A Silicon Micro Dosimeter for High-Altitude Measurements of Cosmic Radiation

James Rosenthal
NASA Langley Research Center
Electronic Systems Branch
Hampton, VA 23681 USA
757-864-3884
james.d.rosenthal@nasa.gov

Bryan Hayes
Department of Physics
Oklahoma State University
Stillwater, OK 74074 USA
405-744-5796
bryan.hayes@okstate.edu

Christopher Mertens
NASA Langley Research Center
Space Radiation Group
Hampton, VA 23681 USA
757-864-2179
christopher.j.mertens@nasa.gov

Abstract—**The small size and low manufacturing costs of semiconductor dosimeters could make them ideal sensors for real-time measurements of biologically harmful radiation at aviation altitudes. This paper presents the system design, accumulated dose measurements, and dose rate calculation results obtained from the Teledyne UDOS001 total ionizing dose (TID) micro dosimeter as part of the NASA Radiation Dosimetry Experiment (RaD-X) stratospheric balloon mission. A commercial class TID sensor was used for the mission, measuring 35 mm x 25 mm x 4.5 mm with a power consumption of 280 mW. The sensor was used to measure accumulated dose for 20 hours, with 18 hours of data at altitudes above 20 km, and it was integrated into the RaD-X payload with a custom interface printed circuit board, which provided power conditioning and signal buffering. An analog-to-digital (ADC) converter was then used to sample the sensors analog output at 15 Hz. To ensure the sensor temperature remained within operating limits (-30° C to 40° C), a thermal control system was used to maintain the temperature of the sensor. Post-flight analysis showed that the TID measured dose rates were in good agreement with an industry standard tissue equivalent proportional counter.**

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1. INTRODUCTION

Penetrating radiation from galactic cosmic rays (GCR) and solar energetic particle (SEP) sources can adversely affect aircraft avionics and the health of airline crews and passengers [1]. The NASA Heliophysics Division's *Living With A Star Program* identified a primary goal of improving the agency's ability to predict air travelers' exposure to biologically harmful radiation by improving our understanding of the cosmic ray transport processes and GCR interactions with the atmosphere. NASA's Langley Research Center (LaRC) has made significant advances in quantifying and documenting aircraft radiation exposure by developing the Nowcast of Atmospheric Ionizing Radiation for Aviation Safety (NAIRAS) model: the first real-time, global, physics-based model that includes both GCR and SEP sources of radiation exposure. In [2] it was reported that NAIRAS may underestimate effective body dose by 50% at lower latitudes ($\leq$50°). To achieve reliable dose assessments outlined by the International Committee on Radiation Units, uncertainty must be $\leq$30% for latitudes $\geq$30°. Therefore, the primary goal of the Radiation Dosimetry Experiment (RaD-X) was to collect and process data from the top of the atmosphere in order to improve cosmic radiation dose assessment and characterize the energy deposition from GCR primaries, reducing the uncertainty of the model at lower latitudes (areas where Earth's magnetic field has higher cutoff rigidities). Additionally, RaD-X also had a secondary goal of identifying and characterizing low-cost radiation measurement solutions that could potentially provide continuous, global measurements for real-time data assimilation into NAIRAS. To this end, the RaD-X payload flew the Teledyne UDOS001 to compare measured data with an industry standard tissue equivalent proportional counter.

The Teledyne UDOS001 total ionizing dose micro dosimeter (herein called the TID sensor) is a silicon-based detector which can measure a total ionizing dose up to 40 kRads. The TID sensor has been used by the Automated Radiation Measurements for Aviation Safety Project (ARMAS), a NASA Small Business Innovation Research Program, led by Space Environments Technologies, that is collecting data from DC-8 and ER-2 flights [3]. Additionally, the particular sensor model has successfully measured cosmic radiation in space on the Cosmic Ray Telescope for the Effects of Radiation (CRaTER) as part of the Lunar Reconnaissance Orbiter (LRO) from 2009-2010 [4]. However, to the best of the authors' knowledge, the sensor had not previously been flown on a stratospheric balloon where it could measure incoming cosmic radiation above the Pfotzer maximum.

The outline of this paper is as follows: the RaD-X mission and payload are described in Section II to provide context for the measurements made by the TID and the flight environment in which it flew. Section III describes the TID sensors specifications and operations in more detail. Measured data collected with the sensor in a laboratory setting with a Cesium (CS)-137 gamma-ray source is provided in Section IV, followed by measured data from the balloon mission. A description of the post-processing algorithm used to analyze the data and calculate dose rate is included, as well as a description and results of the thermal control system used to measure and maintain operational temperatures during flight. The paper concludes with a summary of the results and suggestions of potential follow-on work in Section V.

