DEBRIS IN-SITU IMPACT DETECTION BY UTILIZATION OF CUBE-SAT SOLAR PANELS

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1. ABSTRACT

To analyze the quantity of space debris and micrometeoroids in space, an innovative in-situ impact detection method has been developed at DLR (German Aerospace Center) in Bremen, Germany. The method, Solar panel based Impact Detector “SOLID”, uses solar panels for impact detection. The number of measured impacts depends on the detection area (in this case solar panel area), mission duration and the debris flux (orbit dependent). Since solar panels provide large detection areas, this method allows for the collection of large amounts of data, to be used e.g. for model validation. Furthermore, impact damage can be verified once more to confirm or to refute an impact. Both aspects can significantly improve the quality of model validation by using large amounts of highly reliable data. This paper describes the possibility of utilizing CubeSat solar panels for in-situ space debris and micrometeoroid detection. To evaluate the effectiveness of the SOLID debris sensor, an estimation of currently available total solar panel area of CubeSats was analyzed. The currently available total area of active CubeSats in orbit is estimated to be 6.1 m^2. This number is compared to the retrieved solar panel areas of the Hubble Space Telescope and the European Retrievable Carrier.

2. INTRODUCTION

Due to high relative velocities, collisions of spacecraft in orbit with orbital debris or micrometeoroids can lead to payload degradation, anomalies as well as failures in spacecraft operation, or even loss of mission. The knowledge of small (> 100 µm) but abundant objects in space is low. To analyze the quantity of space debris (SD) and micrometeoroids (MM) in space, an innovative in-situ impact detection method has been developed at the German Aerospace Center (DLR) in Bremen, Germany. The Solar panel based Impact Detector, SOLID, uses solar panels for impact detection. Since solar panels provide large detection areas, this method allows the collection of large amounts of data, to be used e.g. for model validation. A ground verification of this detection method has been performed by hypervelocity impact tests at Fraunhofer´s Ernst-Mach-Institut (EMI), Freiburg, Germany. The objective of this investigation was to test the applicability of the developed method concerning in-situ detection of orbital debris and micrometeoroids. The achieved test results are in agreement with ESA developed damage equations and the functionality of the detector has clearly been demonstrated. The next step will be the verification of the detection method on orbit on the microsatellite TechnoSat of the Technische Universität Berlin, contracted to be launched in 2017.

CubeSats have traditionally been utilized for communication, technology demonstration, science, education and military applications [18]. The number of CubeSats in orbits is continuing to grow and offers new possibilities for the employment of CubeSat solar panels for in-situ debris and micrometeoroid detection. To be able to assess if the SOLID debris detector would be useful on CubeSats we analyzed the total amount of available solar panel area.

3. "SOLID" IN-SITU DETECTION CONCEPT

The functional principle of SOLID detection method has been described in [4], [6]. However, within this paper the principal adaptation of the detection method to a standard solar panel is summarized in the following. Figure 1 shows an example solar panel adapted for impact detection.

