

## RESEARCH ARTICLE

# Thin film cadmium telluride solar cells on ultra-thin glass in low earth orbit—3 years of performance data on the AISat-1N CubeSat mission

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**Abstract**

This paper details 3 years of cadmium telluride (CdTe) photovoltaic performance onboard the AISat-1N CubeSat in low earth orbit. These are the first CdTe solar cells to yield I–V measurements from space and help to strengthen the argument for further development of this technology for space application. The data have been collected over some 17 000 orbits by the CubeSat with the cells showing no signs of delamination, no deterioration in short circuit current or series resistance. The latter indicating that the aluminium-doped zinc oxide transparent front electrode performance remained stable over the duration. Effects of temperature on open circuit voltage ( $V_{oc}$ ) were observed with a calculated temperature coefficient for  $V_{oc}$  of  $-0.19\%/^{\circ}\text{C}$ . Light soaking effects were also observed to increase the  $V_{oc}$ . The fill factor decreased over the duration of the mission with a major contribution being a decrease in shunt resistance of all four of the cells. The decrease in shunt resistance is speculated to result from gold diffusion from the rear contacts into the absorber and through to the front interface. This has likely resulted in the formation of a deep trap state within the CdTe and micro shunts formed between the rear and front contact. Further development of this technology should therefore utilise more stable back contacting methodologies more commonly employed for terrestrial CdTe modules.

**KEYWORDS**

cadmium telluride, cadmium telluride, cover glass, MOCVD, space solar cells

## 1 | INTRODUCTION

Thin film cadmium telluride (CdTe) photovoltaics (PVs) are a well-developed technology for terrestrial applications but have previously been untested in space. This paper reports on 3 years in a low earth orbit (LEO) of the first operational CdTe solar cell to be deployed in space. The novel approach is to directly deposit the CdTe PV material

onto ultra-thin (100-micron) radiation hard cover glass, yielding a lightweight and flexible solar cell.<sup>1</sup> The in-orbit flight test has produced 3-year data, allowing evaluation of the durability of this type of technology towards space power applications.

Currently, multijunction gallium arsenide-based PVs dominate the space power sector with its very high conversion efficiencies providing the high-power density that satellites require. However, emerging

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space-based applications are driving demand for higher specific power (W/kg) and high peak output (>50-kW peak), greater stability to radiation and finally, an order of magnitude lower cost. The direct application of CdTe PV to space grade ultra-thin cover glass has the potential to meet all these requirements and to be a game changer technology.

The cover glass is a cerium-doped aluminosilicate glass, provided by Qioptiq Space Technology, and is laminated on the front surface of most PV solar cells used in space. It remains fully transparent whilst protecting the underlying cells from the high energy protons and electrons of the space environment. Previous reports of laboratory measurements have demonstrated that the CdTe on cover glass has achieved an air mass zero (AM0) conversion efficiency of 12.4%, yielding a cell level specific power of 600 W/kg.<sup>1</sup> This CdTe solar cell structure was shown by the authors to potentially be two orders of magnitude more radiation stable to protons than the multijunction gallium arsenide-based cell.<sup>2</sup> The cells were intentionally irradiated with 0.5-MeV protons incident on the CdTe side of the structure and not through the cover glass to deliberately maximise the damage at the PV junction. The cells were found to show little degradation up to a fluence of  $1 \times 10^{13}$  protons  $\text{cm}^{-2}$ . The stability of the CdTe structure under proton irradiation tests correlates with earlier work by Bätzner et al. who showed that radiation degradation, in thin film CdTe, occurred at two orders of magnitude higher particle fluence than for silicon or triple junction III–V space solar cells.<sup>3</sup>

The opportunity to flight test the thin film CdTe on cover glass arose through a competitive bid process to build a payload for a joint mission between the United Kingdom and Algerian Space Agencies. The AISat-1N mission is a 3-unit CubeSat, built by the Surrey Space Centre, which flew three U.K.-based experimental payloads.<sup>4</sup> The CdTe on cover glass experiment will be referred to herein as the Thin Film Solar Cell Payload (TFSC) Payload. The TFSC Payload was developed by the authors over a 9-month period and needed not only to be able to perform and communicate current voltage (I–V) measurements but to be robust enough to withstand the rigours of launch, deployment and exposure to the space environment. The CubeSat was launched in September 2016 into a  $661 \times 700$  km,  $98.20^\circ$  Sun synchronous orbit. Initial data, in the first few weeks of orbit, showed the TFSC Payload to be fully operational, and the first survey under strong illumination was conducted on the 5 January 2017.<sup>5</sup>

The authors now present 3 years of data from the TFSC Payload. At the point of the last data entry in this paper, September 2019, the AISat-1N had completed over 17 000 Earth orbits with the TFSC Payload experiencing temperature cycles of between  $-4^\circ\text{C}$  and  $51^\circ\text{C}$  throughout. Over the 3 years, 135 surveys of the four CdTe solar cells comprising the payload were completed yielding a rare insight into the relatively long-term performance in space. Indeed, before this mission, there is no reported solar cell performance for CdTe. Historically, the only attempt to test a CdTe solar cell in space was a part of a suite of solar cells technologies to be tested on STRV-1B, launched in 1994. However, the 47 test cells (including one CdTe cell) did not communicate their I–V data back to the ground station.<sup>6</sup>

