Space Environment Characterisation by applying an innovative Debris Detector

Waldemar Bauer
German Aerospace Center (DLR), Institute of Space Systems, Bremen, Germany,
waldemar.bauer@dlr.de
Oliver Romberg
German Aerospace Center (DLR), Institute of Space Systems, Bremen, Germany
oliver.romberg@dlr.de
Merlin F. Barschke
Technische Universität Berlin, Institute of Aeronautics and Astronautics, Berlin, Germany
merlin.barschke@tu-berlin.de

ABSTRACT

The knowledge about small (> 100 µm) but abundant objects in space is low. To analyze the quantity of space debris and micrometeoroids in space, an innovative in-situ impact detection method has been developed at the German Aerospace Center (DLR) in Bremen, Germany. The *Solar generator 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. Such data enhances space debris and micrometeoroid population datasets and permits for related model validation. A ground verification of the detection method has been performed by Hypervelocity Impact (HVI) 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 space 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. This paper presents the already manufactured hardware planned for on orbit test on the Technische Universität Berlin's TechnoSat mission in 2016. The expected numbers of impacts based on corresponding probabilities as well as uncertainties regarding object size estimation are also outlined.

1. INTRODUCTION

The validation of space debris models like ESA´s Meteoroid and Space Debris Terrestrial Environment Reference (MASTER) [1] or NASA´s Orbital Debris Engineering Model (ORDEM) [2] is performed by comparison of simulated results with in-situ measured or orbital observed data. The latter is utilized for large particles and can be obtained from ground based or space based radars or telescopes. Data regarding very small but abundant particles can also be gained by the analysis of retrieved hardware [3], [4]. This has been previously demonstrated, for example with hardware returned from orbit to Earth (e.g. Hubble Space Telescope parts). Furthermore, in-situ impact detectors are an essential source for information on space debris (SD) and micrometeoroids (MM). Such detectors are placed in orbit and collect impact data regarding SD and MM, sending data in near real time via telemetry. Compared to the impact data which is obtained by analysis of retrieved surfaces, the detected data comprises additional information regarding exact impact time and, depending on the type of detector, on the orbit and particle composition [5], [6]. Nevertheless, existing detectors have limitations. As the detection areas are typically small, statistically meaningful numbers of impacts are only obtained for very small [5], [1] particle sizes. Measurements of particles in the size range of hundreds of microns to mm, which are potentially damaging to spacecraft (S/C), require larger sensor areas. To make use of the advantages of in-situ impact detectors and to increase the amount of collected impact data, an innovative and recently patented impact detector system has been developed at the German Aerospace Center (DLR) in Bremen, Germany [7], [8]. In contrast to previous impact detectors, the Solar generator based Impact Detector

(SOLID) is not an add-on component on the S/C. SOLID makes use of existing S/C subsystems and adopts them for impact detection purposes [9], [10]. Since the number of impacts on a target in space depends linearly on the exposed area [11], the S/C solar panels offer an unique opportunity for impact detection. Considering that the SOLID method could be applied to several S/Cs in different orbits, the spatial coverage in space concerning SD and MM can be significantly increased [9]. In this way the method permits the generation of large impact datasets, which can be used for environmental model validation. A preparation for on orbit testing of the developed in-situ detection method "SOLID" on the TechnoSat mission in 2016 is described in the following.

2. TECHNOSAT MISSION

TechnoSat is a nanosatellite that carries a number of different payloads (P/L) for On Orbit Verification (OOV) that is based on the TUBiX20 platform of Technische Universität Berlin. [12], [13]. The launch mass of TechnoSat is 20 kg and the volume is 465 × 465 × 305 mm³. The S/C bus is designed, manufactured, integrated and tested by Technische Universität Berlin. The TechnoSat mission is funded by the Federal Ministry for Economic Affairs and Energy (BMWi) through the German Aerospace Center (DLR) on the basis of a decision of the German Bundestag (Grant No. 50 RM 1219). Fig. 1 shows a CAD model of the TechnoSat S/C in operational configuration.