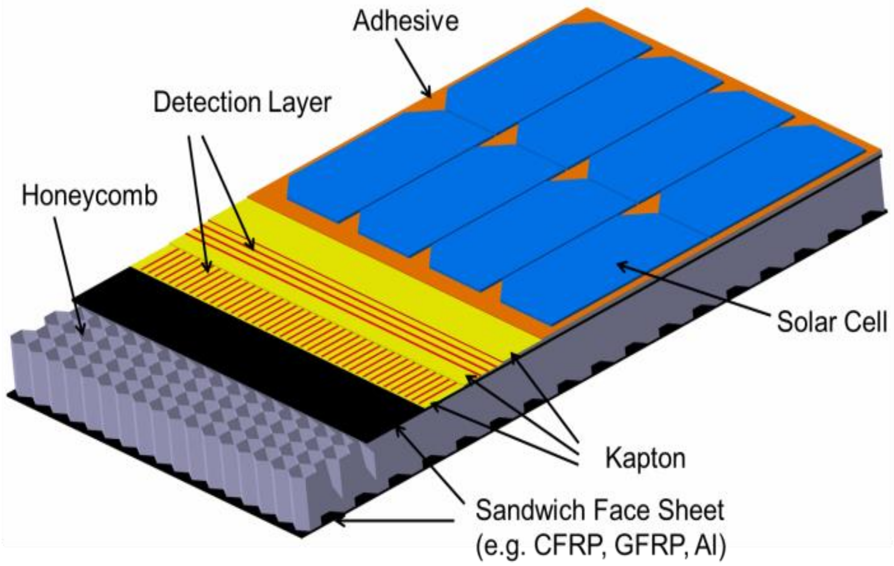

Figure 1: Solar panel adaptation for the SOLID concept

The SOLID concept modifies the insulation layer behind the solar cells of common solar panels. The modified panel integrates two layers of copper lines between the insulation layers (usually Kapton). The two copper layers are aligned in perpendicular directions, forming a detection grid. In case of an impact event, the colliding particle causes damage which can range in depth from the cover glass layer down to the detection layer and consequently cuts several copper lines in the grid. The number and position of the severed strips can be identified by the detection electronics and software. The diameter of the impactor that causes the damage can be estimated by utilizing ESA damage equations provided in [16], [17]. The estimation procedure can be found in [5], [6].

4. IN-ORBIT VERIFICATION

The On Orbit Verification (OOV) of the SOLID detection system will be performed on the TechnoSat mission in 2017. The OOV is carried out in close cooperation between DLR, Bremen, Germany; Technische Universität Berlin, Germany and University Würzburg, Germany. The detection panels provided by DLR will be controlled by utilizing an experiment computer that replicates the board computer of the TechnoSat spacecraft (S/C) developed by Technische Universität Berlin. The software for the SOLID experiment is developed and tested at the University of Würzburg. Figure 2 shows the TechnoSat S/C of Technische Universität Berlin in operational configuration. TechnoSat is a nanosatellite that carries a number of different payloads for OOV [2], [3]. The launch mass of the satellite is 20 kg and its volume is 465 × 465 × 305 mm³.

TechnoSat is equipped with 17 equivalent solar panels. Each of the 17 panels includes six solar cells, which are glued to the printed circuit board (PCB) substrate. Four of the seventeen solar panels were adapted for SD and MM impact detection. Figure 2 right shows a top view of the TechnoSat and the distribution of the four SOLID panels utilized for impact detection.

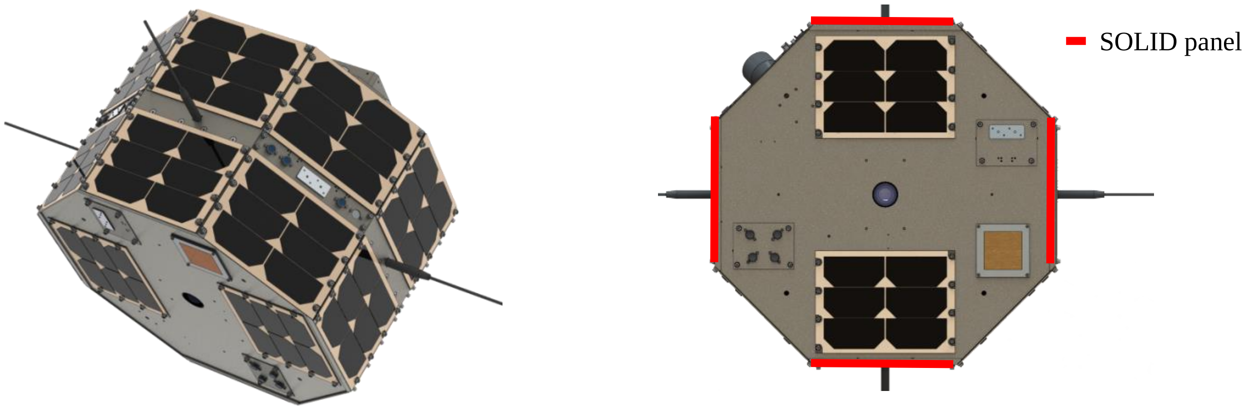

Figure 2: TechnoSat S/C (left) TechnoSat S/C nadir face with SOLID panels indicated (right)

Figure 3 shows a qualification model of a TechnoSat solar panel equipped with SOLID detector for SD and MM impact detection (left) and an enlarged section view of the detection panel, where the X and Y traces behind the solar cells can be seen (right). The two detection layers for the axes X and Y respectively are integrated into the TechnoSat PCB design as shown in Figure 1. The PCB is glued to the aluminum structure panel that is bolted to the primary structure of the TechnoSat S/C. On the top side of the PCB, six solar cells are arranged. The flight hardware is already manufactured and will soon be integrated into the satellite.