2. MISSION OVERVIEW

On September 25, 2015, a TID sensor was flown as part the RaD-X mission to collect data on-board a stratospheric balloon launched from Fort Sumner, New Mexico

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Fig. 1. **RaD-X balloon on the flight line during inflation**

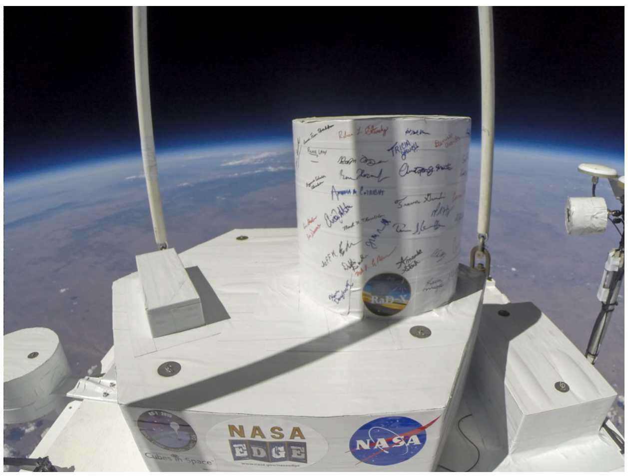

Fig. 2. **Payload in flight near the Region B altitude**

(34.47°N, 104.25°W). The experiment had two primary goals: (1) improve uncertainty in predicting human exposure to biologically-harmful ionizing radiation at aviation altitudes, and (2) assess the performance of a suite of radiation detectors for continuously measuring radiation in aircraft. Twenty hours' worth of science data was collected from four dosimeters: a Far West Technologies Hawk 3.0 tissue equivalent proportional counter (TEPC) microdosimeter, which was the reference dosimeter, the TID sensor, and two other dosimeters. Of the science data, 18 hours were collected above the Pfotzer Maximum at barometric altitudes greater than 20 km, in order to better understand the dosimetric properties of cosmic ray primary particles [5].

Concept of Operations

The key science requirements were to characterize the dosimetric properties of GCR primaries, the main source of biologically harmful radiation in the atmosphere, and the GCR secondary radiations caused by the interaction of primaries and the atmosphere. These measurement requirements led to the formulation of flight requirements: the payload would need to collect data at a high-enough altitude to measure the GCR primaries before they interacted with the atmosphere (>35 km), and it would need to collect data at a lower altitude where radiation was dominated by secondary radiation effects (20-30 km).

The payload would need to loiter at each of these two altitudes for several hours to collect statistically significant

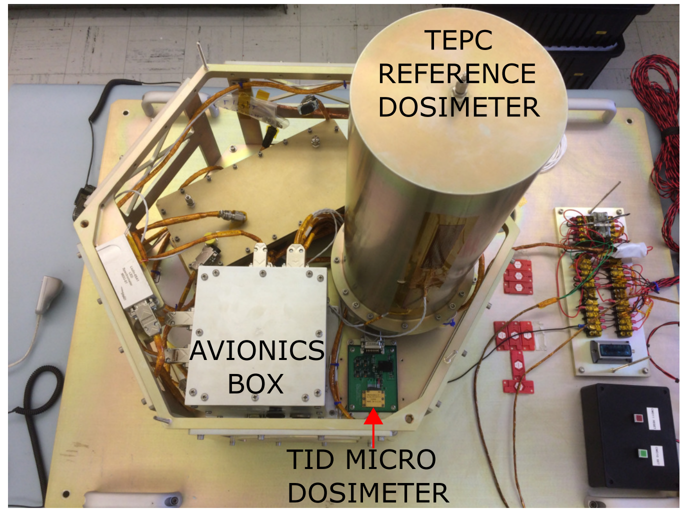

Fig. 3. **Overview photo of the RaD-X payload**

data. RaD-X chose to use a high-altitude balloon over other flight vehicles (sounding rocket, small satellite,...) because it could provide the altitudes and flight durations required by the science goals while remaining within the project schedule, cost, and risk constraints. A sub-orbital, high-altitude balloon flight lasting approximately 18 hours was expected to be sufficient. Collaborating with the Columbia Scientific Balloon Facility (CSBF), a NASA facility managed by Orbital ATK [6], it was decided to launch the balloon in the morning filled with enough helium to arrive and remain at Region B; then as the sun set and the balloon cooled, it would naturally settle down to a lower altitude (the balloon could also be outfitted with releasable ballast to further control its buoyancy), see Fig. 1 and 2. The project therefore proposed a high-altitude balloon mission to, and was granted funding by, NASA Science Mission Directorate's Hands-On Project Experience (HOPE) program that offers employees the opportunity to design, develop, build, and launch a suborbital flight project over the course of 18 months [7]. Our Region B altitude was set based on the requirement to measure the GCR and SEP primaries entering the atmosphere, and the lower Region A altitude was then set based on the requirement to measure the secondaries that increase ambient dose equivalent rate (μSv/hour) and the silicon absorbed dose rate (uGy/hour).

