

# ARMAS Flight System for Operational Aerospace Radiation Measurements

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**In this paper we** describe the Automated Radiation Measurements for Aerospace Safety (ARMAS) operational system that has been developed to produce quality and calibrated absorbed dose measurements for aerospace safety. The ARMAS system is at a Technology Readiness Level (TRL) 9 and has collected over a half million one minute data records through 600 missions on vehicles since 2013 at altitudes from 8-90 km on a wide variety of NASA, FAA, and commercial flights as well as high altitude balloons and a commercial suborbital vehicle. The ARMAS radiation measurement flight system uses the Teledyne micro dosimeter (uDOS001) that directly measures total ionizing dose (TID) absorbed by an internal silicon test mass. Radiation measurements performed aboard commercial airline flights are presented and discussed. The ARMAS flight measurements are also compared to the results obtained by a Tissue Equivalent Proportional Counter (TEPC). Experiments at ground based particle accelerator and radiation producing facilities for further comparisons between the ARMAS system and the TEPC response are introduced.

## Nomenclature

ARMAS FM = *Automated Radiation Measurements for Aerospace Safety Flight Module*

D = Absorbed Dose in a given mass of material

D(Si) = Absorbed Dose in Silicon

D(Ti) = Absorbed Dose in tissue

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DLR	=	German Aerospace Center
HCP	=	Heavy Charged Particle
HPD	=	NASA Heliophysics Division
LANSCE	=	Los Alamos Neutron Science Center
LET	=	Linear Energy Transfer ( $\text{keV } \mu\text{m}^{-1}$ )
LWS	=	NASA HPD Living With a Star program
NAIRAS	=	Nowcast of Atmospheric Ionizing Radiation System
Q	=	Quality factor (also $Q_{\text{SET}}$ for the Rc-derived Q used by SET)
<i>RaD-X</i>	=	NASA <i>Radiation Dosimetry eXperiment</i> balloon mission
<i>RADIAN</i>	=	<i>RADIation environment using ARMAS data in the NAIRAS model</i>
Rc	=	Earth magnetic field cutoff rigidity
SBIR	=	Small Business Innovation Research
SET	=	Space Environment Technologies
<i>TEPC</i>	=	<i>Tissue Equivalent Proportional Counter</i>
TID	=	Total Ionizing absorbed Dose
VDC	=	Voltage Direct Current
$y$	=	Lineal energy ( $\text{keV } \mu\text{m}^{-1}$ )

## I. Introduction and Background

Atmospheric ionizing radiation is the primary source of exposure to high LET radiation at commercial aircraft altitudes in crew and passengers.<sup>1,2,3</sup> High LET radiation is capable of causing double strand breaks in DNA, i.e., a process that can lead to adverse health effects including cancer. It has been noted that this can be an important cause for limiting the careers of aircrew.<sup>4,5</sup> The importance of understanding the exposure environment for humans in aerospace has motivated our team to build a system that (i) produces quality and calibrated absorbed dose measurements at relevant altitudes and latitudes for different geomagnetic conditions and (ii) reports the observations to the ground with sufficient low latency and high time resolution to impact operational decision making. The *Automated Radiation Measurements for Aerospace Safety (ARMAS)* system is that tool and we report here the steps that have been taken to justify a claim for producing quality and calibrated dose measurements.

*ARMAS* has a long lineage of development through the NASA SBIR program. From 2013–2019 NASA *ARMAS* SBIR Phases I, II, IIE, and III have provided automated radiation measurements for aerospace safety.<sup>6,7</sup> More recently, the 2017 NASA Heliophysics Division (HPD) Living With a Star (LWS) *RADIation environment using ARMAS data in the NAIRAS model (RADIAN)* was funded to assimilate *ARMAS* measurements into the NASA Langley Research Center’s (LaRC) *Nowcast of Atmospheric Ionizing Radiation System (NAIRAS)* physics-based radiation model. Finally, the 2018 HPD *ARMAS-Dual Monitor* SBIR Phase I was funded to develop the first radiation monitoring capabilities for the national air-space environment. Evolving from NASA SBIR Phases I–III, *ARMAS* is not only building, demonstrating, and deploying a system that includes a fleet of radiation flight measurement units making real-time dose observations but is able to retrieve those data and immediately process them into tissue-relevant units for use by end users. Having a fleet of instruments that can operationally monitor radiation in aircraft, balloons, rockets, reusable launch vehicles, and satellites with a common detector system enables consistent, real-time identification of radiation hazards during space weather events, including those with solar protons and geomagnetically disturbed conditions.

