

An empirical approach to the measurement of the cosmic radiation field at jet aircraft altitudes

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Abstract

Researchers at the Royal Military College of Canada have accumulated extensive dose measurements performed at jet altitudes on over 160 flights and with a wide variety of detectors including a tissue equivalent proportional counter (TEPC), a smart wide energy neutron detection instrument (SWENDI), bubble detectors, thermoluminescent detectors (TLD) and an ion chamber. The summation of the individual low and high LET results from the latter equipment compared successfully to those from the TEPC on each flight. The data from these numerous worldwide flights have been encapsulated into a program that calculates the radiation dose for any flight in the world at any period in the solar cycle. This experimentally based program, Predictive Code for AIRcrew Exposure (PCAIRE) has been designed to be used by the airline industry to meet national dosimetry requirements. In Canada, for example, such a code can be used, supported by periodic measurements. With this latter requirement in mind and a desire to decrease equipment size, the silicon-based LIULIN-4N LET (linear energy transfer) spectrometer has been assessed to determine its suitability as a mixed field instrument and possible code verification tool. Data obtained from the LIULIN and TEPC in ground-based experiments at the CERN-EC Reference-field Facility (CERF) and on 42 jet-altitude flights have been compared. Analysis of these data has resulted in two different mathematical correlations which can be used to determine the ambient dose equivalent, $H^*(10)$, from the LIULIN absorbed dose output. With either calibration factor, the LIULIN instrument could now be used as a simple, compact and portable detector for routine monitoring.

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1. Introduction

In order to model or to measure the dose received by aircrew, an accurate understanding of the nature of the radiation environment is necessary. The mixed-radiation field at aircraft altitudes is the result of the interaction between cosmic rays (CR) and the Earth's atmosphere.

These cosmic rays can originate from outside our solar system (galactic cosmic radiation, GCR) or from our sun. GCR consists primarily of charged particles (mainly protons, some alpha particles and a few heavier nuclei), with energies up to the TeV range (McDonald and Ptuskin, 2001). Solar energetic particle events (SEP) can also inject a large number of these particles into the atmosphere; however, their energy is much less than that of GCR particles. As a result, the GCR component (as opposed to the solar component) is largely responsible for the radiation dose received by aircrew.

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Upon entering the heliosphere, GCR particles encounter the solar wind and the heliospheric magnetic field, which cycles in intensity with a period of approximately 11 years in conjunction with solar activity (Barth et al., 2003). When the sun's activity is the greatest, the increased solar wind provides the greatest protection against GCR. When the sun's activity is at a minimum, it provides the least protection against GCR. Upon reaching the Earth, the charged particles encounter the Earth's magnetic field. Whether an incoming particle is deflected by this magnetic field or is allowed to reach the atmosphere is a function of the particle's momentum and where the particle interacts with the Earth's magnetic field. For example, if the charged particle vertically enters the Earth's magnetic field at the equator, it will be crossing perpendicular to the Earth's magnetic field lines and will be deflected if the particle has insufficient momentum. At the poles, incoming particles can enter the Earth's atmosphere by travelling parallel to the magnetic field lines so that even low-momentum particles will not be deflected. To a first approximation, this relationship can be quantified in terms of the effective vertical cutoff rigidity (R_c), which ranges from 0 GV at the poles to ~ 17 GV at the equator. Any particles entering the Earth's atmosphere will interact with the atmospheric nuclei, resulting in the production of a cascade of secondary particles, which varies in intensity with altitude.

Aircrew are thus exposed to a permanent source of radiation, which varies in a predictable manner with date (i.e., solar cycle period), geomagnetic latitude and altitude. The actual assessment of this exposure by the airline industry presents unique challenges since the conventional dosimetric approaches of either personal passive dosimetry or area monitoring with fixed instrumentation would be both costly and difficult to manage. Alternatively, since the aircrew exposure on a given route is relatively constant (except for the possibility of sporadic solar energetic-particle (SEP) events), this exposure can be predicted based on theoretical and/or experimental knowledge of the route dose. Such a program, with verification by periodic measurements, would require less infrastructure and would be less costly than the other options. In fact, following guidance from the European Commission and the ICRP, this is the suggested method for assessment of aircraft crew exposure in both the EU and Canada (ICRP, 1997; Transport Canada, 2001; van Dijk, 2003).