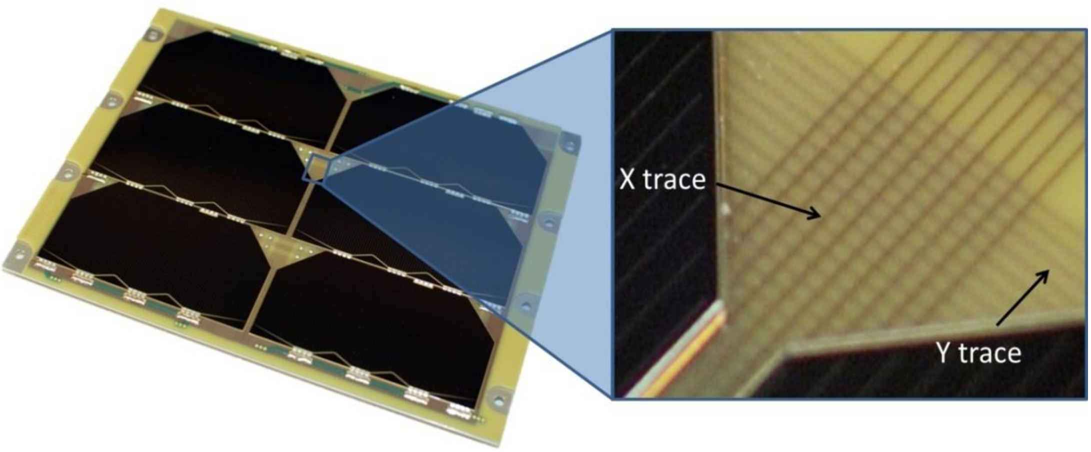

Figure 3: SOLID panel manufactured for the TechnoSat mission (left), enlarged section view of the sensor (right)

Figure 4 shows a schematic view of four SOLID panels and the corresponding SOLID board computer. The panels (1, 2, 3 and 4, see also Figure 2) are controlled via a I2C bus and two panels are connected to each of the two busses. The four panels will be continuously analyzed one after another. The data regarding registered impacts on the panels will be stored by the satellite's on-board computer for subsequent downlink. Additionally, the current status of all panels can be requested as a real-time telemetry for immediate examination. The estimation of the impactor, that caused damage on the panel will be performed on-ground by utilizing ESA developed damage equations [14], [15].