Payload Overview

The payload was broken up into three main segments: the science instrument segment comprised of the TEPC, Raysure, Liulin, and TID dosimeters; the avionics segment that included the avionics stack, barometer, and the Iridium modem; the environmental control segment that used passive and active means to maintain the operational temperatures and, for the TEPC and RaySure, the operational pressures. A fourth segment–the flight segment–consisted of the balloon, gondola, batteries, and CSBF instrumentation panel (CIP). The flight segment was designed and managed by CSBF, and it provided the RaD-X payload power and redundant data down-link/command up-link channels. An overview of the payload is shown in Fig. 3.

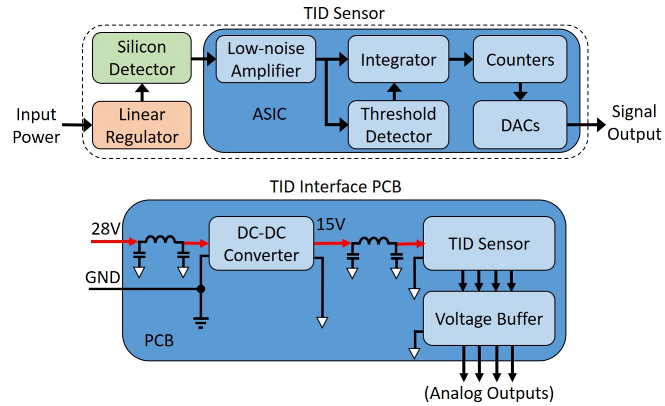

Fig. 4. TID sensor and interface PCB block diagram

3. SILICON-BASED MICRO DOSIMETER

Sensor Operation

The RaD-X payload used the commercial version of the Teledyne UDOS001 total ionizing dose sensor [8]. The sensor dimensions measure 35 mm x 25 mm x 4.5 mm, and it consumes 280 mW of current when supplied with a 28 V voltage. Internally the sensor is comprised of a silicon detector, a linear regulator, and a custom application specific circuit (ASIC). When incident radiation hits the silicon detector, it liberates free charge. If the energy deposited is greater than the nominal threshold of 100keV, the CMOS ASIC within the sensor amplifies the charge and integrates it. When the integrated total charge reaches 13.6 μRads, the internal counter increments, and the internal digital-to-analog converter (DAC) outputs the dose as a scaled voltage on four output pins corresponding to a low, medium, high, and total logarithmically-scaled range. Each pin can output a voltage between 0-5 V with a resolution of 12 μRads. These output voltages are outlined in Table 1, along with other mechanical and electrical specifications [9]. In [4], the integration error was found to have a typical accuracy of +/-20%; however, for many radiation applications this error is acceptable given the much higher uncertainty of simulations.

Sensor Interface Board Design

We developed the custom interface PCB shown in Fig. 5 to provide power regulation and signal buffering between the TID sensor and the analog-to-digital (ADC) of the Avionics Stack. The RaD-X payload was powered by lithium-sulfur-dioxide batteries that provided 28 V to the payload subsystems. To regulate the power for the TID sensor, a CUI Inc. PQM3-3 isolating DC/DC converter was used on the interface PCB to convert the unregulated 28 V to a regulated 15 V. Passive LC filters were included on the input and output of the regulator to reduce ripple using 100 μH inductors and ceramic 47 μF X5R dielectric capacitors for a -3 dB cutoff frequency of approximately 2 kHz. Because of the TIDs relatively high output impedance (10 kΩ) [8], an Analog Devices Inc. AMP04 rail-to-rail instrumentation amplifier with unity gain was used to buffer the output signals and prevent loading of the ADC. The four single-ended outputs of the sensor were sampled at 15 Hz using a Diamond Systems Diamond-MM-32DX-AT Analog I/O Module, which had 32 single-ended ADC input channels, a $\pm$ 10 V input voltage range, and 16-bit resolution (305 μV resolution per LSB). The digitized data was saved on-board in flash memory as well as telemetered to the ground in near real-time via an NAL Research A3LA-RG Iridium satellite modem.

Table 1. TID Sensor Specifications

Parameter	Value(s)	Unit
Total Mass	20	grams
Power	0.28	Watts
Dosimeter outer dimensions	35 x 25 x 4.5	millimeter
Silicon detector dimensions	5 x 5 x 0.25	millimeter
Nominal electronic threshold	100	keV
Maximum energy deposit	15	MeV
Linear Energy Transfer range	0.4 - 60	keV/μm
DAC low range	0 - 3.5	mRads
DAC low step size	13.6	μRads
DAC medium range	0 - 0.88	Rads
DAC medium step size	3.5	mRads
DAC high range	0 - 233	Rads
DAC high step size	0.88	Rads
DAC logarithmic range	0 - 68	kRads
Dose rate	$<10\mu$ - 100m	Rads/sec