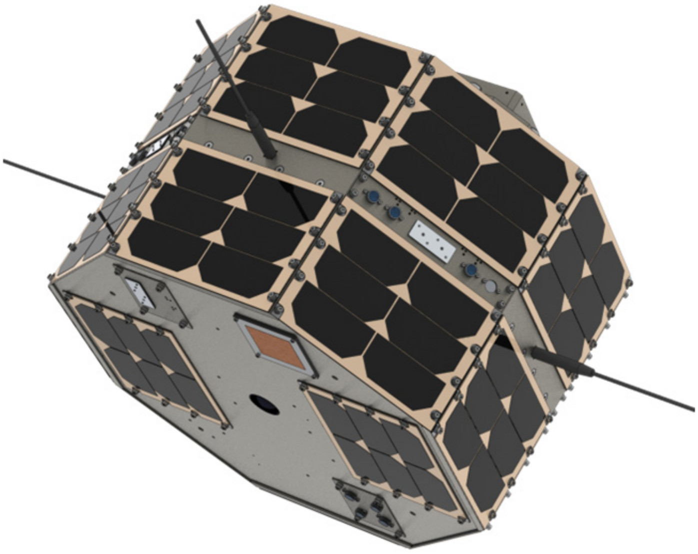

Fig. 1: TechnoSat S/C of Technische Universität Berlin

The TechnoSat P/L´s are provided by different partners. The following gives an overview of the P/L´s foreseen for OOV on the TechnoSat mission. The SOLID P/L for the TechnoSat mission is developed and provided by DLR Bremen, Germany.

1. **Fluid Dynamic Actuator**
   The fluid dynamic actuator is a novel attitude control actuator for small satellites consisting of a closed ring structure that contains liquid metal that is actuated by an electromagnetic pump [14]. The fluid dynamic actuator is developed at Technische Universität Berlin.
2. **Laser Retro Reflectors**
   TechnoSat carries several commercial 10 mm retro reflectors for laser ranging purposes [15].
3. **Reaction Wheel System**
   A newly developed system of four reaction wheels in tetrahedron-configuration of Technische Universität Berlin.
4. **S-Band Transmitter HISPICO**
   HISPICO is an S-band transmitter that provides a payload data rate of 1 $Mbps$ [16]. The transmitter was developed by Technische Universität Berlin together with the IQ wireless GmbH.

5. **Camera**
   A small camera module will provide pictures of the satellite with a resolution of 640 × 480 pixels as payload for the S-band transmitter.

6. **Solar generator based Impact Detector (SOLID)**
   Solid is a space debris and micrometeoroid in-situ impact sensor that utilizes satellite solar panels for detection of objects with a diameter in the range 100 μm up to 1 cm.

7. **Star Tracker STELLA**
   A star tracker for nanosatellites that was developed by the University of Würzburg [17].

3. FLIGHT EXPERIMENT

The TechnoSat S/C is equipped with 17 equivalent solar panels. Each of the 17 panels is equipped with six solar cells, which are glued to the printed circuit board (PCB) substrate. Those panels are connected in parallel to provide the S/C with sufficient power. Four of the seventeen solar panels were adapted for SD and MM impact detection. Fig. 1 shows a top view of the TechnoSat S/C and the distribution of the four panels utilized for impact detection.

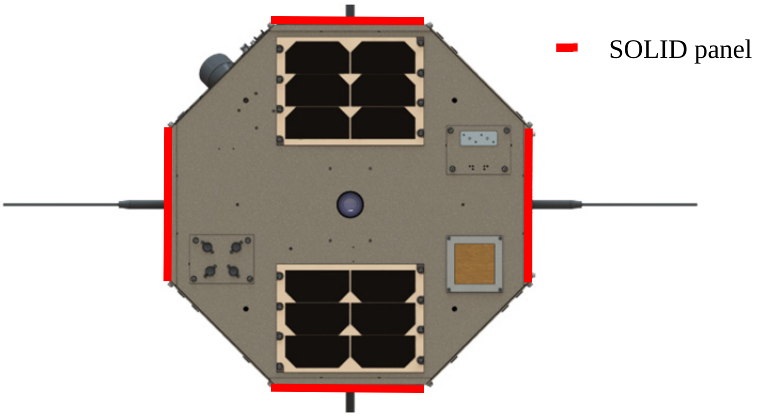

Fig. 2: TechnoSat S/C Nadir face with SOLID panels indicated

The functional principle of SOLID detection method has been described in [9], [10]. However, within this paper the principal adaptation of the detection method to a standard solar panel is summarized in the following. Fig. 3 shows an example solar panel adapted for impact detection.