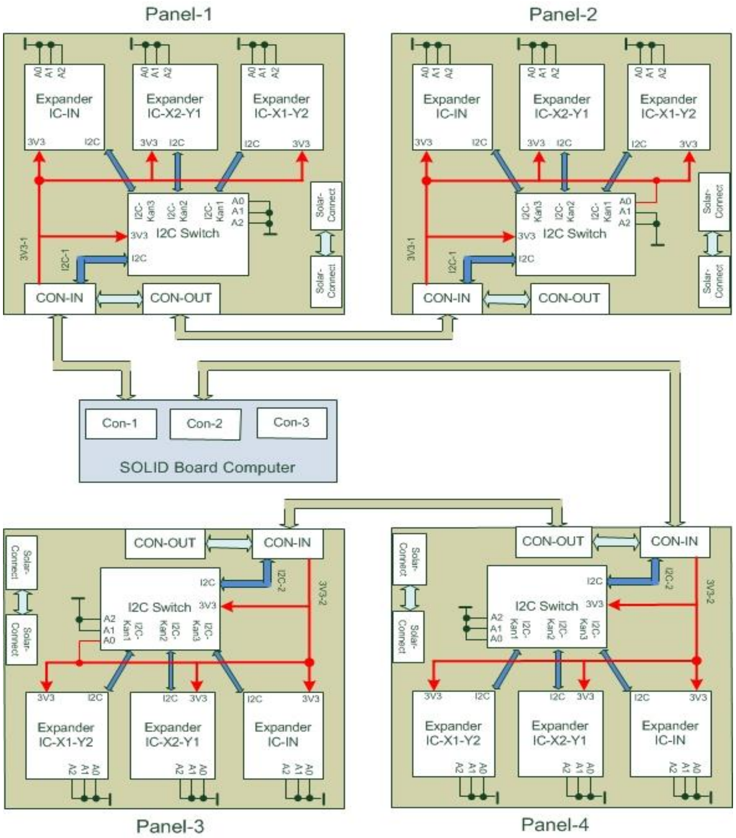

Figure 4: Manufactured SOLID Panel for SD MM detection

5. CUBE-SAT UTILIZATION FOR IN-SITU DEBRIS DETECTION

The environmental models like MASTER (ESA) or ORDEM (NASA) are validated by measured data. Objects larger than 1-2 cm can be statistically detected by ground based systems (limited coverage). Objects that are below this threshold need to be detected by space based systems e.g. in-situ impact detectors. Based on simulation results of e.g. MASTER model, it is understood that the quantity of objects in space is increasing nearly exponentially with decreasing object diameter. Consequently, a spacecraft in orbit will encounter a large number of impacts with smaller objects and a low number of impacts with larger objects. Because of this fact, the impact detector should have a large detection area and shall operate over a long time period in orbit to provide a statistically reliable quantity of measurement data. For example the solar panels of a satellite placed in an orbit at 800 km attitude and 98 ° inclination will detect ca. 1,51E 02 impacts of 100 µm and ca. 9,53E -05 impacts of 1 cm objects per m² per year. This means that objects with a diameter of 100 µm will impact every 2.4 days and objects with a diameter of 1 cm every 10,000 years. This analysis was performed by using the MASTER model. A sun oriented surface was chosen to represent deployed solar panels of a satellite. Only objects that hit the sun eliminated side (solar cell

covered side of the solar panels) are considered. However, for debris detection the SOLID detection layer can also be placed on the back side of the solar panel to detect the objects impacting from the back side. Furthermore, objects having a millimeter diameter will penetrate the panel. In this way, a higher number of impacts will be detected and the impact interval is lower.
Comparing to large satellites like the Hubble Space Telescope (HST), CubeSats are only able to provide a very small solar panel area. Furthermore, the solar panels of CubeSats are often body mounted. Therefore, only small objects (e.g. 100 µm) can be detected by using solar panels of one 1U CubeSat. Moreover, the CubeSats are designed for short operational lifetimes (e.g. 1 year). However, deployable solar panels for CubeSat missions were developed in the past such as 1U Outernet Platform [7], 2U RAIKO [10] or 3U Delfi-n3Xt [21]. Furthermore, the CubeSat community is growing rapidly and the number of satellites is increasing year by year. In this way, retired CubeSats are replaced by new ones. Figure 5 shows the relationship between the number of satellites and clients. The private companies contributed in 2014 and 2015 more than 2/3 of the total number of CubeSats.