Delamination, of thin film PV for space applications, has been considered to be of particular concern to the research community

since a research programme, conducted by Dutch Space B.V., investigating thin film copper indium gallium diselenide (CIGS), on titanium foil, suffered delamination from the substrate at the interconnects when subject to the thermal cycling that might be encountered in space.<sup>7</sup> However, after these results, new interconnects were developed and a flight experiment conducted on the Delfi-C<sup>3</sup>, 3-unit CubeSat in a LEO.<sup>8</sup> The CIGS cells, on titanium foil, showed no signs of degradation over the initial 3-month monitoring period during which time they were subject to temperature changes of  $70^\circ\text{C}$  twice a minute due to the quick rotation of the CubeSat and the cells' low heat capacity. This demonstrated that the revised interconnect method had resolved the delamination issue.<sup>8</sup> More recently (2018), Ascent Solar Technologies, Inc. have developed a prototype flexible CIGS module, which has been delivered to the International Space Station for a 1 year in-orbit assessment of the technology.<sup>9</sup>

Thin film flexible PVs for space applications are receiving an increasing amount of attention from both the research and industrial communities, and thus, it is timely that we report on the 3-year in-orbit performance of the CdTe on cover glass technology. The mission to launch, deploy and capture in-orbit data from a laboratory prepared CdTe solar cell was an ambitious one. The potential sources of failure beyond that of the satellite launch and the TFSC Payload's electronics hardware and software were as follows:

- Displacement and ionisation damage of the TFSC Payload materials by space radiation
- Delamination of the thin films and or electrical contacts from temperature cycling
- Interdiffusion of contacts and heterojunctions

## 2 | EXPERIMENTAL

A unique approach for space solar cells was taken, where the CdTe device structure was deposited directly onto the 100-micron cover glass using the superstrate configuration. Metalorganic chemical vapour deposition (MOCVD) was used to deposit all semiconductor layers except the evaporated gold back contacts (see Figure 1A). Aluminium-doped zinc oxide was the first layer deposited and formed an extremely well-adhered transparent conducting electrode (TCE). This is followed by a thin, high resistance, layer of zinc oxide to reduce micro shunts. Both these initial layers were deposited at atmospheric pressure, using a nitrogen carrier gas. The glass/TCE structure was then moved to another atmospheric pressure MOCVD reactor, but using hydrogen carrier gas, for deposition of CdZnS n-type and arsenic-doped CdTe p-type layers and finally a chlorine heat treatment to passivate grain boundaries.<sup>10</sup> The surface was then rinsed with deionized water and the structure annealed in air for 90 min at  $170^\circ\text{C}$  before revealing the TCE bus bars by mechanical scraping. Gold contacts were evaporated onto both the bus bars and the CdTe back surface defining four separate cells, as shown in Figure 1B.

The  $60 \times 60$ -mm cover glass sample therefore contained  $4 \times 1 \text{ cm}^2$  cells, defined by the back contacts, with a common front

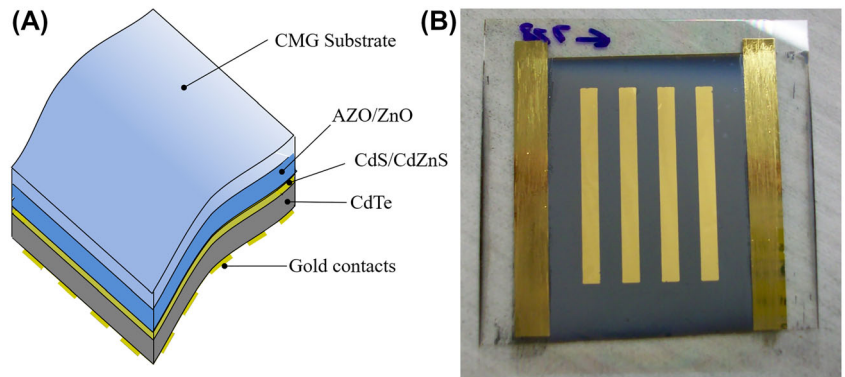
TCE. Using  $4 \times 1 \text{ cm}^2$  defined cells increased the complexity of the experiment but generated more data and built in a certain degree of redundancy if one of the cells were to fail during the mission. External electrical contacting was then made possible through use of a second piece of cover glass with evaporated gold tracks that were offset by 5 mm and secured using a space qualified double side adhesive polyimide provided by GTS Flexible Materials Ltd. The polyimide had holes over each of the contacts that were filled with a conductive silver epoxy to enable rugged external connections to the printed circuit board (PCB). The silver epoxy introduced an increase to the series resistance; however, in the short time frame given to prepare the payload, it was decided that this approach offered the most durable electrical connection between the cells and the external circuit. Further details can be found in Underwood et al.<sup>5</sup> The external PCB, Figure 2A, also had an LM35 temperature sensor configured to measure in the range of  $-56^\circ\text{C}$  to  $+148^\circ\text{C}$  mounted centrally in intimate contact with the back of the cover glass. This sensor then allowed the TFSC Payload temperature to be measured each time the four cells were surveyed.