In light of this guidance, scientists at the Royal Military College (RMC) of Canada have been collecting and analyzing radiation data from numerous worldwide flights throughout the current solar cycle, which is expected to reach its minimum in 2007. Since 1999, ambient dose equivalent rates have been measured by RMC on over 160 flights, which have spanned the entire cut-off rigidity potential of the Earth's magnetic field. Using those data for which the actual inflight altitude and geo-

graphical positions were known, mathematical correlations have been developed between the GCR radiation dose and altitude, latitude and time in the solar cycle (Lewis et al., 2001, 2002, 2004). These mathematical correlations provide the basis for the development of a Predictive Code for Aircrew Radiation Exposure (PCAIRE) which provides an ambient dose equivalent, $H^*(10)$, value for a given flight route (Lewis et al., 2004). In order to validate the use of this code, $H^*(10)$ must be measured periodically on representative routes. Previously, these measurements have been conducted with a tissue equivalent proportional counter (TEPC) as the preferred instrument for measuring the mixed field radiation at aircraft altitudes (Taylor et al., 2002). With a desire to increase the operational ease of these periodic measurements, a Si-based LIULIN semiconductor spectrometer (Spurny and Dachev, 2003) has been assessed by comparing its response to that of the TEPC on several flights as described in this paper.

2. Materials and methods

2.1. Tissue equivalent proportional counter

A battery-powered tissue equivalent proportional counter (TEPC) has been designed by Battelle Pacific Northwest National Laboratories (and subsequently upgraded by Far West Technologies to the HAWK TEPC) for portability and simplicity in airline flight measurements. The detector is a propane-filled sphere (12.7 cm in diameter) with an outer wall consisting of A150 polymer. Together, the propane and the polymer simulate a microscopic volume (2 μm in diameter) of tissue. An anode wire with a high potential (~ 700 V) runs through the centre of the detector and acts as the sensing element. As radiation passes through the detector, it ionizes the propane, which results in a current spike through the anode as the charge collects on the wire. The current spike thus produced is amplified and converted to a voltage spike by a preamplifier. A multi-channel analyzer (MCA) then quantifies the voltage spike and records the data produced every minute. The absorbed dose (in Gy) recorded by the TEPC is a function of the linear energy for a given channel, y , and the number of counts within the channel, $n(y)$, such that:

$$D = \frac{0.204}{d_d^2} \sum_{i=0}^{\infty} y_i n(y_i), \quad (1)$$

where d_d is the diameter of the TEPC sphere in microns (Lewis et al., 1999). Similarly, the dose equivalent (in Sv) is given by

$$H_{\text{TEPC}} = \frac{0.204}{d_d^2} \sum_{i=0}^{\infty} q(y_i) y_i n(y_i), \quad (2)$$

where $q(y)$ is the quality factor, which has been replaced by the $Q(\text{LET})$ relationship recommended in ICRP-60 (ICRP, 1991) for the present analysis.

In order to relate this dose equivalent measured by the TEPC, H_{TEPC} , to the ambient dose equivalent, $H^*(10)$, the TEPC must be calibrated to obtain a multiplication factor, f , which can be applied to H_{TEPC} (Nunes et al., 1996) such that

$$H^*(10) = f \cdot H_{\text{TEPC}}. \quad (3)$$

A past calibration of the TEPC at the Physikalisch Technische Bundesanstalt (PTB) in 2000 showed a consistent over-response of $\sim 15\%$ to all types of radiation (gamma and neutrons); hence, a correction factor of $f = 1/1.15 = 0.87$ was applied uniformly to all TEPC data (Lewis et al., 2001, 2002). A more recent calibration effort at the PTB and at the National Physics Laboratory (NPL), UK showed that the over-response of the new HAWK version of the TEPC was $\sim 25\%$ for neutrons (i.e., for poly-energetic and mono-energetic neutrons between 0.25 and 5 MeV) and $\sim 5\%$ for gamma radiation (Lewis et al., 2004). Since the HAWK can provide separate estimates of the low-LET (“gamma”) contribution (for $y < 10 \text{ keV}/\mu\text{m}$) and the high-LET (“neutron”) contribution (for $y \geq 10 \text{ keV}/\mu\text{m}$), these individual contributions can be multiplied by the corresponding correction factor (i.e., $f = 1/1.05$ and $1/1.25$, respectively) and then summed to give an alternative estimate of $H^*(10)$. Using the latter correction procedure for the radiation field at aircraft altitudes produces $H^*(10)$ values that are virtually identical (within $\sim 2\%$) to those obtained using the former simpler procedure. (This agreement arises since the radiation dose equivalent at jet altitudes and at northern latitudes is comprised of approximately 50% neutrons and 50% low-LET radiation so that a correction factor based on the average of the 5% and 25% over-responses is relatively accurate.) In light of this agreement, the correction factor of $f = 1/1.15$ has been used for routine measurements obtained at jet altitudes for the sake of simplicity.