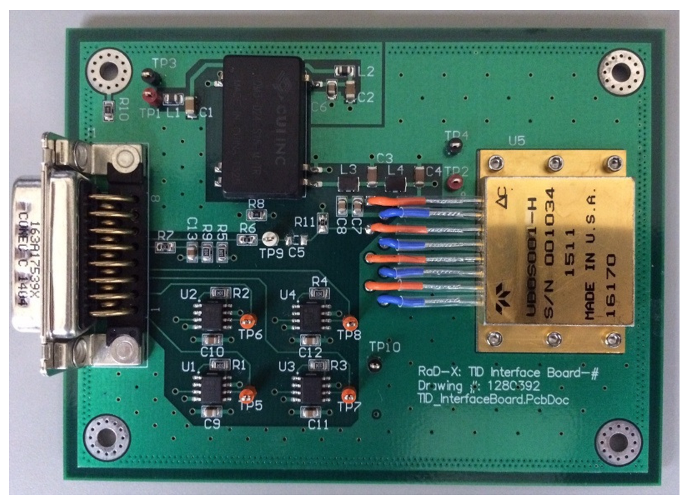

Fig. 5. Photo of the TID interface PCB

4. MEASUREMENT DATA

Laboratory Measurements

Data from the TID was collected in the laboratory to show how the sensor responded to sources with different levels of radioactivity. For example, for a radiation source with ten times as much radioactivity as another, we would expect to see a dose rate that is ten times higher. The RaD-X payload was powered from an Agilent E3647A power supply set to 28 V; aside from the power supply, flight-hardware (cables, flight computer) was used, though the laboratory configuration deviated from flight because the RaySure dosimeter and its DC-DC converter were not connected electrically. Cs-137 sources of 10 and 1 μCurie radioactivity were used. We placed the Cs-137 source on a 0.635 cm (0.25 in) aluminum plate as pictured in Fig. 6. Additionally, we placed a 5 cm piece of L200 minicell polyethelyne foam (not shown in

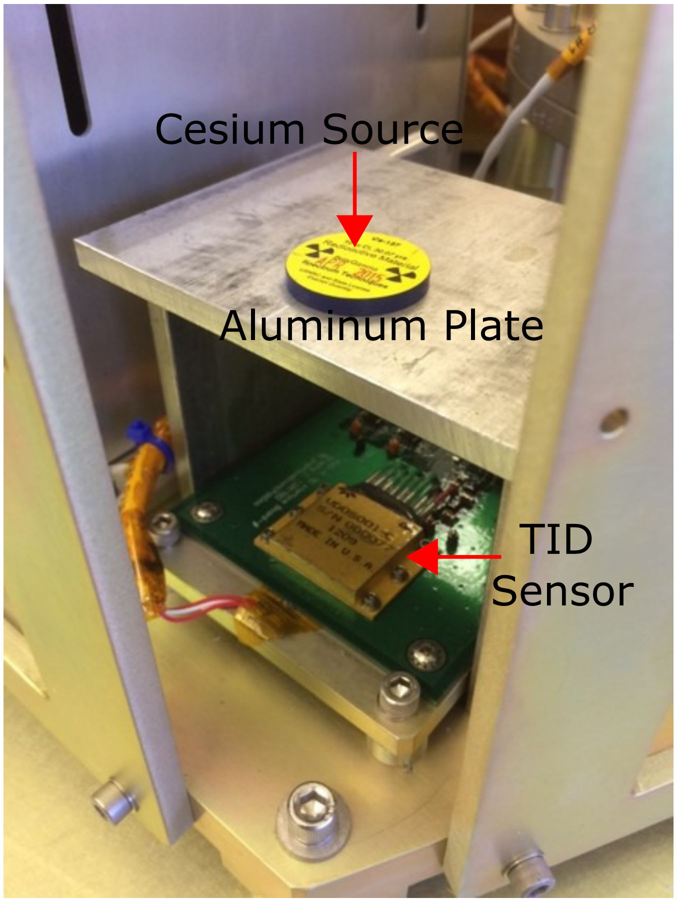

Fig. 6. **Measurement set up with a Cs-137 gamma ray source**

Fig. 6) between the sensor and the aluminum plate to attenuate any secondary electrons that might be generated in the air gap and to provide us data that would be comparable with our other instruments housed in 0.635 cm (0.25 in) aluminum pressure vessels lined with the same foam. Based on the relative radioactivity of the sources, we expected that the 10 μCurie source would yield a measured dose rate ten times higher than the 1 μCurie source.

Dose rate in Gy/hour can be estimated from the TID sensor by converting the number of steps measured on the output channels and dividing by the time duration. Note that there are 100 Rad per Gy.

$$\text{\# of steps} * \frac{\text{Rad}}{\text{step}} * \frac{0.01\,\text{Gy}}{\text{Rad}} * \frac{1}{t} = \text{Dose Rate}\left[\frac{\mu\text{Gy}}{\text{hour}}\right] \quad (1)$$

For the 10 μCurie source, we can see from the data in Fig. 7 that the TID sensor's low range channel incremented 30 steps over a duration, t, of approximately 70 minutes (1.17 hours), yielding a dose rate of 3.75 μGy/hour.