The *ARMAS* system is at a Technology Readiness Level (TRL) 9 and has collected over a half million one-minute data records through 600 missions on vehicles since 2013 at altitudes from 8 – 90 km, including the NASA Armstrong Flight Research Center’s (AFRC) 747 (SOFIA), DC-8, G-III, and ER-2, the NOAA G-IV, the NSF/NCAR G-V, and the FAA Bombardier Global 5000. *ARMAS* has also flown on numerous commercial Boeing and Airbus jets, the World View Enterprises Stratocraft high altitude balloon, a stratospheric glider, and a commercial suborbital vehicle.<sup>7</sup>

Since commercial and high-flying military aircraft personnel are continually exposed to both cosmic and secondary particle radiation, an accurate assessment of the absorbed dose and dose equivalent received by aircraft crew members and frequent flyers is an important part of a radiation protection program. The *Tissue Equivalent Proportional Counter (TEPC)* is the defacto industry standard and measures energy deposition in simulated volumes that are comparable to those of a living cell.<sup>8,9</sup> The *TEPC* uses materials and gases that are essentially equivalent to human tissue in chemical composition. Measurements taken with the *TEPC* are used to calculate radiation absorbed

dose, average radiation quality factor, and dose equivalent. *TEPCs* have been well characterized in a variety of controlled radiation environments such as particle beam lines and this has provided confidence in their use for operations.<sup>9,10,11</sup>

## II. Materials and Methods

### A. ARMAS

The *ARMAS* radiation measurement flight system uses Teledyne micro dosimeters (uDOS001, Figure 1) developed by Aerospace Corporation and manufactured under license by Teledyne. The uDOS001 directly measures total ionizing dose (TID) absorbed by an internal silicon test mass. The detector size is 3.56×2.54×0.10 cm. By accurately measuring the energy absorbed from heavy ions, alphas, protons, neutrons, electrons, and gamma rays ( $\gamma$ -rays), an estimate of the absorbed dose in silicon is made. The micro dosimeter provides repeatable measurements of TID in silicon over a wide range of energies (60 keV to >15 MeV) and operating temperatures (-30 to +40°C). In *ARMAS*, the instrument is typically operated at aircraft cabin temperatures (15–25°C); for environments colder than -15°C passive thermal insulation is used. The micro dosimeter operates from input power voltages >13 VDC. Figure 2 is a diagram of the *ARMAS* instrument measurement concept and Figure 3 shows an *ARMAS* Flight Module 7 (FM7) with Bluetooth capability.

The accumulated dose is reported via three DC linear and one pseudo-logarithmic output channels in units of millivolts, giving a dose resolution of 14  $\mu$ rads and a measurement range exceeding 100 krad. Each channel (ch1–ch4) has a resolution of 256 steps, i.e., values of 0–255, and when a lower channel rolls over to 0 the next higher channel is incremented by 1. Level 0 (L0) raw data is reported as the output of the four channels, each having a value of 0–255. In addition to the uDOS and DC/DC converter to provide ch1–ch4 information, a microprocessor ( $\mu$ proc) is used to accumulate the absorbed dose measurements over time, which can be variable but 10 s is used operationally. Along with an input GPS signal for time and position, the output L0 information is both stored on an internal micro SD card data logger as well as sent externally via one of several systems. Depending upon the given configuration of the *ARMAS* instrument, the L0 and GPS information may be sent via Iridium satellite link, Bluetooth to a paired smart phone or tablet, or Ethernet.<sup>6</sup>

External to the instrument, the *ARMAS* v9.46 algorithms convert the L0 data into L1 TID  $D(Si)$  (in  $\mu$ Gy) by the conversion equation (1)

$$TID = ch1 * 14.0 \times 10^{-2} + ch2 * 3.6 \times 10 + ch3 * 0.9 \times 10^4 \quad \mu Gy. \quad (1)$$

The pseudo-logarithmic output in channel 4 is not used in the data calculation.