2.2. LIULIN-4N LET spectrometer

The LIULIN-4N LET spectrometer, manufactured by Solar Terrestrial Influences Laboratory, has a PIN semi-conducting silicon-based diode as its detector. A PIN diode is composed of three layers of material: (i) a P layer doped with a pentavalent element, such as arsenic; an N layer doped with a trivalent element, such as gallium; and an intrinsic (I) layer comprised of pure silicon. Once a potential voltage is established across the PIN diode, the loosely bound electrons in the P layer will migrate toward the N layer and, conversely, the holes in the N layer will migrate toward the P layer. Equilibrium is eventually established within the diode.

As radiation passes through the diode, it produces electron/hole pairs, which results in a current spike in the diode. The current spike is converted to a voltage spike and quantified by an analogue to digital converter (ADC). Like the TEPC, the amplitude of the voltage spike is proportional to the amount of energy deposited within the detector. The voltage spikes are sorted by an MCA into 256 energy channels. In a manner similar to the methodology used for the TEPC, the LIULIN absorbed dose is given by:

$$D = a \sum_{i=0}^{255} i \cdot n(i), \quad (4)$$

where i is the channel number, $n(i)$ is the number of counts within the channel, and a is a constant determined by the manufacturer’s calibration process (Dachev et al., 2002). In this case, a value of $a = 9.33 \times 10^{-5}$ is expected to give the dose in tissue in units of μGy . The data-sampling period for the LIULIN, which can be defined by the user as anywhere between 5 s and 1 h, was set at 20 min for the current at-altitude experiments.

2.3. In-flight measurements

Radiation levels at jet altitudes have been measured with a TEPC (before and after upgrading to the HAWK) on over 160 flights since 1999. On selected flights, the TEPC measurements were supplemented by measurements with bubble detectors (BD-PNDs manufactured by Bubble Technology Industries), thermoluminescent detectors (TLDs), a battery-powered Eberline FHT 191 N ionization chamber (IC) and an Eberline SWENDI extended range neutron detector. The small LIULIN detector was introduced as part of the equipment suite in May 2003 and was used in conjunction with the TEPC on 42 flights between 28 May 2003 and 9 January 2004 (Kitching, 2004). These flights included domestic (North American) routes, trans-Atlantic routes, trans-Pacific routes, trans-equatorial routes and routes within the southern hemisphere, so that the entire range of cutoff rigidity values ($R_c = 0$ to $\sim 17 \text{ GV}$) was covered. Details on the exact flight path and altitude changes were recorded by the cockpit crew and by the internal GPS (Global Positioning System) incorporated directly into the HAWK model of the TEPC.

3. Results and discussion

The minute-by-minute dose equivalent rate data (\dot{H}) recorded by the TEPC on flights between 1999 and 2002 were averaged over 30-min intervals in order to improve the statistics. These data were then normalized to an

altitude of 10.7 km (or atmospheric depth of $h_0 = 243 \text{ g cm}^{-2}$) using the following relationship (Lewis et al., 2002):

$$f_{\text{Alt}}(h) = \frac{\dot{H}(h)}{\dot{H}_0} = e^{-\xi_s(h-h_0)} \left[\frac{1 - e^{-(k_0 - \xi_s)h}}{1 - e^{-(k_0 - \xi_s)h_0}} \right] + \frac{k_0 - \xi_s}{\beta k_0} \left[\frac{e^{-k_0 h}}{e^{-\xi_s h_0} - e^{-k_0 h_0}} \right], \quad (5)$$

where h is the atmospheric depth (in g cm^{-2}) at which the data is recorded and $\beta = 3$ is an effective proportionality constant for the production of secondary particles from primary-particle interactions as determined from balloon-borne flights. The parameter $k_0 = 0.016 \text{ cm}^2 \text{ g}^{-1}$ accounts for the attenuation of primary particles in the atmosphere, and is fitted to transport code calculations in order to provide a maximum value of the function in Eq. (5) at the Pfozter maximum, where the radiation levels in the atmosphere are observed to reach a maximum due to secondary-particle buildup (Lewis et al., 2004). ξ_s is the effective relaxation length for the given particles in the atmosphere, which is a function of the vertical cutoff rigidity, R_c (in GV), as follows (for altitudes $>7.6 \text{ km}$):