For the 1 μCurie source, we can similarly see from the data in Fig. 7 that the TID sensor's low range channel incremented 3 steps over a duration, t, of approximately 70 minutes (1.17 hours), yielding a dose rate of 0.375 uGy/hour.

During testing, we found that the sensor was sensitive to flashes of light (e.g. the flash from a smartphone camera),

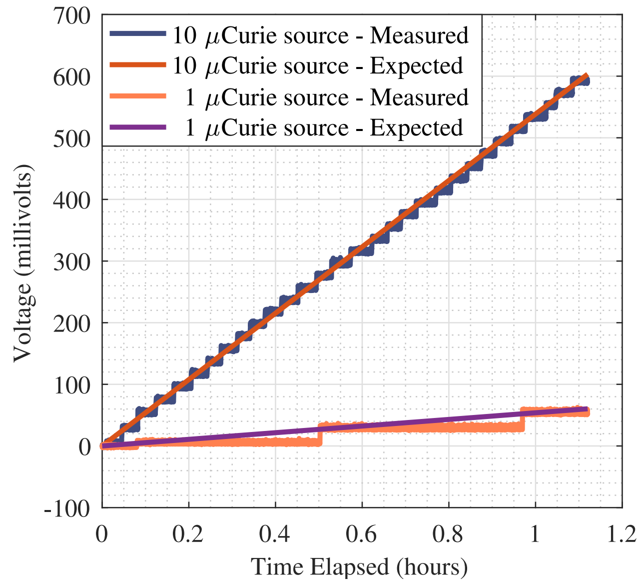

Fig. 7. **Lab measurements versus expected results with Cs-137 source, TID low channel**

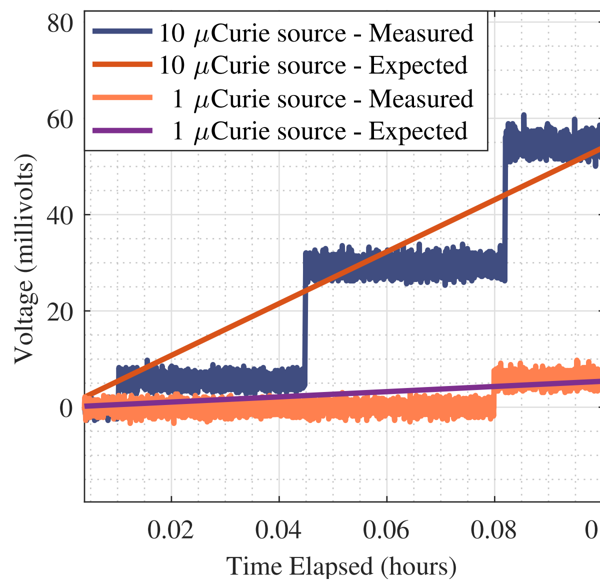

Fig. 8. **Lab measurements versus expected results with Cs-137 source, observed noise ∼7 mV peak-to-peak**

which would be reported as large spikes in accumulated dose. To prevent this during flight and subsequent testing, we consulted Teledyne and placed a thin line of opaque epoxy resin at the junction where the sensor's pins enter the main case.

Prior to flight, the four dosimeters were evaluated by exposing them to Cobalt-60 gamma rays and Californium-252 fission radiation (neutrons and gamma rays) at Lawrence Livermore National Laboratory (LLNL). Although the tests did not simulate the radiation environment experienced by the RaD-X mission, they did provide a functional test of the TID sensor, and the results showed reasonable agreement with the standard benchmark measurements performed by LLNL calibration facility. More information about these tests and results can be found in [10].