L2 ( $dD(Si)/dt$ : absorbed dose rate  $S_i$ ,  $\mu$ Gy  $h^{-1}$ ) is the time derivative of the L1 TID. L3 dose equivalent rate ( $dH/dt$ :  $\mu$ Sv  $h^{-1}$ ) is calculated as shown in equation (2)

$$dH/dt = dD(Si)/dt \times Q_{SET} \times 0.81 \quad (2)$$

where the Quality factor at the location of measurement,  $Q_{SET}$ , is derived using a fit to the results of  $Q$  vs. cutoff rigidity ( $R_c$ ) by the method shown in Figure 4 using equation (3).<sup>12</sup>

$$Q_{SET} = 2.175 - 0.066 \times R_c + 0.001 \times R_c^2 \quad (3)$$

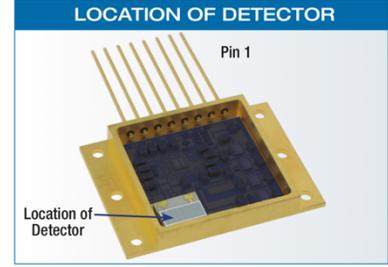


Figure 1. Teledyne uDOS001.

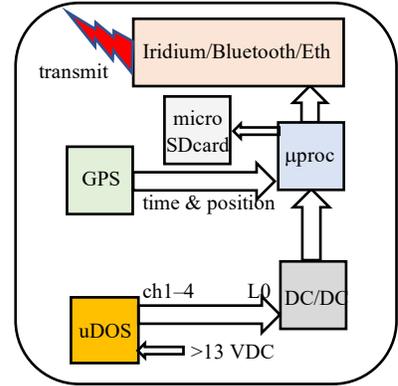


Figure 2. *ARMAS* concept.



Figure 3. *ARMAS* instrument.

This method using equation (3) was also verified by *TEPC* measurements of  $Q$  in Gersey *et al.*, 2012.<sup>13</sup> The factor of 0.81 in equation (2) is used to calibrate *ARMAS* v9.46 to *NAIRAS* v1. The L3 ambient dose equivalent rate ( $dH^*(10)/dt$ :  $\mu\text{Sv h}^{-1}$ ) is calculated using equation (4)

$$dH^*(10)/dt = dD(Si)/dt \times Q_{\text{SET}} \times 2.0 \quad (4)$$

where 2.0 is the normalization factor to a phantom body compared with *NAIRAS*.

The L4 effective dose rate ( $dE/dt$ :  $\mu\text{Sv h}^{-1}$ ) is calculated using equation (5)

$$dE/dt = dH^*(10)/dt \times W_{\text{T\_sum}} \times Fr \times Wr(z, Gv, \text{species}) \quad (5)$$

where  $W_{\text{T\_sum}}$  is the tissue weighting factors across all tissue and is set to 1.0,  $Fr$  is the calculated secondary species fraction binned by  $Gv$  0–17 including alphas and HCPs, neutrons, protons, photons, electrons, pions and muons (Figures 5 and 6), and  $Wr(z, Gv, \text{species})$  is the radiation weighting factor for HCPs, alphas, neutrons, protons, photons, electrons, pions/muons using the values of 20, 20, 5, 5, 1, 1, and 1, respectively.<sup>14</sup> The *ARMAS* v9.46 data use a calibration to the *RaD-X* balloon mission results to obtain  $\pm 24\%$  RMS uncertainty in the observations.