$$\xi_s = \begin{cases} 0.0085 \text{ cm}^2 \text{ g}^{-1}, & R_c < 4 \text{ GV}, \\ -4.714 \times 10^{-4} R_c + 0.01039, & 4 \text{ GV} \leq R_c \leq 11, \\ 0.0052 \text{ cm}^2 \text{ g}^{-1}, & R_c > 11 \text{ GV}. \end{cases} \quad (6)$$

These normalized TEPC data are plotted versus the vertical cutoff rigidity R_c (which is derived for a given geographical latitude and longitude using the International Geomagnetic Reference Field, IGRF-1995) in Fig. 1(a) (Lewis et al., 2004). In this figure, the data have been sorted according to the solar activity for the month of the flight, as indicated by the ground-level neutron count rate data from the Climax neutron monitor (NGDC, 2004). (Specifically, the 1999 data were obtained in a period in the mid-range of solar activity just past the solar minimum when the weighted average of the Climax count rate was 400,400 counts per hour; and the 2001–2002 data were obtained in a more active portion of the solar cycle when the weight average of the Climax count rate was 374,500 counts per hour.) Comparable curves can also be derived from the summation of independent measurements of the low-LET (ionizing) and high-LET (neutron) components using an IC and an extended-range neutron monitor (Lewis et al., 2004; Schrewe, 2000), as shown in Fig. 1b. The increased scatter in the TEPC data (Fig. 1(a)) compared to the summed IC and neutron monitor data (Fig. 1(b)) results from the presence of very high-LET particles that are

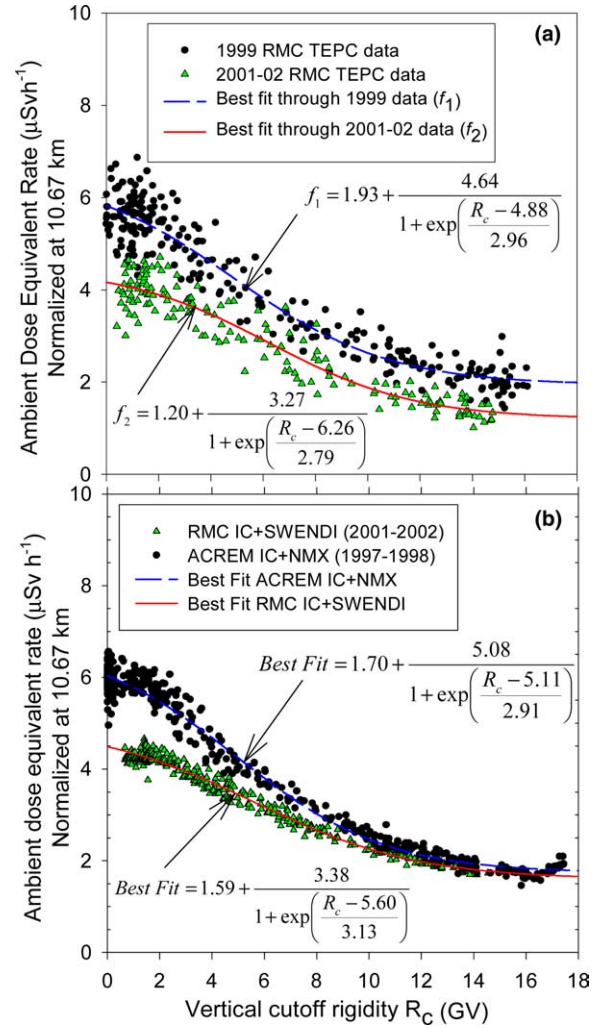


Fig. 1. (a) Ambient dose equivalent rates measured by a TEPC (normalized to an altitude of 10.7 km) plotted as a function of vertical cutoff rigidity. f_1 and f_2 show the equations of the best-fit polynomials through the 1999 (near solar minimum) and 2001–2002 (near solar maximum) data, respectively. (b) Similar presentation of combined RMC IC+SWENDI (2001–2002) and ACREM IC+NMX (1997–1998) ambient dose equivalent rate data (normalized to 10.7 km).

produced intermittently by the fragmentation of atmospheric nuclei by high-energy protons. Although these particles deposit only a minor fraction of the dose, according to Eq. (2) a single high-LET event can contribute a large fraction of the dose equivalent in detectors for which the reading is derived from the frequency (LET) distribution of events, such as the TEPC and LIULIN (EURADOS, 2004). For detectors which do not measure an LET distribution, such as ionization chambers and neutron monitors, the $H^*(10)$ reading is related directly to the energy absorbed by the detector and the corresponding statistical uncertainties are much lower.