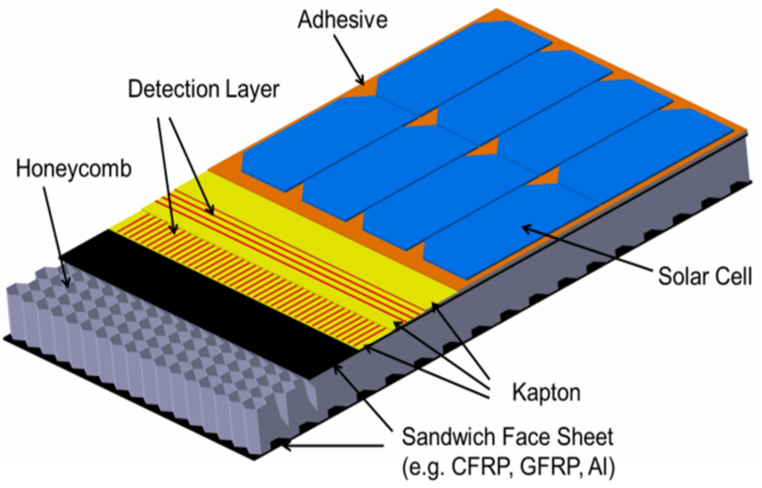

Fig. 3: Solar panel adaptation for SOLID concept

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 [3], [4]. The estimation procedure can be found in [18].

The on orbit verification of the SOLID detection method 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 S/C developed by Technische Universität Berlin. The software for the SOLID experiment is developed and tested at the University of Würzburg. Fig. 4 shows a schematic view of four SOLID panels and the corresponding SOLID board computer.

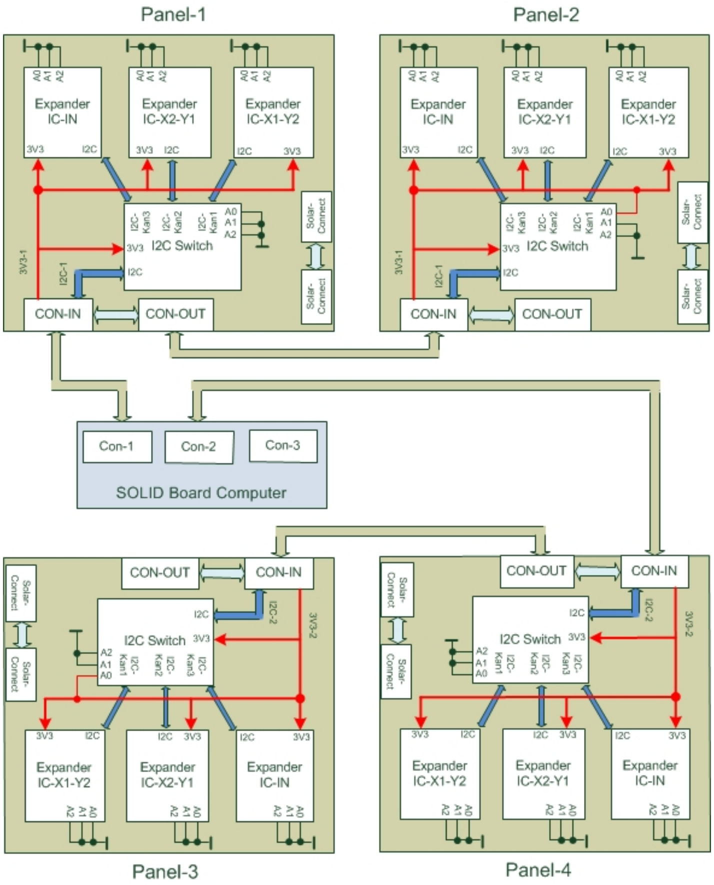

Fig. 4: Manufactured SOLID Panel for SD MM detection

The panels (1, 2, 3 or 4) are controlled via I2C bus and two panels are connected to each of the two busses. The four panels will be analyzed continuously one after another. The data regarding registered impacts on the panels will be stored by the satellite’s on-board computer for a 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 [3], [4]. The estimation procedure can be found in [9], [18].

Fig. 5 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 Fig. 3. 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.