## B. TEPC

Energy deposition spectra produced by a *TEPC* can be used to calculate absorbed dose and to estimate the average quality of radiation during a flight. A diagram of the active volume of the *TEPC* used in this study is shown in Figure 7, and is a right cylinder 1.78 cm long and 1.78 cm in diameter. The walls of this right cylinder are fabricated from tissue equivalent A-150 plastic and are 1.9 mm thick. The right cylinder is enclosed in stainless steel walls of 0.89 mm thickness. The active volume is then enclosed in an aluminum cylinder, which measures 2 in. in diameter and is 12 in. long (henceforth, the active volume chamber, including the 2×12 aluminum enclosure, is referred to as a ‘chamber’). The active volume of the *TEPC* is filled with low-pressure propane gas to simulate a right cylinder with a 2-micron diameter and length. An anode wire runs the length of the cylinder and is kept at a potential of 640 volts relative to the cylinder walls.

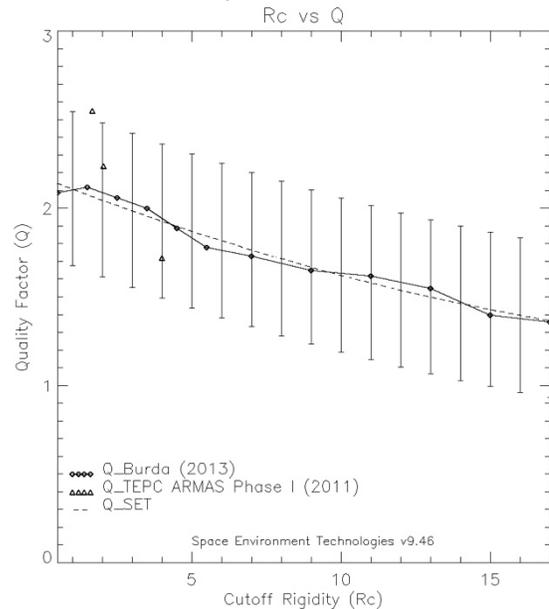
The electronics for the *TEPC* are housed in an aluminum cylinder 6 inches (in.) in diameter and 6 in. long (the electronics container is called ‘the spectrometer’). These two separate pieces of the system are linked by a robust steel-braided cable, which also protects the wiring harness and electronically links the two.

When a high-energy particle enters the *TEPC* active volume, charge is collected at the anode wire and processed by a pre-amplifier. The signal then moves to a shaping amplifier, is converted into a digital pulse height via an analog to digital converter (ADC) and stored on a flash-ROM card. This information is then translated into lineal energy (the energy deposited in the active volume by a single energy deposition event) in units of  $\text{keV } \mu\text{m}^{-1}$ . A Lineal Energy Transfer (LET) spectrum is created from these measurements that is then used to calculate the absorbed dose, average quality factor ( $Q$ ) and dose equivalent of the radiation in tissue.