The internal PCB, Figure 2B, housed the electronic circuitry required to receive commands from the CubeSats onboard computer (OBC), survey each of the four cells I–V curves and the LM35 and store the data ready for upload to the CubeSats OBC. Table 1 shows the I–V measurements for the final flight model selected to fly on the CubeSat. The measurements were carried out at the Surrey Space Centre to ensure basic functionality of the assembled TFSC Payload with the onboard I–V measurement circuit. The laboratory was not equipped with a solar simulator; however, an uncalibrated 25-W halogen light source was used to verify the functionality of the control PCB (Figure 2B). The low short circuit current ( $I_{sc}$ ) was expected due

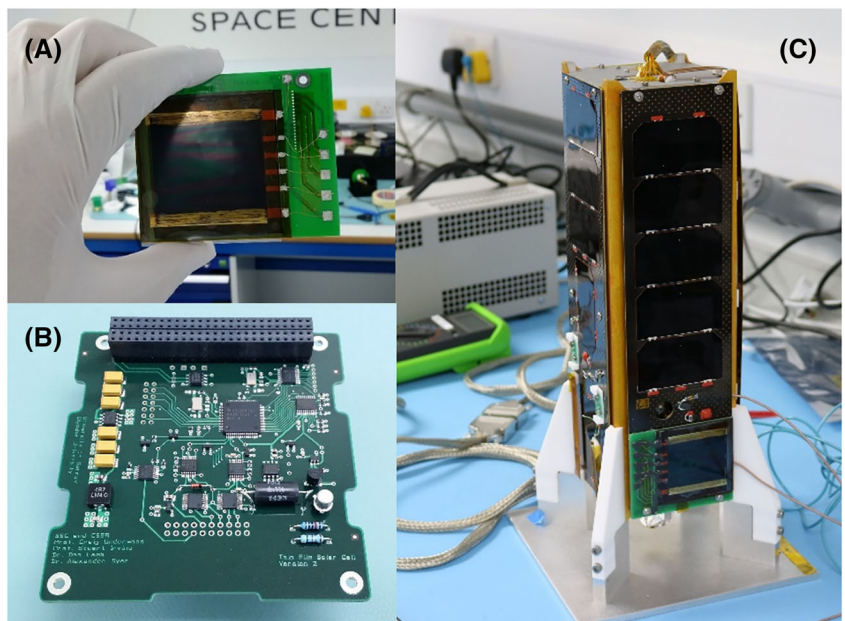
**TABLE 1** Uncalibrated I–V measurements of flight model using a non-uniformly illuminating 25-W halogen torch

	Cell 1	Cell 2	Cell 3	Cell 4
$I_{sc}$ (mA)	5.3	6.7	7.5	9.5
$V_{oc}$ (mV)	844	845	853	849

**FIGURE 1** (A) The CdTe device architecture on 100-micron cover glass. (B) A CdTe device deposited on to  $60 \times 60$ -mm 100-micron-thick cover glass;  $4 \times 1 \text{ cm}^2$  cells defined by gold contacts to the CdTe with two common contacts to the TCE



**FIGURE 2** Figure 2A shows the external PCB of the encapsulated TFSC Payload. Gold contacts for the four cells and two common bus bars can be seen on the top and bottom of the glass. These were connected to the PCB electronic circuit via indium/tin solder and gold wires. Figure 2B shows the internal PCB that, when commanded automatically, measures the four cells and the LM35 temperature sensor. Figure 2C is the assembled 3-unit CubeSat showing the face with the TFSC Payload experiment attached alongside the conventional multijunction solar cells that provide power to the spacecraft



to the low incident power of the 25-W lamp. The variation in short circuit current, across the four cells, is due to the non-uniform illumination the 25-W lamp produced. The open circuit voltage ( $V_{oc}$ ) was not expected to be significantly affected by the illumination intensity.

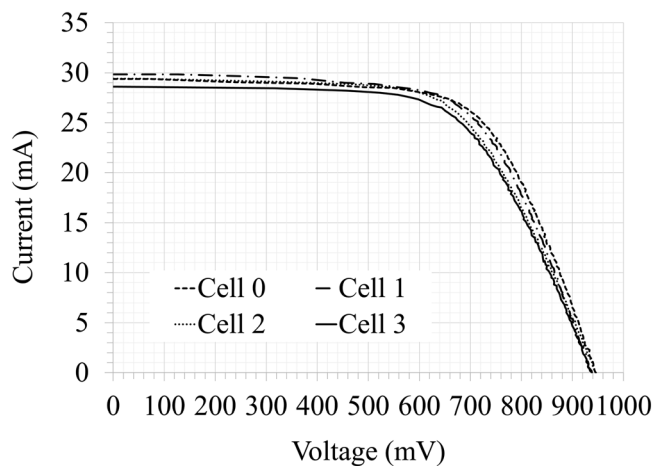
This paper sets out to evaluate the durability of the CdTe payload in the space environment, over the duration of the CubeSat mission, through analysis of the relative changes of the in-orbit cell performance.