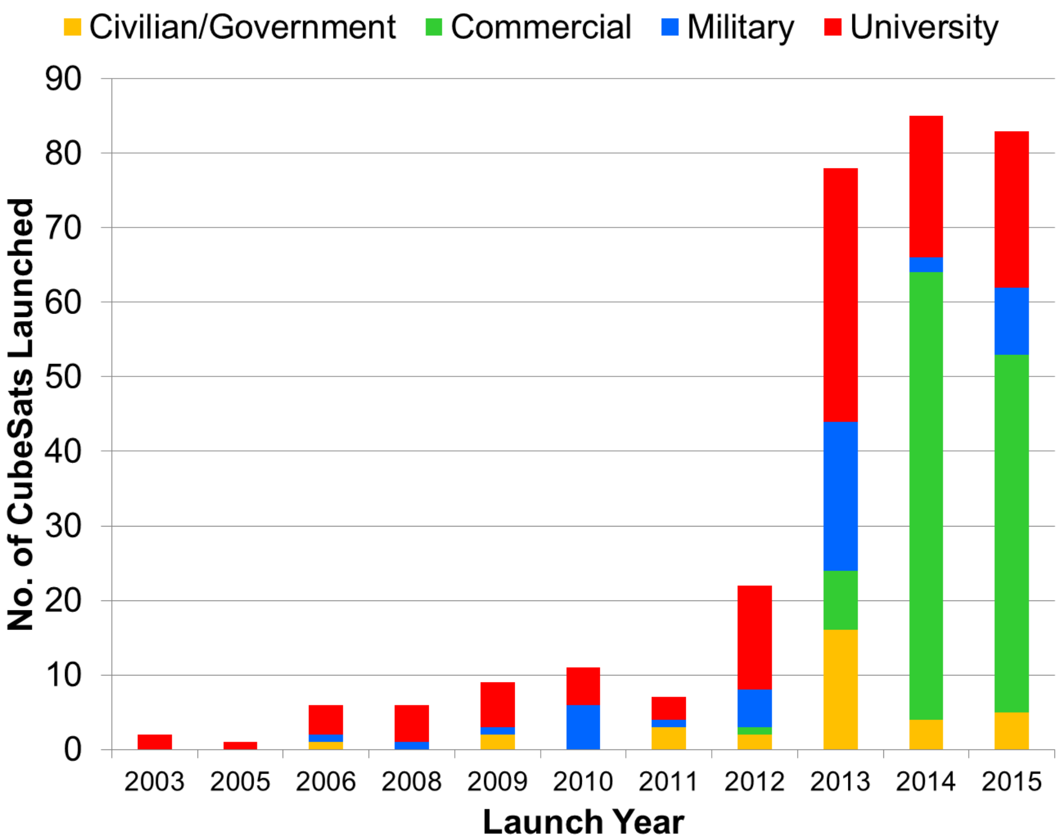

Figure 5: CubeSat by contractor type [19] [15]

Figure 5 indicates also that, particularly in recent years, the number of launched CubeSats is growing considerably. Therefore, we analyzed the possibility of the utilization of CubeSats solar panels for debris and micrometeoroid impact detection. Those satellites could potentially provide real time in-situ measurement data of impacting objects for e.g. environmental models validation or spacecraft health monitoring. Research was performed regarding currently available CubeSats in orbit by using following sources:

- NORAD TLE [12] and Online Satellite Catalog (SATCAT) [13],
- Michael Swartwout CubeSat database [20],
- UCS Satellite Database [22],
- Gunter's Space Page CubeSat database [14].

Table 1 shows a list of CubeSats provided by country of origin between 30.06.03 and 15.04.16 (total number including demised CubeSats). The major portion of CubeSats have been contributed by the USA (220) followed by Japan (19) and Germany (7). The countries indicated with zero have not provided CubeSats until now, but are intended to do so in the near future. Since June 2003, 313 CubeSats have been launched. The majority 54 % (169) of the launched satellites are confirmed to be still in orbit. Almost 23 % (72) of the total number are still fully operational and 4 % (11) are only partially functional. The failed satellites represent 11 % (33), and of these failures 55 % (18) were declared to have failed on deployment. For 17 % (53) of CubeSats the status is unknown and 46 % (143) are demised.

Table 1: Number of CubeSats provided by country

Country	Launched	Active	Country	Launched	Active
USA	220	42	Israel	1	1
Japan	19	2	Norway	1	0
Germany	7	4	Pakistan	1	0
Denmark	6	3	South Africa	1	1
Singapore	6	2	Ukraine	1	1
UK	5	2	Estonia	1	0
Brazil	3	0	Uruguay	1	1
Spain	3	1	Iraq	1	1
Peru	3	0	South Korea	1	0
China	3	0	Greece	1	0
CIS	2	2	Romania	1	0
Netherlands	2	1	India	1	1
Switzerland	2	1	Taiwan	1	0
Ecuador	2	1	Hungary	1	0
Argentina	2	2	Austria	0	0
Turkey	2	0	Belize	0	0
Lithuania	2	0	Australia	0	0
Vietnam	2	0	Finland	0	0
Belgium	2	2	Colombia	0	0
Italy	2	0	Czech Republic	0	0
Canada	2	1	Portugal	0	0
Poland	1	0	UAE	0	0
France	1	0	**Total**	313	72

Figure 6 shows the number of CubeSats distributed over different altitudes (left) and inclinations (right) respectively, excluding those which have already demised (see also Table 1) or for which orbital data is not available (19 satellites). Since some of the satellites are placed into an eccentric orbit, the apogee was chosen for this analysis for “altitude” indication.