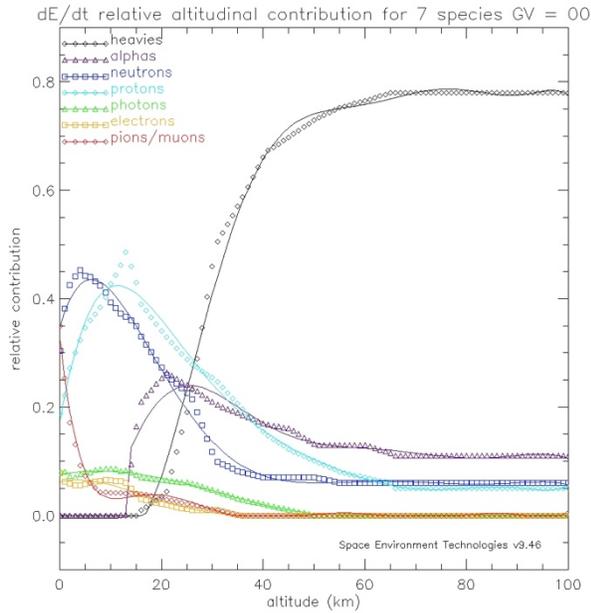
## III. Results and Discussion

### A. Flight comparisons between *ARMAS* and *TEPC*

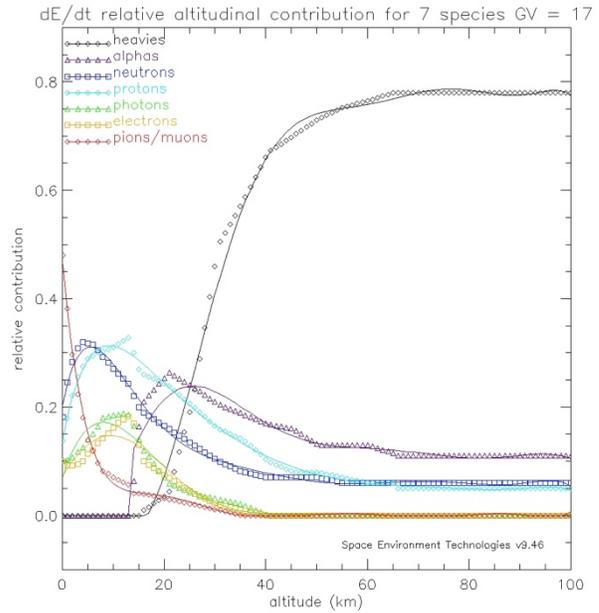
While the current version of *ARMAS* processing software (v9.46) is calibrated to the *NAIRAS* model and the *RaD-X* balloon mission results, independence of data and model has not been achieved with the previous work. In order to obtain a truly independent calibration of *ARMAS* that can improve the models, our team has been making comparative measurements between *ARMAS* and *TEPC* since 2011. Gersey *et al.* and Tobiska *et al.* describe early



**Figure 4.  $Q_{\text{SET}}$  as the dashed line fit to the Burda measurements of Quality factor ( $Q$ ) (diamonds with error bars) and validated with Gersey *TEPC* data (triangles).**



**Figure 5. Relative contribution by altitude for 7 species at GV = 0.**



**Figure 6. Relative contribution by altitude for 7 species at GV = 17.**

comparisons between *TEPC* on a commercial carrier flight in the cargo hold 25 August 2011 at 9.8 km (Houston – Los Angeles) and *ARMAS* on a similar commercial flight path for comparable geomagnetic conditions (Los Angeles – New Orleans and Los Angeles – Washington DC).<sup>3,13</sup> Figure 8 shows the comparisons of the *TEPC* and *ARMAS* measurements as well as including *NAIRAS* climatology and DLR observations (Germany to Mauritius, DUS–MRU). We note that, in general, there is reasonable agreement between the derived observations and model; *ARMAS* v9.46 produces slighter higher dose equivalent rates than *TEPC*.

A second comparison was made between *ARMAS* and *TEPC* on two commercial flights (Los Angeles – Denver and Denver – Los Angeles) 20 May (11.3 km) and 23 May 2018 (11.6 km), respectively, for very similar quiet geomagnetic conditions. Table 1 shows very good comparison between the two instruments using the *ARMAS* v9.46 algorithm based on *NAIRAS/RaD-X* although we consider there is still room for improvement. For example, the method used by *ARMAS* to derive Q may work generally well for aircraft altitudes but may not work well for altitudes above 30 km. The *TEPC* would give a more accurate measured Q value than the derived quantity at higher altitudes. It is important to note that the *TEPC* is less sensitive to  $\gamma$ -rays, which are detected by *ARMAS*. Though the tissue effectiveness is low for  $\gamma$ -rays, there is still some effect on crew and passengers. The objective of our ongoing work is to improve the *ARMAS* algorithm for absorbed dose and dose equivalent calculations by using *TEPC* as the calibration standard.