### 3 | RESULTS

#### 3.1 | Assumptions and calibrations

This section presents an analysis of the I-V curves collected over the 3-year duration of the in-flight mission. The latest data acquisition presented (September 2019) was after the AlSat-1N had completed some 17 000 earth orbits. Temperature data from both the internal sensor of the AlSat-1N CubeSat and the LM35 sensor in contact with the back of the TFSC Payload ranged between  $-31^{\circ}\text{C}$  and  $+32^{\circ}\text{C}$  and  $-3.8^{\circ}\text{C}$  and  $+51^{\circ}\text{C}$ , respectively. Over the duration of these orbits, the TFSC Payload was commanded to take 135 surveys of the cells. The surveys, made possible by the internal board of the TFSC Payload, rely on an 8-bit DAC to set the programmed current sink. Whenever the payload is switched on, the onboard circuit automatically measures four current and voltage values for each current step. There are 256 sample points per cell, each giving 12-bit voltage and 12-bit current, thus providing 1024 I-V readings. To summarise, one survey of all four cells gives 2048 readings in total and in addition, four temperature values, all taking just over 1 s to complete. With the time span between the readings being very short, the temperature of the final cell will be considered when plotting the cell performance with respect to temperature variations.

Figure 3 shows typical I-V curves for the four cells (surveyed January 2017). The curves are smooth indicating there is no apparent noise, and the measurements are of good quality.



**FIGURE 3** Typical I-V curve for all  $4 \times 1 \text{ cm}^2$  cells when TFSC Payload is well illuminated in orbit. January 2017, solar flux of  $124 \text{ mW/cm}^2$  and cell temperature  $10^{\circ}\text{C}$

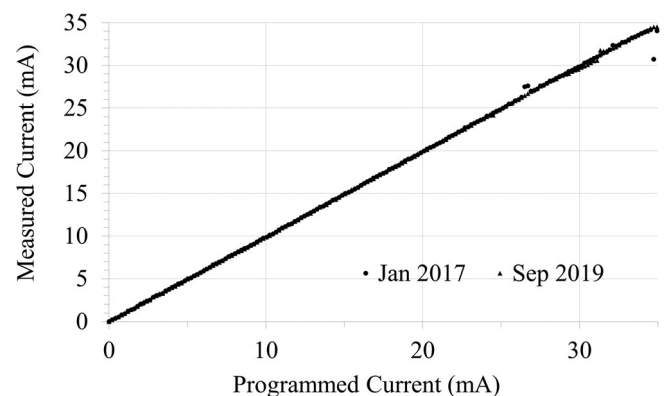
The internal circuit board of the TFSC Payload consists of a programmable current sink to drive the solar cells. This value determines the amount of voltage developed across the cell, and correspondingly the current is measured across a 10-Ohm precision resistor. The programmed current itself is not included in the telemetry files; it rather records the *actual* current which is measured across the precision resistor via an instrumentation amplifier. It is found, however, that the measured current and the theoretical programmed current are in very close agreement, and this good consistency between the two current readings is indicative of no anomalies in the working of the I-V circuit. Similarly, the voltage developed across the cell is measured by a second precision instrumentation amplifier. Both amplifiers' outputs are digitised to 12-bit precision, with the current set to measure in the range 0.00–40.96 mA and the cell voltage set to measure in the range 0.000–1.024 V.

Figure 4 illustrates an excellent correlation between the programmed and measured current for two of the surveys of Cell 0 separated by 30 months in orbit. The values are observed to be so close that the I-V curves can be considered to be plotted against the theoretical value of current. This approach has been followed throughout the following analysis of the TFSC Payload data, where the  $I_{sc}$  is extracted from the I-V curves and hence are the values of the programmed current.

To fully understand the performance of the solar cells, it was important to verify which data points were actually valid. For a satellite in LEO, there are three primary sources of electromagnetic radiation: solar illumination (known as insolation), infrared radiation emitted from the Earth's surface (day and night) and the fraction of incident sunlight which is reflected off the Earth termed as albedo. The Earth's albedo is a function of cloud cover and season.<sup>11</sup> Average values for solar cell power from the albedo effect can be more than 10% of that derived from direct insolation alone.

Data surveys were carefully filtered from the analysis if they met the following criteria:

- Surveys with the cells displaying close to zero  $I_{sc}$  and low cell temperature were inferred to have been completed in a dark phase of the CubeSats orbit.