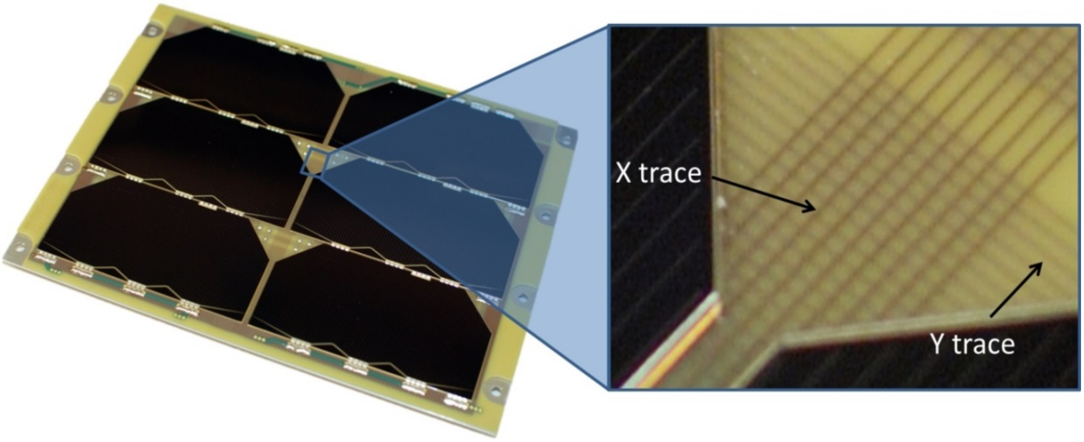

Fig. 5: SOLID panel manufactured for the TechnoSat mission (left), enlarged section view of the sensor (right)

4. ESTIMATION OF EXPECTED IMPACTS

TechnoSat will be launched into a 600 km sun synchronous orbit in 2016 to fulfil its mission with a duration of 12 months. The estimation of expected impacts was performed by utilizing the ESA tool MASTER2009 (Meteoroid and Space Debris Terrestrial Environment Reference), that has been developed at the Technische Universität Braunschweig, Germany. Since the detection system is expected to identify impacting objects with a diameter $\mathrm{d_p} > 100\ \mu\mathrm{m}$ at a relative velocity of $\mathrm{v_p} \approx 15\ \mathrm{km/s}$ ($\mathrm{d_p} > 70\ \mu\mathrm{m}$ at $\mathrm{v_p} \approx 70\ \mathrm{km\ /s}$), the analysis was performed for objects larger than $100\ \mu m$. The parameters for the performed impact analysis with MASTER2009 defined as following:

- Particle diameter: $\geq 100\ \mu\mathrm{m}$.
- Simulation epoch: 01.05.2009.
- Target shape: sphere.
- Semi-major axis: 6931 km; eccentricity: 0,001; inclination: 97.8 °.
- Sources: SD; MM Jenniskens-McBride.

Tab. 1 provides an overview of objects with a diameter $\mathrm{d_p}$ larger than 100 μm, the corresponding impact fluxes as well as the impact interval on a detector area of $1\ m^2$. The impact frequency for objects larger than $100\ \mu m$, is ca. $4.8\ \mu Hz$, which means ca. 150 impacts per year.

Tab. 1: Results of space debris impact analysis with MASTER2009: Impact flux **F**; impact interval $\boldsymbol{\Delta t}$ percentage of MM impacts on a generic spherical satellite with a total area of $\boldsymbol{1\ m^2}$.

$\boldsymbol{d_p}$ ($\mu\boldsymbol{m}$)	$\boldsymbol{F}$ $(\boldsymbol{1/(m^2\ year)})$	$\boldsymbol{\Delta t}$ $(\boldsymbol{day, year})$	$\boldsymbol{MM}$ (%)
> 100	$1.53E\ 02$	$2.4\ days$	4.3
> 200	$9.77E\ 01$	$3{,}7 days$	1.4
> 300	$1.37E\ 01$	$26.6\ days$	16.4
> 400	$5.95E00$	$61.3\ days$	22.8
> 500	$1{,}53E00$	$238.6\ days$	45.6

Each solar panel of TechnoSat has a detection area of ca. $200\ cm^2$. The total detection area of four SOLID panels amounts to ca. $0.08\ \mathrm{m}^2$. This area was considered for the impact analysis for SOLID panels on TechnoSat. Tab. 2 represents the expected number of impacts, impact interval as well as SD and MM impacts on four SOLID panels on TechnoSat.