The best-fit polynomials to these data (f_1 and f_2 in Fig. 1(a)) provide solar-minimum and solar-maximum

“boundaries” for expected at-altitude ambient dose equivalent rates (Lewis et al., 2004). Using Lagrange polynomials to interpolate between f_1 and f_2 for other points in the solar cycle, it is then possible to predict the dose equivalent rate at any geographical position at any time in the solar cycle. These mathematical correlations, along with those in Eqs. (5) and (6) which account for variations in altitude, form the basis for the Predictive Code for Aircrew Radiation Exposure (PCAIRE), the development and validation of which has been described by Lewis et al. (2004).

With the PCAIRE software code in place to predict the ambient dose equivalent on any flight route, periodic validation of the code with in-flight measurements is necessary. The small size, easy operation, relatively low cost and large data storage capacity of the LIULIN make it an ideal candidate for these periodic measurements. The LIULIN provides output in terms of absorbed dose, D_{LIULIN} , which can be compared directly to the absorbed dose measured by the HAWK TEPC, D_{HAWK} . (For example, the in-flight absorbed dose measurements for typical flights over various regions of the globe are shown in Table 1). For each of the 42 flights on which the LIULIN was compared to the HAWK TEPC, the integrated (route) absorbed dose from the LIULIN was in excellent agreement with the integrated TEPC absorbed dose, with a ratio of D_{HAWK}/D_{LIULIN} of 1.01 ± 0.04 (Kitching, 2004). Furthermore, D_{LIULIN} changes in the same manner as D_{HAWK} throughout a given individual flight. For example, the data recorded by

both instruments on a flight from Singapore to London (Fig. 2) show the same increase in dose rate as both the latitude and altitude increase throughout the flight. This excellent agreement between the absorbed dose measurements of the two instruments supports the applicability of the scale factor ($a = 9.33 \times 10^{-5}$ in Eq. (4)), which was developed in ground-based calibrations, to

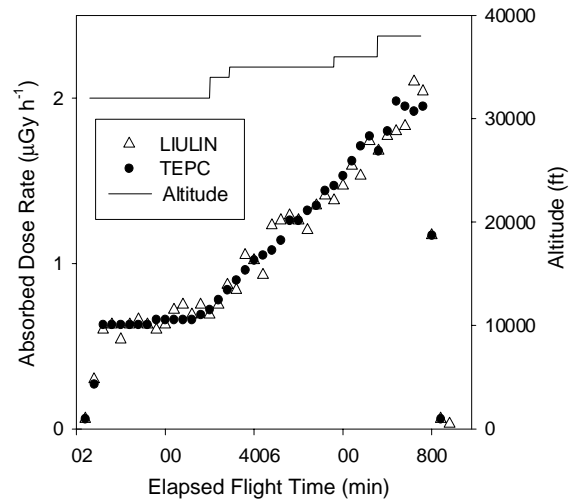


Fig. 2. Twenty minute averages of the absorbed dose rate measured by the LIULIN (open triangles) and TEPC (black circles) during a flight from Singapore to London on 2 December 2003. The solid line represents the altitude changes in feet (according to the right-hand axis).

Table 1
Comparison of TEPC and LIULIN measurements onboard selected passenger flights

