPC and RaySure measurements. The best way to address this uncertainty would be to conduct more collateral measurements with the same two instruments, whether in-flight or in a more representative ground test facility such as a spallation neutron source. Unfortunately, the opportunity to perform these experiments has not yet arisen, but we are hopeful it will be possible in advance of any future flights. We note that none of the amendments to RaySure calibration scale factors has a significant impact on the slope of the dose equivalent altitude profile, i.e., RaySure data imply a plateauing effect in this altitude range, whereas TEPC data imply a slight increase. More data are required to explore whether this subtle difference is a real consequence of the RaySure calibration factors or an artifact due to the limited statistics of a single flight. As discussed earlier, standard deviations of dose rates for each instrument and in each altitude bin are large and overlapping. We cannot say with certainty that the modest increase in TEPC dose rates at ~120 kft is real. The erratically high TEPC dose rate at 50 kft, and the dip in RaySure dose rate at 125 kft, both reveal how limited the statistics are, and thus, how difficult it is to draw conclusions. On balance the best fit between the data sets implies a silicon-to-tissue dose conversion factor of around 1.2. Although lower than previously assumed, this is within the spread of previous calibration measurements and consistent with basic LET ratios of protons, electrons, and alpha particles at appropriate energies. If this TEPC instrument is underestimating absorbed dose, as implied by some ground test data, then agreement between the two instruments would be maintained with a dose conversion factor closer to 1.4. Systematic uncertainties such as these, of the order of 10%, are common within the field of dosimeter calibration. Future experiments will aim to reduce these uncertainties and constrain further the profile of dose rates as a function of altitude.

6. Future Work

As shown in Figure 9, the systematic uncertainty associated with the correct silicon-to-tissue conversion factor for absorbed dose is significant. This effectively precludes the possibility of validating any fine tuning calibration of RaySure in the subtly different radiation environment at high altitudes. However, we aim to revisit this issue in the future with additional data from follow-on experiments.
of the quality factors applied to RaySure data. However, there are reasons why such fine tuning could be of value. Some of these are enumerated below.

1. As altitude increases the assumption of an isotropic radiation field increasingly breaks down. This will have consequences for the angular distribution of secondary particles in a planar detector.
2. Directly ionizing primary particles are not thought to contribute heavily to dose equivalent due to low weighting factors. However, they will affect the fraction of dose due to indirect ionization (the constraining function), which is a key factor in the calculation of net quality factors.
3. The composition and energy distribution of indirectly ionizing particles changes with altitude. This has a knock-on effect on the distribution of secondary particles within the detector and, hence, on appropriate quality factors.

The relatively good agreement between TEPC dose rates and RaySure dose rates using existing quality factors implies that none of these factors would have a large effect on the RaySure calibration. A substantial increase in the quantity of high altitude data, coupled with an improved understanding of the tissue-to-silicon dose conversion factor through cross calibration on the ground, should enable the influence of some of these factors to be extracted and validated. Establishing the consequent effect on RaySure quality factors will be a primary objective of future experimental campaigns.

7. Conclusions

The RaD-X experiment has provided a unique opportunity to examine the performance of the RaySure monitor in a new environment. The long duration of the mission has enabled the collection of sufficient counts from the critical high LET (but low count rate) component of the high altitude radiation environment to make quantitative comparisons between RaySure and the TEPC instrument, albeit with significant uncertainties remaining. The analysis of these data presented in this paper leads us to the following conclusions.

1. The altitude profile for absorbed dose (both in silicon and in tissue) illustrates the Pfotzer-Regener maximum in atmospheric ionization rates at around 60,000 feet.
2. The influence of indirectly ionizing particles (particularly primary cosmic ray protons) at higher altitudes effectively eliminates this peak in the altitude profile for dose equivalent. This is due to the high relative biological effectiveness (RBE) of dose from high LET secondaries from interactions with these particles, as reflected in quality factors applied during the calculation.
3. This “disappearance” of the Pfotzer-Regener maximum in the context of dose equivalent has not previously been observed from balloon flights that have carried simpler instruments with no calibrated response to indirectly ionizing particles [Wissmann et al., 2013; http://Earthtosky.net/the-research]. Therefore, for radiation protection considerations, it should not be assumed that biological dose rates decrease at very high altitudes in the stratosphere.
4. The energy deposition spectrum from RaySure provides direct evidence of this high LET population of particles above the Pfotzer-Regener maximum. Further evidence can be found in the lineal energy spectra produced by the TEPC instrument [Mertens et al., 2016]. We do not, however, find a very significant change in this spectrum in the altitude ranges just above and just below 100,000 feet.
5. The original calibration factors for calculating dose equivalent from RaySure count rates, lead to very good agreement with TEPC data below the Pfotzer-Regener maximum, and very reasonable agreement at higher altitudes. Improved agreement can be obtained with alternative dose conversion factors, though more data and more work is required to establish the precise behavior of these as a function of altitude. A series of high-altitude balloon flights carrying both RaySure and TEPC instruments, ideally covering a range of geomagnetic cutoff rigidities, would be of great value in answering these questions. These observations are significant for the various platforms that may, or already do, operate in high altitude environments: high-altitude passenger balloons, space tourism vehicles, military jets, long-duration observing platforms, and putative unmanned aerial vehicles (UAVs) for internet communications services. The similarity between the high-altitude terrestrial environment and the Martian surface environment means that this experiment should also be of interest to future manned missions to Mars, where the exposure of astronauts to the radiation environment will be a very significant consideration. Although these measurements were performed during quiescent space weather conditions, future work should also focus on the effects of extreme space weather. A large solar particle event (SPE) can lead to substantial increases in
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References

Dose rates at commercial aviation altitudes [Dyer et al., 2007]. At higher altitudes enhancement factors are likely to be significantly greater, potentially leading to unacceptably high levels of exposure to passengers and crew, even during a relatively short flight. These, and other, considerations will hopefully be explored in follow-on research programs.