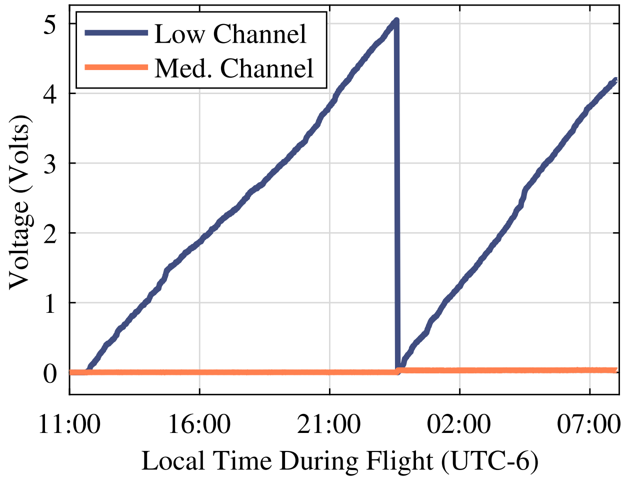

Fig. 9. Flight data showing the TID low and medium channels

Flight Measurements

At the conclusion of the flight, accumulated dose data from the TID was plotted and used to calculate instantaneous dose rate, which was then compared to the dose rate measured by the TEPC reference dosimeter. A plot of the analog voltages measured on the low range channel from the TID shows significant noise–nearly 150 mV peak-to-peak. This noise was initially found during environmental testing of the payload, and we traced the source to a DC-DC switch-mode power regulator used by another instrument which injected noise onto the 28 V supply. While the noise is significant compared to the amplitude of the signal, the RaD-X team decided to accept the risk of noisy TID data during flight and post-process the data afterwards. Flight data showing accumulated dose from the TID low and middle channels is shown in Fig. 9. Fig. 10 enlarges a portion of this raw ADC data overlays data post-processed with a moving average filter of the form shown in Eq. 2 [11]. In Eq. 2, $\mathbf{x}$ is the raw voltage measurement, $\mathbf{y}$ is the averaged signal, and M is the number of points in the average, in this case 901 data points, to provide a 1 minute average of the raw 15 Hz ADC samples.

$$\mathbf{y}[i] = \frac{1}{M} \sum_{j=\frac{-(M-1)}{2}}^{\frac{M-1}{2}} \mathbf{x}[i+j] \qquad (2)$$

To compare the TID measurements to the other instruments, we needed to calculate instantaneous dose rate from the measurements. After the flight, it was found that the moving average filter could not be used for analysis of the flight data. The statistical fluctuations caused by the noisy DC-DC converter were large enough that applying the filter would also alter the shape and magnitude of the average absorbed dose rates at different altitudes. For calculating the dose rates in Table 2, the RaD-X science team instead developed the interleave and filtering algorithm outlined in Fig. 12. The digitized TID data was first split into five minute intervals–a large enough interval had to be chosen to capture a change in accumulated dose. The voltages were then converted to accumulated dose in units of μGray based on the expected voltage steps in the TID outputs, outlined in Table 1 (note that there are 100 Rad/Gy). Next, the numerical derivative was calculated for each five minute interval, and then the data was de-interleaved to provide an instantaneous measurement of dose rate (μGy/hour) for each of the 15 Hz data points. After this, a digital low-pass filter was applied with a cut-off frequency of 0.25 Hz to filter out power line noise. These calculations showed good agreement with the industry standard TEPC, as shown in Table 2 and in Fig. 11. Further details and analysis of all four dosimeters can be found in [12].

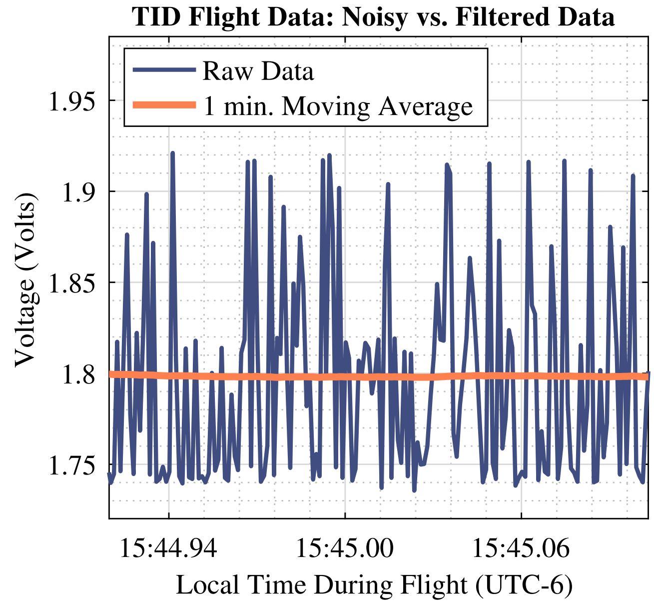

Fig. 10. Flight data zoomed in showing noise on the TID low channel and initial post-processing using a 1 minute average

Table 2. Comparison of dose rates between the TID sensor and the TEPC reference dosimeter

Barometric Altitude (km)	TID Dose Rate (uGy/hour)	TEPC Reference Dosimeter Dose Rate (uGy/hour)
24.6	3.52 ± 0.70	3.05 ± 0.48
36.6	2.55 ± 0.51	2.58 ± 0.41

Thermal Control Measurements

We used a combination of passive and active thermal control to ensure the TID sensor temperature stayed within its operating range. The passive thermal control consisted of an insulating foam cover. We used commodity "blue foam," 0.032 g/cm^3 polyethylene, around the entire payload. Even with the foam insulation, worst-case thermal simulations of the payload in flight showed the sensor's temperature descending below its operational limit. To mitigate this risk, we added an active temperature control system comprised of a Minco CT325 miniature DC temperature controller, a 3-wire 1 kΩ platinum resistance temperature detector (RTD), and a Minco 10 W thermofoil heater. The thermal controller was set to activate at temperatures less than or equal to 5°C, and the RTD and heater were attached to the aluminum mount where the TID interface board was fastened. The system also allowed us to monitor the temperature of the TID interface board via a temperature sense output from the CT325. This signal was digitized by the flight computer's ADC, saved on-board, and telemetered down to provide