Flight route	Date	Enroute altitude (feet)	Time at altitude (min)	Absorbed dose, D (μGy)		Ambient dose equivalent, $H^*(10)$ (μSv)		
				HAWK	LIULIN	HAWK	LIULIN (Q vs. R_c)	LIULIN (Spectral)
Zagreb (Croatia) – Trenton, ON (Canada)	02-Aug-03	34,000	146	12.0	11.8	28.5	26.5	26.6
		36,000	230					
		38,000	36					
		39,000	94					
Ottawa, ON (Canada) – Moscow (Russia)	22-Sep-03	33,000	334	11.8	11.3	28.0	25.8	26.3
		35,000	59					
		33,000	54					
Singapore – Sydney (Australia)	08-Dec-03	33,000	19	6.95	6.63	10.6	11.2	12.4
		35,000	206					
		37,000	133					
Sydney (Australia) – Johannesburg (South Africa)	03-Jan-04	30,000	72	20.7	19.9	45.9	41.4	46.5
		31,000	218					
		33,000	40					
		35,000	84					
		37,000	271					
Johannesburg (South Africa) – Sydney (Australia)	05-Jan-04	29,000	20	17.4	17.3	38.1	37.0	41.6
		33,000	285					
		37,000	317					

at-altitude measurements. Furthermore, these data suggest that the LIULIN may be viable as a routine-monitoring device; however, this will only be possible after the development of a method to determine $H^*(10)$, the operational quantity recommended for monitoring aircrew radiation exposure, from the LIULIN data. Two such methods were investigated and are described below.

In the first method, the ambient dose equivalent is calculated from the absorbed dose with a knowledge of the average quality factor, \bar{Q} , according to the relationship:

$$H^*(10)_{LIULIN} = \bar{Q} \cdot D_{LIULIN}. \quad (7)$$

Published theoretical transport code calculations (O'Brien et al., 1996; Schraube et al., 2000) indicate that the relative contribution of neutrons to the dose equivalent at jet altitudes remains essentially constant for altitudes between 30,000 and 40,000 feet (9.1–12.2 km). Since the composition of the radiation field remains relatively constant within this altitude range (typical of commercial flights), the average quality factor is also expected to be relatively independent of altitude within this range. It will, however, vary with geographical position (quantified by the R_c value), much in the same way that the ambient dose equivalent rate depends upon R_c (see Fig. 1). As such, a correlation of \bar{Q} as a function of R_c was developed from the HAWK TEPC data recorded on 12 flights between 22 September 2003 and 9 January 2004. Using these data, \bar{Q}_{HAWK} values were obtained over 60-min periods by taking the ratio of the summed minute-by-minute H values to the summed D values, i.e.,

$$\bar{Q}_{HAWK} = \frac{\sum_{t=1}^{60} H_t}{\sum_{t=1}^{60} D_t}. \quad (8)$$

These values are plotted as a function of R_c (also averaged over the same one-hour periods) in Fig. 3. Plotting the linear relationship of Fig. 3 as a function of geographical coordinates (Fig. 4) clearly demonstrates the effect of aircraft location on the \bar{Q} value. An estimate of $H^*(10)$ for a given flight can then be obtained by the summation of the individual D_{LIULIN} measurements, each multiplied by the appropriate \bar{Q}_{HAWK} value (corresponding to the aircraft's geographical location during the 20-min LIULIN measurement period). Note, that this methodology can only be applied to measurements obtained over the stated altitude range and cannot be applied to the takeoff or landing portions of the flight.

Alternatively, in a manner similar to that utilized in the TEPC analysis, the ambient dose equivalent can be obtained by direct analysis of the LIULIN spectrum. As mentioned in Section 2.2, the LIULIN partitions data into 256 channels, each with a constant ΔLET

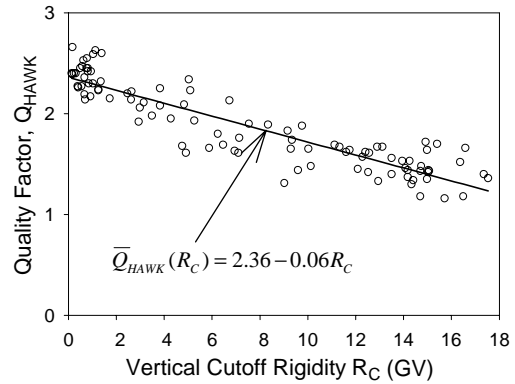


Fig. 3. Average quality factor as determined from in-flight measurements with the HAWK TEPC (integrated over one hour) plotted as a function of vertical cutoff rigidity. The equation resulting from a linear regression analysis of the data is shown in the lower portion of the figure.