**FIGURE 4** The measured current (mA) versus programmed current (mA) showing excellent linearity of an in-orbit survey of Cell 0 in January 2017 and September 2019



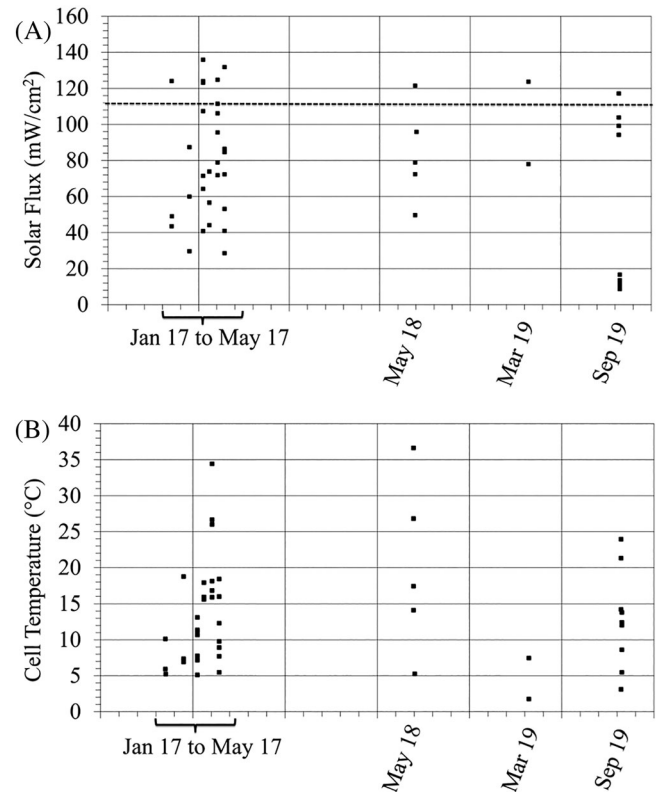
- Surveys with low  $I_{sc}$  but a higher cell temperature were considered to be lit by the Earth's albedo rather than direct solar radiation.
- Cells with low  $I_{sc}$  values and were shown by the Sun-sensor readings to have a very shallow angle relative to the Sun.
- Telemetry files that were found to have corrupted data over part of the I–V curve.

Taking these criteria into account resulted in 66% of the surveys being removed from analysis. It should be pointed out, however, that this was not unexpected, as there was no active control of the pointing of the test cells towards the Sun, and so for each survey, it was a matter of chance whether there was favourable illumination of the cells. We did consider putting an optical trigger into the circuit so the cells were only measured when the Sun was at normal incidence—however, we abandoned this, as we could not be sure that the spacecraft would ever be in such a configuration. We instead decided to obtain what cell measurement data we could and derive the solar incidence angle retrospectively from the spacecraft's attitude determination system—principally the analogue Sun-sensor mounted on the same facet as the test cells.

The in-orbit surveys were obtained over 3 years of operation, including observations in the month of January when the Earth is around perihelion and in the month of June when the Earth is around aphelion. There are other sufficient data points available which indicate the cells making different angles with the Sun's position, thus providing with a wide range of incident solar flux values. The TFSC Payload is located on one of the side panels of the CubeSat; see Figure 2C. The CubeSat gently rotates at around  $2^\circ$  per minute, and therefore, the attitude of the TFSC Payload continuously changes in such a way that the Sun may make any angle to it. To normalise the data for solar angle effects, the spacecraft carries an independent Sun-sensor aligned to be normal to the experimental cells.<sup>12</sup> In order to compute the incident solar flux on the TFSC Payload, for different observation dates, the corresponding solar irradiance values have been obtained from NASA's SORCE (Solar Radiation and Climate Experiment) mission data.<sup>13</sup> Due to Earth's varying distance from the Sun, the total solar irradiance fluctuates by about 6.9% throughout a year<sup>14</sup> (from about  $140 \text{ mW/cm}^2$  in early January to about  $132 \text{ mW/cm}^2$  in early July). The Sun-sensor onboard the AISat-1N is a simple planar photodiode which gives a 10-bit binary output, which would correspond to readings ranging from 0 (for zero illumination) to 1023 (for full illumination) without calibration. By making multiple observations of raw Sun-sensor readings over time, we determined that a calibration scale factor of 0.8 should be applied to the raw Sun-sensor output to be equivalent to an incident solar flux of  $140 \text{ mW/cm}^2$ . Applying these principles, it was then possible to calculate the calibrated solar flux for any one data acquisition.