**Table 1. *TEPC* and *ARMAS* v9.46 comparison on same commercial flights**

Detector	Date	Flight	Absorbed dose rate ( $\mu\text{Gy/h}$ )	Dose equivalent rate ( $\mu\text{Sv/h}$ )	Average Q (unitless)
TEPC	20 May 2018	LAX – DEN	2.37	4.69	1.97
ARMAS	20 May 2018	LAX – DEN	2.94	5.73	2.18
TEPC	23 May 2018	DEN – LAX	2.51	5.48	1.95
ARMAS	23 May 2018	DEN – LAX	2.64	5.28	2.00

**B. Ground facility comparisons between *ARMAS* and *TEPC***

The *ARMAS* and *TEPC* instruments have been exposed together at multiple space radiation ground based facilities during the past seven years. The objective of these cross comparison efforts has been to establish a known baseline for a wide range of radiation fields to compare the responses of the instruments. A variety of particles and photons have been measured, including heavy ions ( $\text{Fe}^+$ ) at Brookhaven NASA Space Radiation Laboratory (NSRL), neutrons at Los Alamos Neutron Science Center (LANSCE), protons at Loma Linda University Medical

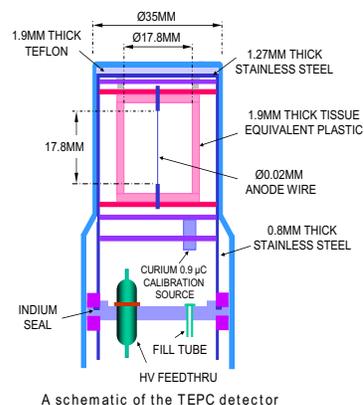
Center (LLUMC), and  $\gamma$ -ray beams at Lawrence Livermore National Laboratory (LLNL). This on-going work is being prepared for presentation in a separate peer-review publication.

#### IV. Conclusions

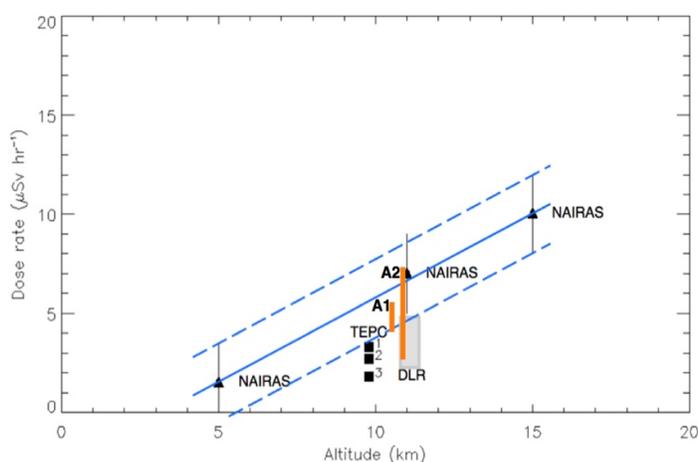
In this paper the instrument comparison and calibration activity for the *ARMAS* automated radiation measurement system for aerospace safety was introduced. The *ARMAS* system utilizes a radiation detector based on the Teledyne micro dosimeter (uDOS001) that produces real time TID measurements during flight missions and the system further provides derived dose equivalent, ambient dose equivalent, and effective dose rates. Comparisons of *ARMAS* and *TEPC* measurements taken aboard commercial airline flights have been made and it was determined that the results were in good agreement. A method for flying the two detectors together to calibrate the *ARMAS* system output using the *TEPC* results was introduced. Future work is planned to use previous controlled experiments at ground based radiation producing facilities to better understand the *ARMAS* system response in comparison to the *TEPC* response and these results will form the basis of a future publication.

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**Figure 7. Active volume of the TEPC.**



**Figure 8. Dose equivalent rate comparison for NAIRAS (triangles), TEPC (squares), ARMAS FM (A1 and A2 orange bars), and DLR DUS-MRU TEPC (gray rectangle).**

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