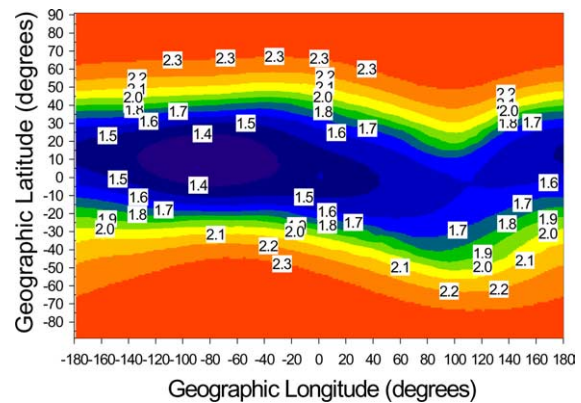


Fig. 4. Contour plot of \bar{Q}_{HAWK} as a function of geographic latitude and longitude.

bin width. By applying an appropriate quality factor, $Q(LET)$, to each channel, the ambient dose equivalent can be calculated using an equation analogous to Eq. (2):

$$H^*(10)_{LIULIN} = a \sum_{i=0}^{255} Q(LET)_i \cdot i \cdot n(i). \quad (9)$$

In order to use this method, it is essential to determine the appropriate channel width (ΔLET) so that the correct value of LET can be assigned to the channel. A value of $\Delta LET = 0.5 \text{ keV } \mu\text{m}^{-1}$ for the channel width was determined experimentally by comparing the LIULIN data to the HAWK data from a flight from Sydney to Johannesburg on November 8, 2003 (Kitching, 2004). Using this channel width to determine the LET for each channel, the value of Q associated with each channel was determined using the $Q(LET)$ relationship recommended in ICRP-60 (ICRP, 1991), which in turn allows for a calculation of $H^*(10)$ from any LIULIN spectrum.

The two different methods of determining $H^*(10)$ from the LIULIN data (i.e., methods based on Eq. (7) or Eq. (9)) are compared to integral values of $H^*(10)$ from the TEPC for five different flights in Table 1. (Note that the data from these flights were not used in any of the model development.) Both methods are well within the 20% error inherent within both the HAWK and the LIULIN, with the $Q(R_c)$ methodology giving slightly lower estimates than the spectral analysis method. Given that both methods work equally well, the preferred method involves the direct analysis of the LIULIN spectrum since this method has the advantages of not requiring knowledge of the aircraft position and having no restrictions on the altitude range. Thus, this spectral method was used to estimate the route $H^*(10)$ for all of the flights (excluding the flight used for the LIULIN bin width determination). As shown in Fig. 5, the $H^*(10)$ values obtained from the LIULIN agree extremely well with those obtained by the TEPC, indicating that the LIULIN could be used as a more convenient alternative to the TEPC for the purposes of periodic validation of aircrew exposure estimates.

The large storage capacity and long battery life of the LIULIN means that it can take measurements continuously for an extended period of time (Spurny and Dachev, 2003). (For example, with the 20-min sampling period used in the current study, the LIULIN recorded data continuously for approximately ten weeks before the batteries died.) While this continuous operation is not necessary for code validation, it allows for the detection of sporadic changes in the jet-altitude radiation field, such as those which may occur immediately before and during intense solar energetic particle events (SEP). In fact, the long-term (approximately two months) use of a LIULIN on board a Czech Airlines A310-300 Airbus led to the at-altitude measurement of increased radiation levels during ground level event 60 (GLE 60) on 15 April 2001 (Spurny and Dachev, 2001). These data, in turn, have been correlated to data from ground-level neutron monitors, resulting in the development of a predictive model for the estimation of the additional exposure that may result from an SEP (Lewis et al., 2004). This SEP model has been successfully tested against an independent measurement during the same GLE;