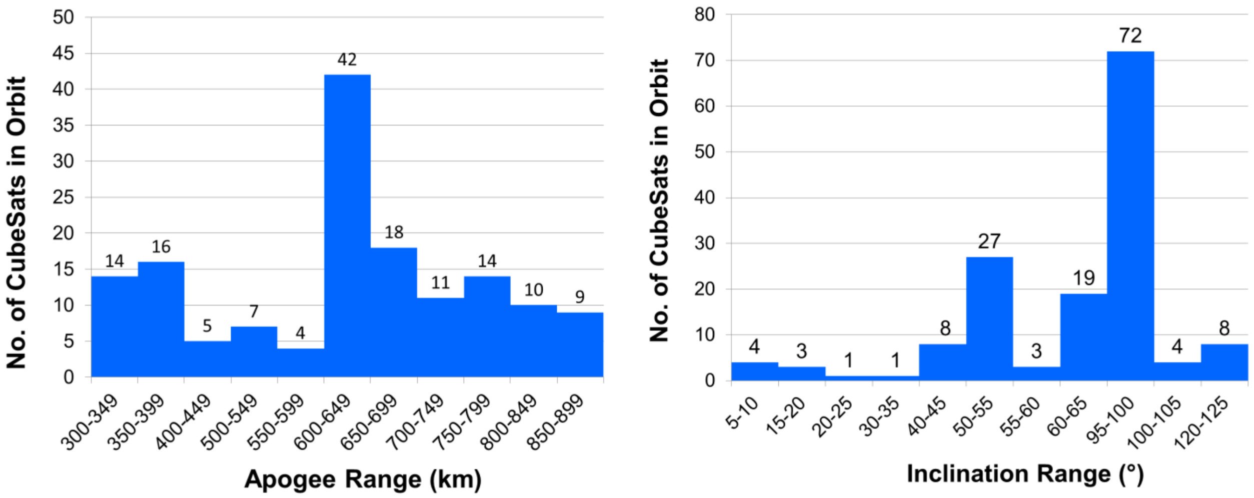

Figure 6: Number of CubeSats at specific altitudes (left) and inclination (right) as of April 2016

Examination of these two figures show that more than half of all CubeSats (85 or 57% of total) are placed within an altitude range of 600 - 800 km, with the majority of these lying within an inclination range of 95-100°. A second distribution of CubeSats can be found within an altitude range of 300 - 400 km (30 or 20% of total) and an inclination of 50 - 55°. The latter is largely represented by the PlanetLabs “Flock” [18] constellation as well as several CubeSats provided by Japan [18], which are launched into space via the Falcon 9 / Dragon (for U.S. satellites) or the H-IIA / HTV (for Japanese satellites) and then deployed from the ISS.

Figure 7 merges the information regarding the altitude and the inclination of CubeSats. The majority of CubeSats (38) are released at altitudes between 600 km to 650 km and an inclination of 95 -100°.