### 3.2 | Intersurvey variation

Figure 5A is a plot of the range of incidence solar fluxes ( $\text{mW/cm}^2$ ), as calculated by the previously described methodology, for each of the

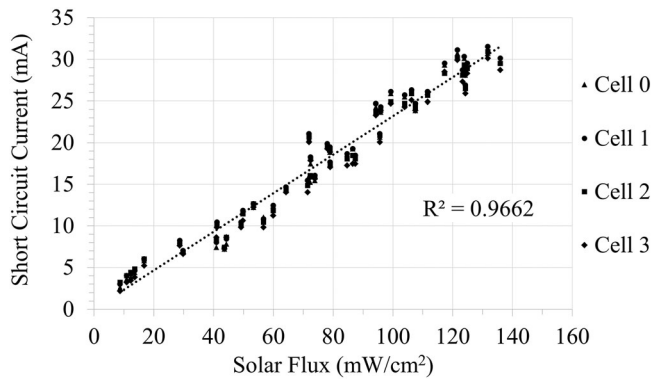


**FIGURE 5** (A) A plot of incident solar flux ( $\text{mW/cm}^2$ ) and (B) plot of cell temperature ( $^\circ\text{C}$ ) for each of the valid surveys between January 2017 and September 2019. The dashed line in (A) denotes cell measurements with solar fluxes of over  $115 \text{ mW/cm}^2$

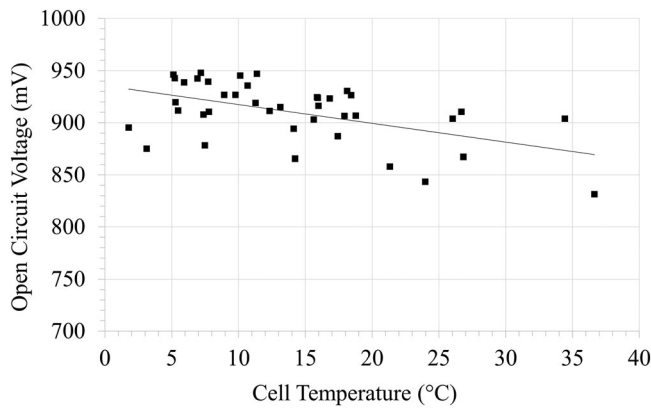
valid surveys between January 2017 and September 2019. The focus of the analysis of the I–V parameters of the cells is under strong AM0 illumination; therefore, only cell measurements with solar fluxes of over  $115 \text{ mW/cm}^2$  have been included in the following analysis (as denoted above the dashed line in Figure 5A). Figure 5B is a plot of the TFSC Payload cell temperature for each of the valid surveys between January 2017 and September 2019. The cell temperatures, as measured by the LM35 temperature sensor, ranged between  $-1.8^\circ\text{C}$  and  $+36.6^\circ\text{C}$  with the AISat-1N core temperature ranging between  $-2.5^\circ\text{C}$  and  $+31.6^\circ\text{C}$  for the equivalent survey points. There was a linear relationship between the two temperature readings with the TFSC Payload being a few degrees Celsius higher than the AISat-1N core. It should be noted that the surveys receiving solar flux above  $115 \text{ mW/cm}^2$  and thus subject to more detailed analysis had cell temperatures across the whole range.

Figure 6 is indicative of the relationship between the  $I_{sc}$  and the calculated solar flux. The linear regression for Cell 0 is typical, and the  $R^2$  of 0.97 demonstrates that the TFSC Payload is performing as expected for a solar cell subject to increasing illumination intensity.

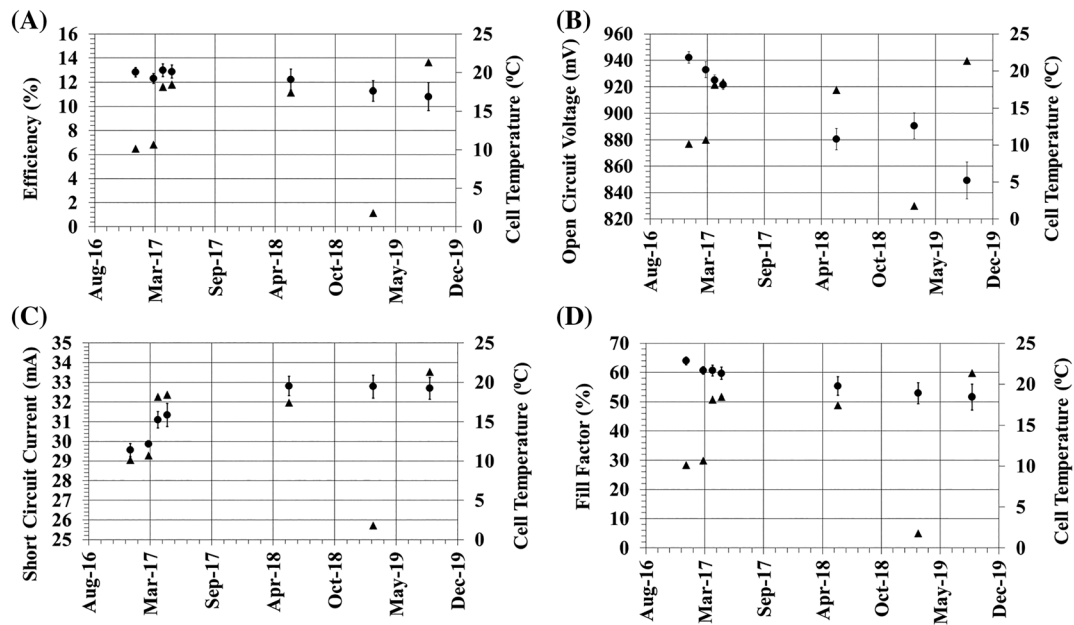
$V_{oc}$  of CdTe solar cells is known to increase with decreasing temperature. Virtuani et al. measured the temperature coefficient for CdTe solar cell  $V_{oc}$  to be  $-0.24\%/^\circ\text{C}$ .<sup>15</sup>  $V_{oc}$  in CdTe, has also been shown to improve by  $\sim 4\%$  following light soaking due to filling of trap states in the absorber.<sup>16</sup> Figure 7 is a plot of  $V_{oc}$  (mV) versus cell