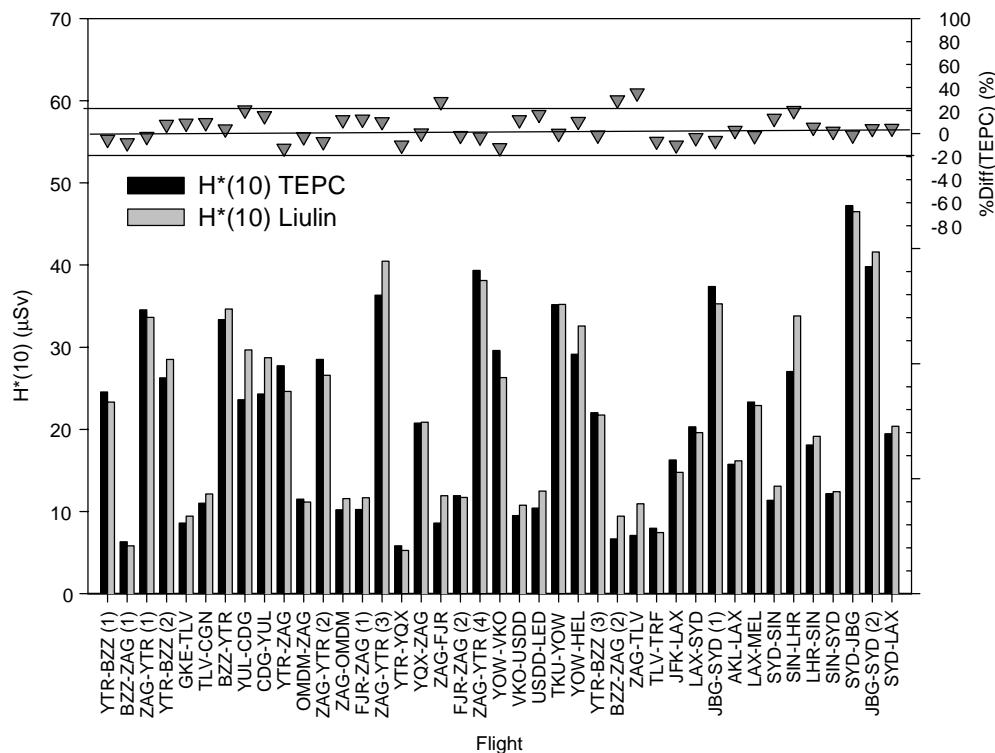


Fig. 5. Comparison of $H^*(10)$ values obtained from a spectral analysis of the LIULIN data compared to $H^*(10)$ values obtained from the HAWK TEPC on 41 jet-altitude flights. The triangles in the upper portion of the figure show the percentage difference between the two values of $H^*(10)$ on each flight. The following airport codes are used to designate the point of departure and the point of arrival: AKL – Auckland, New Zealand; BZZ – Brize Norton Air Force Base, United Kingdom (UK); CDG – Paris, France; CGN – Cologne/Bonn, Germany; FJR – Fujairah, United Arab Emirates (UAE); GKE – Geilenkirchen, Germany; HEL – Helsinki, Finland; JBG – Johannesburg, South Africa; JFK – John F. Kennedy Airport, New York City, United States (US); LAX – Los Angeles, US; LED – St. Petersburg, Russia; LHR – Heathrow Airport, London, UK; MEL – Melbourne, Australia; OMDM – Minhad, UAE; SIN – Singapore; SYD – Sydney, Australia; TKU – Turku, Finland; TLV – Tel Aviv, Israel, TRF – Oslo, Sweden; USDD – Salekhard, Russia; VKO – Moscow, Russia; YOW – Ottawa, Canada; YQX – Gander, Canada; YTR – Trenton, Ontario, Canada; YUL – Montreal, Canada; ZAG – Zagreb, Croatia.

however, additional data is required for further validation of the model. As such, the measurement campaign with both the TEPC and LIULIN will be continued on as many flights as possible.

4. Conclusions

1. TEPC data obtained during 1999 and 2002 have been used to develop mathematical correlations between the at-altitude dose equivalent rate and the vertical cutoff rigidity. These correlations have been encapsulated into an empirically based computer code for the prediction of aircrew exposure to galactic cosmic radiation (PCAIRE).
2. The response of a LIULIN-4 spectrometer was compared to that of the HAWK TEPC on 42 flights in 2003–2004 covering the full range of cutoff rigidity values. On all flights, the absorbed dose measured by both instruments agreed to within 5%. These data provide an in-flight validation of the calibration factor determined by the manufacturer in ground-based studies.
3. Two different methods of determining the route $H^*(10)$ value from the LIULIN data were examined. Although both methods are valid, the most convenient method involves a direct analysis of the LIULIN spectrum using a Δ LET value of $0.5 \text{ keV } \mu\text{m}^{-1}$. This method produces $H^*(10)$ values which agree very well the $H^*(10)$ values measured by the TEPC (within the 20% error inherent within both instruments). With this mathematical correlation in place, the LIULIN offers a viable option for the periodic evaluation of PCAIRE predictions.
4. As a supplement to the PCAIRE code, a simple empirical model has been developed for the prediction of the enhanced exposure that may result during an SEP. Measurements with the LIULIN will be continued in an effort to record data during an SEP, which could then be used for further validation of the SEP model.

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