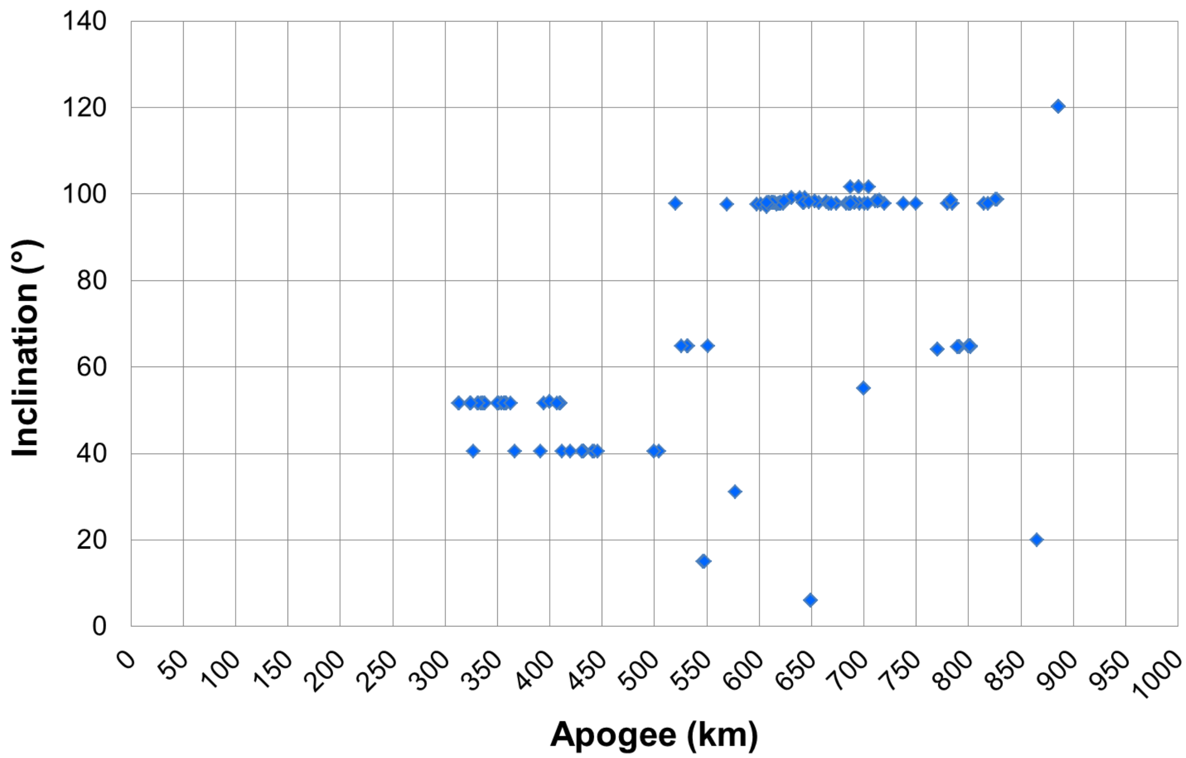

Figure 7: Distribution of CubeSats apogee vs inclination as of April 2016

Figure 8 shows CubeSats in orbit subdivided by type (number of units: U) of the spacecraft. The total number of CubeSats without demised CubeSats is indicated on the left and the still active spacecraft in orbit are presented on the right of Figure 8. The majority of CubeSats are the 3U (47% of active) type followed by 1U (25% of active) type.

The estimation of the detection area was done with an average of 80 cm² per solar panel of 1U CubeSat. This number is slightly larger than the area covered by 2 solar cells, which results in ca. 60 cm² (e.g. 28% AZURSPACE TJ solar cell: 30,18 cm² each [1]) and is derived from CubeSat panel design developed at DLR. The total detection area of one 1U CubeSat results in 480 cm², for a 1.5U CubeSat in 640 cm², for a 2U CubeSat in 800 cm², and for a 3U CubeSat in 1120 cm². For a 6U CubeSat, the area was chosen equal to a 3U CubeSat, since not all sides are generally covered by solar cells. Furthermore, for this analysis the solar panels are assumed to be body mounted for all type of CubeSats and accommodation aspects (e.g. integration of patch antenna) are neglected.

Using data of CubeSats from above mentioned databases, it was found that the distribution of CubeSats can be assumed as follow: 0.5U (2); 1U (18); 1.5U (10); 2U (6); 3U (34), 6U (2). Based on this information the total solar panel area is estimated. The total solar panel area of the 72 active CubeSat´s results in 6.1 m². At the 600-650 km altitude range the total solar panel area of those satellites is about 2.5 m².

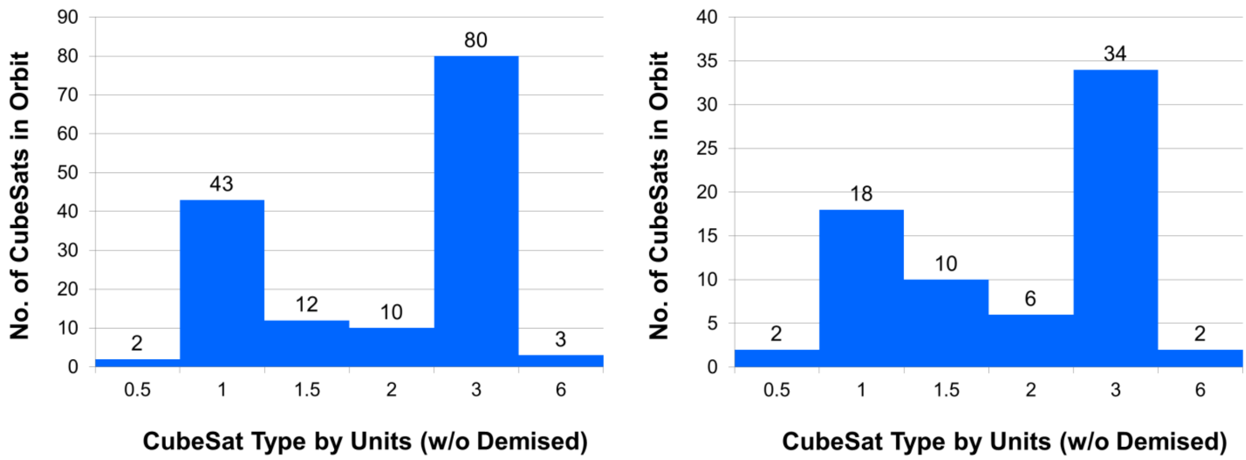

Figure 8: Total number of CubeSats by units without demised (left) and still active (right) as of April 2016

Table 2 shows a summary of the missions of which the solar panels were retrieved from space for Post Flight Analysis (PFA). The measurement data (e.g. damage size, number) were utilized for ESA´s MASTER-model validation.