**FIGURE 6** A plot of  $I_{sc}$  (mA) versus solar flux ( $mW/cm^2$ ) for each of the four cells (surveyed between January 2017 and September 2019)



**FIGURE 7** The  $V_{oc}$  (mV) versus cell temperature ( $^{\circ}C$ ) for all valid surveys between January 2017 and September 2019



**FIGURE 8** The mean (circles) and standard deviation (lines) I–V parameters for surveys receiving solar flux above  $115 mW/cm^2$  over the duration of the mission. Cell temperature (triangles) for each survey is shown on the secondary y-axis. (A) Mean and standard deviation efficiency (%) for the four cells. (B) Mean and standard deviation  $V_{oc}$  (mV) for the four cells. (C) Intensity corrected mean and standard deviation  $I_{sc}$  (mA) for the four cells. (D) Mean and standard deviation fill factor (%) for the four cells

temperature ( $^{\circ}C$ ) for all valid surveys of the TFSC Payload in orbit. A linear regression of the data indicates, over this narrow range of temperatures, the temperature coefficient for  $V_{oc}$  is  $-0.19\%/^{\circ}C$ . However, this conclusion should be treated with care as it was not possible to delineate the data for cell temperature only, due to the surveys being conducted under a range of solar fluxes, potentially different light soaking durations and where  $V_{oc}$  is also observed to reduce over the 3-year time frame (Figure 8B).

Figure 8A–D shows the mean and standard deviation of I–V parameters for each of the four cells and for all surveys in-orbit of illuminance above  $115 mW/cm^2$ . Also included are the cell temperatures at each survey point. In Figure 8A, the mean and standard deviation efficiency of the four cells is shown to decrease over time irrespective of cell temperature. The mechanism for this decrease in efficiency can be elucidated by considering further the cells mean I–V parameters. Mean and standard deviation  $V_{oc}$ , shown in Figure 8B, decreases from 942 mV in January 2017 to 849 mV in September 2019. For convenience, at laboratory scale, gold is used to form the Ohmic back contact to the CdTe absorber material. However, gold has a relatively high diffusion coefficient in CdTe and can be expected to diffuse over time into the CdTe at room temperature. Gold is known to introduce a deep acceptor trap state in CdTe at around 263 meV above the valence band.<sup>17</sup> Therefore, an increase in deep trap density from gold diffusion could provide the explanation for the observed decrease in  $V_{oc}$  over the 3-year duration in orbit. The in-orbit, intensity corrected, mean and standard deviation  $I_{sc}$ , shown in Figure 8C, increases early on in the mission from 29.6 to 31.3 mA (January–May 2017) and then remains relatively stable until the final data acquisition September 2019. This initial increase in  $I_{sc}$  could be explained via the light-soaking mechanism explained previously. Figure 8D shows the mean

and standard deviation fill factor over time. The fill factor decreases steadily and independently of cell temperature from 63.9% in January 2017 to 55.8% in September 2019.

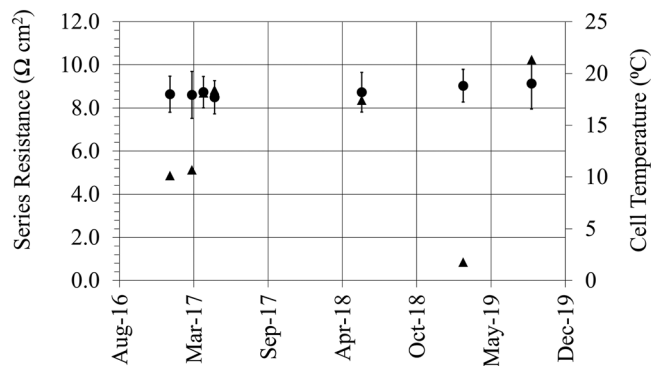
Series resistance, shown in Figure 9, does not contribute to the observed decrease in fill factor remaining relatively consistent from the laboratory measurements through to the most recent survey in September 2019. This signifies that the MOCVD produced aluminium-doped zinc oxide TCE has remained unchanged and that the front and rear electrical contacts to the cells have proven robust. The steady decrease, in fill factor, is caused by a decrease in shunt resistance over time seen in Figure 10. In-orbit, the cells have exhibited a decrease in shunt resistance over the 3-year mission from 590 to 106  $\Omega \text{ cm}^2$ .