Tab. 2: Results of space debris impact analysis with MASTER2009: total expected number of impacts on TechnoSat SOLID panels $\mathbf{N_{Tech}}$; impact interval $\boldsymbol{\Delta t_{Tech}}$, expected impacts of SD and MM on SOLID panels during one year mission duration.

$\boldsymbol{d_p}$ $(\mu \boldsymbol{m})$	$\boldsymbol{N_{Tech}}$ $(\mathbf{1}/\boldsymbol{year})$	$\boldsymbol{\Delta t_{Tech}}$ $(\boldsymbol{day, year})$	$\boldsymbol{SD}$ $(\mathbf{1}/\ \boldsymbol{year})$	$\boldsymbol{MM}$ $(\mathbf{1}/\ \boldsymbol{year})$
> 100	$1.2E\ 01$	$30.6\ days$	11.42	0.51
> 200	$7.6E\ 00$	$47.9\ days$	7.51	0.11
> 300	$1.1E\ 00$	$341.6\ days$	0.89	0.18
> 400	$4.6E-01$	$2.2\ years$	0.36	0.11
> 500	$1{,}2E-01$	$8.4\ years$	0.06	0.05

With regards to MASTER2009 analysis, the impact velocity in the TechnoSat orbit of SD debris lies predominantly at ca. $15\ km/s$ and of MM at ca. 20 km/s. For an appropriate validation of MASTER ca. 10 measurements of certain diameter per year are required [19]. This number can be assumed as an average value, in case that the evaluation of impact data occurs once a year and no information regarding temporal and spatial distribution of objects in space is available. By utilization of in-situ detectors like SOLID, information regarding spatial and temporal object distribution can be gained. This will lead to a lower amount of measurement data required for validation purposes. However, the required number of measurements for model validation needs to be analyzed for MASTER and ORDEM respectively. Additionally, new and so far not explored SD and MM sources can be identified and included into the environmental models. An example for such sources is the interaction of Interplanetary Dust Experiment (IDE) on Long-Duration Exposure Facility (LDEF) S/C with solid motor particles released by re-entry firings. A detailed description of this investigation can be found in [20].

As can be seen from Tab. 2, ca. 12 impacts of $100\ \mu m$ objects and ca. $7-8$ impacts of $200\ \mu m$ objects can be expected on four SOLID panels of TechnoSat during one year. The probability for 12 impacts of $100\ \mu m$ objects amounts to $54\ \%$ and for 10 impacts of the same diameter to $76\ \%$. For the $200\ \mu m$ objects the probability is $55\ \%$ for $7-8$ impacts and $17-28\ \%$ for 10 impacts. For the probability calculation the Poisson distribution was applied as described in [5].

The uncertainty regarding the object size estimation results mainly from the selected sensor design. The estimation of the average damage diameter on the sensor is outlined in [18]. For the ground tested design the deviation was identified with 8% for $500\ \mu m$ objects, 24.5 % for $1.5\ mm$ objects and 29 % for $2\ mm$ objects.

5. CONCLUSION

A new in-situ detection method SOLID (Solar generator based Impact Detector) for on orbit testing on the TechnoSat mission in 2016 is described. The foreseen system architecture as well as already manufactured hardware for flight qualification for this mission is presented. The expected impact rates were analyzed by utilizing ESA environmental model MASTER2009. The corresponding probabilities of impacts as well as the uncertainties regarding the object size estimation are outlined. By applying this detection method to different spacecraft in different orbits, spatial and temporal data can be generated and new debris sources can be identified. The data can be utilized to update environmental models like MASTER and ORDEM.

6. ACKNOWLEDGEMENTS

The work was funded by DLR (Deutsches Zentrum für Luft- und Raumfahrt) in the frame of the system analysis research activities. The contribution to the flight experiment by Prof. Montenegro (University Würzburg, software), Mr. Alexei Pissarskoi (DLR Bremen, sensor design) is gratefully acknowledged.

7. REFERENCES

[1] S. Flegel, J. Gelhaus, M. Möckel, and Wiedemann, C, Kempf, D, “Maintenance of the ESA MASTER Model,” Final Report, Institute of Aerospace Systems (ILR), Technische Universität Braunschweig (TUBS), May. 2011.