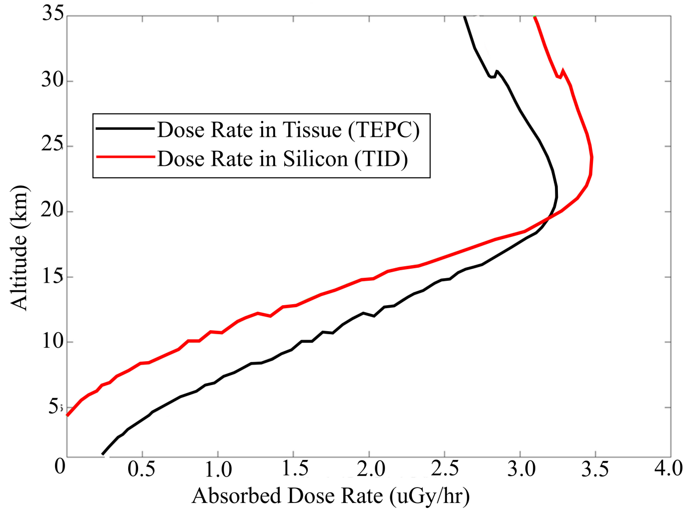

Fig. 11. **Comparison of the post-processed absorbed dose rats measured by the TID sensor and the TEPC reference dosimeter**

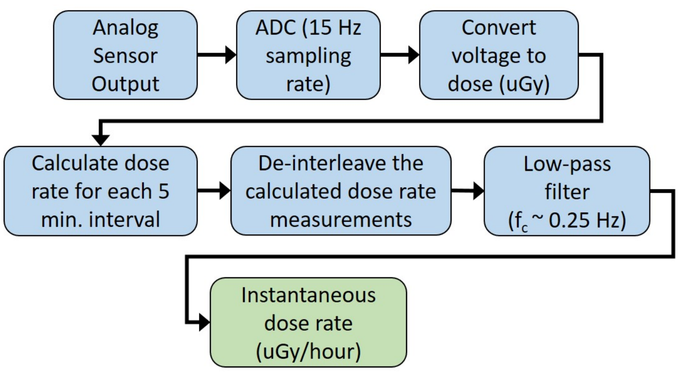

Fig. 12. **Overview of the interleave and filtering algorithm applied post-flight to the TID data**

near real-time temperature measurements. The voltage was then easily converted to temperature by multiplying by 100, based on the Minco CT325 data sheet. As the figure of the TID temperature shows, the sensor maintained a temperature between 5-30°C for the duration of the approximately 30 hour flight.

5. SUMMARY

The RaD-X mission was the first time that the Teledyne UDOS001 total ionizing dose (TID) micro dosimeter was flown on a high-altitude balloon together with a reference tissue equivalent proportional counter. The sensor was integrated into the RaD-X payload through a custom interface printed circuit board. It measured accumulated dose for 20 hours, with 18 hours of data at altitudes above 20 km. The accumulated dose data was then used to calculate the silicon absorbed dose rate. Post-flight analysis of the data showed that the TID sensor measured dose rates of 3.52 and 2.55 μGy/hour at barometric altitudes of 24.6 and 36.6 km; this is in good agreement with the reference TEPC, a Far West Technologies Hawk 3.0, that measured 3.05 and 2.58 μGy/hour at the same altitudes. Future updates to the TID sensor system will include placing an ADC on the interface PCB to reduce sensitive analog signal paths between the sensor and the avionics, and automated adjustment of the

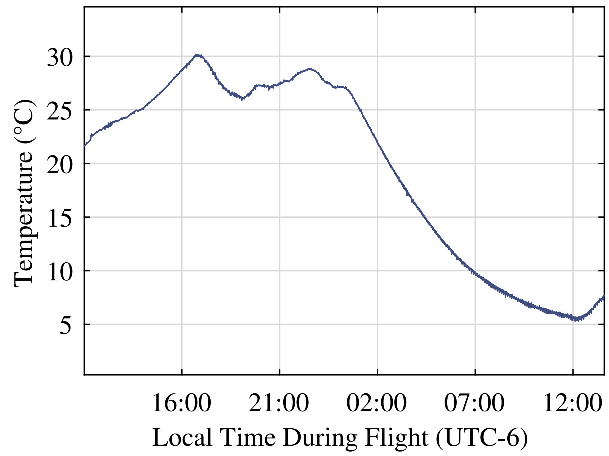

Fig. 13. **TID temperature measured during flight**

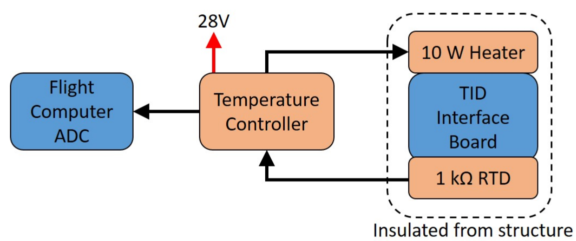

Fig. 14. **Active temperature control system block diagram**

accumulated dose based on the sensor's temperature. On a payload scale, the noisy switch-mode power converter will be replaced or removed from the system to ensure that the TID manufacturer's guideline of <100 mV power supply ripple are met during flight.