This can be attributed to microshorts that can form between the metal back contact and the front TCE. Ground irradiation tests indicate that the cells should be robust against the effects of radiation experienced over this relatively short time in LEO. More likely is that the increase in shunting is due to the in-diffusion of the gold

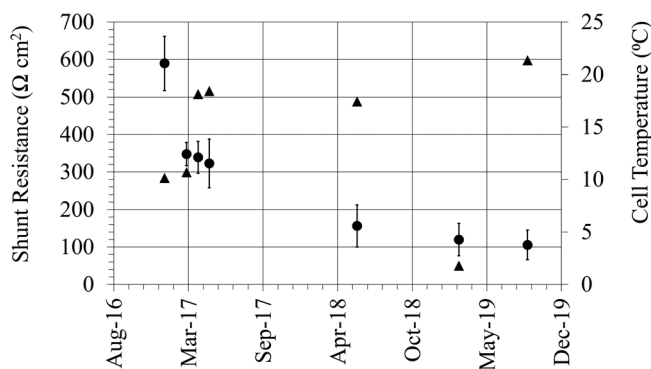
back contact into the CdTe absorber, along the grain boundaries and down to the TCE. Any scale-up to monolithically interconnected modules might be expected to employ an alternative metalized back contact to gold with either a diffusion blocking layer or a slower diffusing metal such as nickel. Metal in-diffusion into CdTe solar cells has been shown to lead to two typical detrimental effects: the formation of microshorts between the rear and front contacts of the solar cell leading to alternate pathways for the current to flow and/or the formation of deep level defects within the CdTe.<sup>17-19</sup> These two factors will act to decrease shunt resistance and as previously stated could explain the decrease in  $V_{oc}$  seen in Figure 8B. The TFSC Payload has been subject to recorded temperatures of up to 51°C and likely for significant periods of time over the 3-year mission. Batzner et al. used secondary ion mass spectrometry depth profiling to show that, under accelerated lifetime testing of 80°C and 1 Sun constant illumination, gold was found to interdiffuse from the back contact and accumulate at the front contact.<sup>19</sup> The TFSC Payload was designed to last for a 1-year mission lifetime, and it was not within the remit of the payload build to develop an alternative back contact to the cells. However, any future module level demonstration of the CdTe TFSC would require a new back contact architecture to be developed to realise the true potential of these space deployed solar cells.

## 4 | CONCLUSIONS

The TFSC Payload remains the only reported I-V data for CdTe solar cells from space. The TFSC Payload, originally designed for a 1-year in-orbit data acquisition, has provided 3 years of I-V measurements. After the rigours of launch and deployment, 17 000 orbits and cell temperature variations between at least  $-3.8^\circ\text{C}$  and  $+51^\circ\text{C}$ , there is no evidence of delamination observed from the I-V data. The increase in  $V_{oc}$  in space is explained by the lower cell temperatures and extended light soaking. The  $V_{oc}$  temperature coefficient, for the relatively small range of temperature experienced by the TFSC Payload, is calculated to be  $-0.19\%/^\circ\text{C}$ . The aluminium-doped zinc oxide TCE performance remains unaffected after 3 years in space. The relative change in the I-V parameters over time is then attributed to ageing effects with the gold back contact, but maintenance of the high  $I_{sc}$  value indicates good robustness of the CdTe device. It appears that in-diffusion of the gold back contact is producing microshorts leading to a decrease in the shunt resistance and thus the fill factor. If gold diffusion is the cause of the reduced shunt resistance, then it is likely that the creation of deep level traps within the CdTe that are acting to also reduce the  $V_{oc}$  over time. Clearly, an alternative back contact architecture needs to be developed before the next in-orbit trials of this technology. With the current world record conversion efficiency for thin film CdTe being 22.1% AM1.5, the ultimate ambition of a space ready CdTe solar cell is a radiation and thermally stable device structure with 20% AMO efficiency, a specific power of  $>1.5 \text{ kW/kg}$  and a significantly lower production cost to current multijunction technology.



**FIGURE 9** Mean (circles) and standard deviation (lines) series resistance ( $\Omega \text{ cm}^2$ ) over the duration of the mission for surveys receiving solar flux above  $115 \text{ mW/cm}^2$ . Cell temperature ( $^\circ\text{C}$ ) (triangles) for each survey is shown on the secondary y-axis



**FIGURE 10** Mean (circles) and standard deviation (lines) shunt resistance ( $\Omega \text{ cm}^2$ ) over the duration of the mission for surveys receiving solar flux above  $115 \text{ mW/cm}^2$ . Cell temperature ( $^\circ\text{C}$ ) (triangles) for each survey is shown on the secondary y-axis

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