[2] J.-C. Liou, M. J. Matney, Anz-Meador, P. D, D. Kessler, M. Jansen, and J. R. Theall, “The New NASA Orbital Debris Engineering Model ORDEM2000,” NASA/TP—2002-210780, May. 2002.

[3] J. McDonnell, A. D. Griffiths, M. K. Herbert, L. Berthoud, J. C. Zarnecki, W. C. Carey, J.-C. Mandeville, C. Lemcke, G. A. Graham, G. Fairlie, and D. J. Catling, “Meteoroid and debris flux and ejecta models, Final Report, ESA Contract No. 11887/96/NL/JG,” ESA, 1998.

[4] J. McDonnell, “Post-Flight Impact Analysis of HST Solar Arrays - 2002 Retrieval, Final Report, ESA Contract No. 16283/NL/LvH,” ESA, 2005.

[5] H. Klinkrad, *Space debris, Models and risk analysis*. Berlin, New York, Chichester, UK: Springer; Published in association with Praxis Pub, 2006.

[6] G. Drolshagen, H. Svedhem, E. Grün, O. Grafodatsky, and U. Prokopiev, “In Situ Measurement of Cosmic Dust and Space Debris in the Geostationary Orbit,” in *Proc. of the Second European Conference on Space Debris*, 1997, pp. p. 129.

[7] W. Bauer and O. Romberg, "Solargenerator", DE-Patent DE102012000260.

[8] W. Bauer and O. Romberg, "Solar Generator", US Patent 8593165B2.

[9] W. Bauer, O. Romberg, C. Wiedemann, G. Drolshagen, and P. Vörsmann, “Development of in-situ Space Debris Detector,” *Advances in Space Research*, 2014, pp. 1858–1869, 2014.

[10] W. Bauer, O. Romberg, A. Pissarskoi, C. Wiedemann, and P. Vörsmann, “In orbit debris-detection based on solar panels,” *CEAS Space J*, vol. 5, no. 1-2, pp. 49–56, 2013.

[11] IADC, *PROTECTION MANUAL: IADC-04-03*. Version 5.0. Available: http://www.iadc-online.org/Documents/IADC-2004-03,%20IADC%20Protection%20Manual,%20Version%205.pdf (2013, Dec. 24).

[12] M. Barschke and K. Gordon, Eds, *TUBiX20 – A Generic Systems Architecture for a Single Failure Tolerant Nanosatellite Platform*. Toronto, Canada, 2014.

[13] M.F. Barschke, H. Adirim, O. Balagurin, W. Ballheimer, L. Dornburg, H. Kayal, D. Noack, C. Nitzschke, N. Pilz, H. Wojtkowiak, and K. Brieß, Eds, *TechnoSat - A Nanosatellite Mission for On-Orbit Technology Demonstration: Nitzschke, N. Pilz, H. Wojtkowiak and K. Brieß*. Logan, USA,, 2013.

[14] D. Noack and K. Brieß, “Laboratory investigation of a fluid-dynamic actuator designed for CubeSats,” *Acta Astronautica*, vol. 96, pp. 78–82, 2014.

[15] G. Kirchner, L. Grunwaldt, R. Neubert, F. Koidl, M. Barschke, Z. Yoon, and H. Fiedler, Eds, *Laser Ranging to Nano-Satellites in LEO Orbits: Plans, Issues, Simulations.*

[16] K. Briess, R. Alavi, Jäckel K, and H. Podolski, Eds, *S-Band Communication for Nano- and Pico Satellites for Cross Platform Compatibility*, 2008.

[17] O. Balagurin, Kayal H, and H. Wojtkowiak, Eds, *Validation and qualification of a CMOS based miniature star tracker for small satellites*, 2012.

[18] W. Bauer, O. Romberg, and R. Putzar, “Experimental verification of an innovative debris detector,” *Acta Astronautica*, vol. 117, pp. 49–54, 2015.

[19] H. Krag, "Validierung des MASTER-Modells im Kleinteilchenbereich", E-Mail, Nov. 2013.

[20] S. Stabroth, “Dust particle impacts due to re-entry firings of solid rocket motors,” Dissertation, Aachen.