Table 2: Retrieved solar panels of HST and EuReCa from space; FPA = Post Flight Analysis, D_M = mission duration, h = altitude, i = inclination, A_{SZ} = total analysed solar panel area [8, 9, 11, 16, 17]

Spacecraft	Mission			Orbit		Area
	$Start$	End	D_M (days)	$h\ (km)$	$i\ (°)$	$A_{SZ}(m^2)$
HST (PFA1)	24.04.1990	08.12.1993	1320	614	28,5	20,73
HST (PFA2)	04.12.1993	03.03.2002	3011	614	28,5	41,46
EuReCa	01.08.1992	24.06.1993	326	495	28,5	20,04

The estimated solar panel area of CubeSats is lower than that of retrieved hardware from space. However, the data gained from missions (see Table 2) represents an accumulated number of impacts over the mission duration. Using CubeSats the data can be provided in real-time and from different orbits year by year. In this way, the required number of measurements for model validation might be lower. However, this issue was not investigated so far and is a core competence of the Technical University Braunschweig.

Table 3 summarizes the requirements of the SOLID debris detector for a CubeSat mission. SOLID is a secondary payload that can be flown on any satellite and in any orbit. As mention above, the system is already developed for a nanosatellite and a CubeSat at DLR and can be easily adapted to different solar panel design (e.g. nano, micro and mini satellites also with deployable solar panels). The design philosophy of SOLID is to utilize already existing satellite systems for impact detection. SOLID is a low cost payload (manufacturing cost for CubeSat ~ 1-5 k€), that has low requirements regarding e.g. mass, volume, data rate.

Table 3: Requirements imposed SOLID debris detector for satellite missions

Criteria	**Requirement**
Dimensions	Adaptable to different solar panel design
Mass	~ 200 g/m² + electronics + wire
AOCS	Knowledge regarding the orientation of the S/C at the time of impact is beneficial (e.g. housekeeping data at the time of impact, angular rate over time about x, y, z axis).
Pointing	No
Altitude range (km)	All altitudes possible
Inclination range (°)	All inclinations possible
Temp. op.; standby (°C)	+/- 100 °C; +/- 100 °C (SOLID solar panel)
Power op. ; standby (W)	~ 150 mW; tbd. (architecture dependant)
Science data	200 bytes per impact (data per day is depending on detection area and orbit)
Downlink	tbd. (e.g. 1 x per day / week)
Duration of operation	mission life time
Moving parts	No
Radiation limitation	No (SOLID solar panel)
Potential risks	Low, no disturbance of primary payload. SOLID can be switched off if required.

6. CONCLUSION

The knowledge regarding small but abundant space debris and micrometeoroid objects in space is low. Those objects are however relevant for space missions e.g. for sensitive scientific payloads such as optical telescopes. Since the available data is insufficient and after the retirement of the Space Shuttle, only very limited hardware can be retrieved from space for analysis, and so new sensor technologies are required. Considering this need, a new type of sensor was developed at DLR. The in-situ detection system SOLID utilizes subsystems of a spacecraft for impact detection. The core element of the system is a solar panel equipped with a SOLID sensor, which provides a large detection area for in-situ debris detection. A verification of the detection method was performed by Hypervelocity Impact (HVI) tests at Fraunhofer EMI, Freiburg, Germany. The OOV will be performed on the TechnoSat mission of the Technische Universität Berlin in 2017.

The growing number of CubeSats in different orbits could potentially contribute to the characterization of the space environment in the future. Furthermore, small satellites offer an excellent opportunity to test systems in orbit prior to implementation on a large satellite for operational use. Therefore, an analysis was performed regarding the number of available CubeSats in orbit. The estimation of the total detection area was performed under consideration of active CubeSats only, since this number of satellites would potentially provide measurement data once equipped with a SOLID sensor and placed in orbit. The currently available total solar panel area of active CubeSats in orbit is estimated to be 6.1 m². By applying SOLID detection method to different spacecraft in different orbits, an environmental database can be generated. This database contains information regarding the impact time and the spatial distribution of objects in space. The measured data can be used to complement the Space Surveillance Network (SSN) catalog data and close the gap where presently only limited data exists. The data gap exists between ground based measurements and measurements gained from retrieved hardware e.g. Long Duration Exposure Facility (LDEF), Hubble Space Telescope (HST), European Retrievable Carrier (EURECA). Furthermore the collected data can be used for environmental models validation, risk assessment for critical space assets and also for space-based systems optimization.

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