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REFERENCES

[1] J. W. Wilson, C. J. Mertens, P. Goldhagen, W. Friedberg, G. D. Angelis, J. M. Clem, K. Copeland, and H. B. Bidasaria, "Atmospheric Ionizing Radiation and Human Exposure," *NASA Technical Report/TP-2005-213935*, 2005.

[2] C. J. Mertens, M. M. Meier, S. Brown, R. B. Norman, and X. Xu, "NAIRAS Aircraft Radiation Model Development, Dose Climatology, and Initial Validation," *Space Weather*, vol. 11, no. 10, pp. 603–635, 2013. [Online]. Available: http://dx.doi.org/10.1002/swe.20100

[3] W. K. Tobiska, D. Bouwer, D. Smart, M. Shea, J. Bailey, L. Didkovsky, K. Judge, H. Garrett, W. Atwell, B. Gersey, R. Wilkins, D. Rice, R. Schunk, D. Bell, C. Mertens, X. Xu, M. Wiltberger, S. Wiley, E. Teets, B. Jones, S. Hong, and K. Yoon, "Global Real-Time Dose Measurements Using the Automated Radiation Measurements for Aerospace Safety (ARMAS) System," *Space Weather*, vol. 14, no. 11, pp. 1053–1080, Nov 2016.

[4] J. E. Mazur, W. R. Crain, M. D. Looper, D. J. Mabry, J. B. Blake, A. W. Case, M. J. Golightly, J. C. Kasper, and H. E. Spence, "New Measurements of Total Ionizing Dose in the Lunar Environment," *Space Weather*, vol. 9, no. 7, pp. 1–12, July 2011.

[5] C. J. Mertens, "Overview of the Radiation Dosimetry Experiment (RaD-X) Flight Mission," *Space Weather*, vol. 14, no. 11, pp. 921–934, Nov 2016.

[6] "Columbia Scientific Balloon Facility (CSBF)," https://www.csbf.nasa.gov/, accessed: 2017-09-30.

[7] "NASA Hands-On Project Experience (HOPE)," https://appel.nasa.gov/developmental-programs/hope/, accessed: 2017-09-30.

[8] Teledyne, "Radiation Micro Dosimeter," http://www.teledynemicro.com/product/radiation-dosimeter, accessed: 2017-09-30.

[9] C. D. Lindstrom, J. D. Sullivan, B. K. Dichter, F. A. Hanser, D. Carssow, and G. E. Galica, "Characterization of Teledyne Micro Dosimeters for Space Weather Applications," *Solar Physics and Space Weather Instrumentation IV*, Sep 2011.

[10] T. Straume, C. J. Mertens, T. C. Lusby, B. Gersey, W. K. Tobiska, R. B. Norman, G. P. Gronoff, and A. Hands, "Ground-Based Evaluation of Dosimeters for NASA High-Altitude Balloon Flight," *Space Weather*, vol. 14, no. 11, pp. 1011–1025, Nov 2016.

[11] S. A. Smith, *The Scientist and Engineers Guide to Digital Signal Processing.* California Technical Publishing, 2011.

[12] C. J. Mertens and et al., "Cosmic Radiation Dose Measurements from the RaDX Flight Campaign," *Space Weather*, vol. 14, no. 11, pp. 874–898, Dec 2016.

BIOGRAPHY

James Rosenthal *received his B.S. in electrical engineering from the University of Minnesota–Twin Cities in 2013. He is currently an electrical engineer in the Electronics Systems Branch at NASA Langley's Research Center while pursuing graduate studies in electrical engineering at the University of Washington. James served as the electrical lead for the RaD-X engineering team, and his subsequent work has focused on instrumentation for small spacecraft as well as the development and application of ultra-low power wireless backscatter communication systems.*

Bryan Hayes *is a current Physics PhD student at Oklahoma State University. He received his Bachelors of Science in Physics at the University of La Verne in 2016 and as an undergraduate was an intern at NASA Langley as a part of the RaD-X science team. His research interests involve instrumentation of low-cost micro-dosimeters to characterize the space radiation environment and quantification of dose from cosmic radiation for aircrew and astronauts.*

Dr. Christopher J. Mertens *received his PhD in physics from the Georgia Institute of Technology in 1995. He is currently a senior research physicist in the Space Radiation Group of the Research Directorate at NASA Langley Research Center in Hampton, VA. His current research focus is the physics of space weather phenomenology, atmospheric and space ionizing radiation and dosimetry, and space environment modeling.*