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Modelling of the Materials Classification of In-Orbit Debris using DISCOSweb and other sources.

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Abstract

Space debris is a topic of growing concern as the space industry evolves. This paper describes the findings of a new model used to classify the materials used in current orbital objects. It utilises data from sources including ESA's DISCOS (Database and Information System Characterising Objects in Space) web to create a consistent and unified dataset which provides better understanding of the types of materials involved with orbital debris. As well as adding a material property to each piece of debris, the change in material properties over time due to degradation sources in orbit is included. The manufacturing methods used to produce these objects are also considered. The paper presents results from a variety of scenarios relating to debris removal and recycling.

Keywords: Space Debris Materials; Low Earth Orbit; DISCOSweb; Space Manufacturing.

Nomenclature:

dd = density distribution percentage of space debris object
DISCOSweb = Database and Information System Characterising Objects in Space web
ESA = European Space Agency
ESOC = European Space Operations Centre
FAA = Federal Aviation Administration
GEO = Geosynchronous Equatorial Orbit
JAXA = Japan Aerospace Exploration Agency
LEO = Low Earth Orbit
$m_{material}$ = mass of 1 sheet of the material (e.g. aluminium)
m_{object} = mass of the space object
N_A = average estimate number of material sheets or panels
N_m = estimate number of material sheets or panels (in terms of mass)
N_v = estimate number of material sheets or panels (in terms of volume)
NASA = National Aeronautics & Space Administration
NRC=National Research Council
ODPO=Orbital Debris Program Office
OECD = Organisation for Economic Co-operation & Development
V_{object} = volume of space object (e.g payload or rocket body)
V_s = volume of 1 panel or sheet of material (e.g aluminium)
$\rho_{material}$ = density of material
UKSA=United Kingdom Space Agency

1. Introduction

Space debris is a topic internationally of growing concern. A report from ESA states "'Business as usual' space activities will lead to a progressive, uncontrolled increase in debris objects, with collisions

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becoming the primary debris source" (ESA, 2017a). The OECD reports that up to 10% of total mission costs are currently dedicated to protecting spacecraft from space debris (OECD, 2020). There is estimated to be more than 9400 tonnes of debris in orbit with more than 28000 objects being tracked and an estimated 900000 objects of size from 1 cm to 10 cm and 128 million objects of size less than 1 cm (ESA, 2017b). Many different approaches have been proposed for treating debris including deorbiting; reducing the orbital lifetime; moving spacecraft to lesser used orbits at end of mission; and active debris removal (NRC, 1995). Identified methods for active debris removal include harpoons, nets, tethers, sling satellites, lasers, and claws. However, it was not until recently that funding towards developing the technology for missions to remove space debris have been tested with RemoveDEBRIS (2018) and further planned by ESA's ClearSpace-1 (ESA, 2019) JAXA's ADRAS-J (JAXA, 2021) and the UK Space Agency's Active Debris Removal Call (UKSA, 2021).

Space debris is thus not only a menace for space operations but ironically also is a potential source of useful in-space material. While surveys of the current debris environment have been proposed and performed to varying levels of success, many of these sources are considered separately (e.g. ESA's DISCOSweb and ESOC; NASA's ODPO; and the University of Texas' AstriaGraph). A team of space researchers at the University of the West of England (UWE) have looked at space debris mitigation and usage in recent years so identification of objects and their content is an integral part of their research plans.

This paper describes the findings of a new model developed so as to classify the materials found in current orbital objects. It takes data from sources including ESA's DISCOS (Database and Information System Characterising Objects in Space) web and space-track.org and collates it into a consistent and unified dataset. DISCOSweb provides a detailed database of more than 40,000 registered objects including information on their size, mass and orbital path. Some of these objects are debris, some are active spacecraft. The UWE model provides a better understanding of the types of materials involved with orbital debris as it adds material properties to each piece of debris (wherever possible). Furthermore, the change in material properties over time due to degradation sources in orbit is included to give further insight. Added features include COSPAR ID, more geometric information and manufacturing methods used to produce these objects.

Analysis from the database allows for the identification of the type of debris in space and can help determine which ones could be useful to capture or deorbit in the future. Another part of the model analyses material density distribution of debris as a function of where in the vicinity of Earth's orbit this debris lies. This enables identification of specific types of debris that can be targeted by different removal methods, allowing a greater removal target to be obtained from such a mission.

2. Model development

The UWE model has utilised information from DISCOSweb and other sources using SQL, Python and the ESA DISCOS API. The extracted data is stored in JSON file format and used to create the new database, via conversion from JSON format to a Tabular format, with translation into an SQL Database. From this, specific enquiries can be made to recognise objects or aspects of interest and to perform statistical calculations.

2.1 Identifying and classifying Debris Objects by shape

Each object is first identified as whether debris or an active item. It is then recorded as from a propulsive device into orbit such as a rocket, or from a payload. A classification system of objects by shape has then been adopted here. The classes for rockets include e.g. Sphere & Cone; Cylinder; Cylinder with Nozzles; Cylinder with Cones; Double Cone, and Irregular. Whereas the classes for payload include e.g. Box; Box with Panels; Cylinder; Cylinder with Cones; Cylinder with Panels; Sphere; Cone; Cone with Cylinder.

Statistical analysis is used to evaluate the most likely object type according to shape (Table 1 for rocket debris). The objects are then classified and the number of objects in each category recorded.

Table 1: Examples of likely rocket debris type with probability for some typical shape classes

Class	Likely debris type (with % probability)
Sphere & Cone	Payload Assist Module (78%), Launch Vehicle Engine (21.7%)
Cylinder	Rocket stage 2 (95.8%), Rocket stage 3 (0.04%)
Cylinder with Nozzles	Upper Stage Engine (100%)
Cylinder with Cones	Second Stage (87.5%), Third Stage (12.5%)

2.2 Identifying Materials in Debris

The model was then expanded by adding a material property to each object wherever possible (examples provided in Table 2). Useful data sources include (amongst others): Bhat (2018), Smithsonian (2021), Spilker (2019), Thiokol (2011). In some cases, assumptions have needed to be adopted. For example, it has been assumed that rocket bodies contain 90% medium to 10% high density materials (Opiela, 2009) whereas in the case of payloads, a typical material density distribution is 70% low, 27% medium and 3% high (Opiela, 2009). Plastics are in the low density range (1.4 g cm^{-3}), aluminium (2.8 g cm^{-3}) is an example of medium density and steel (8 g cm^{-3}) of high density.

Table 2: Examples of analysis of rocket debris objects for significant percentages of material

Shape	***Main Materials***	***Extra Materials***
Sphere + Cone	• 2000/7000 series Aluminium for Tanks • Silicon, Lithium, Manganese, Magnesium	• Stainless Steel, Stainless Fabric, Rubber (Silicone), Plastic, Nylon, Paint, Steel, Synthetic Fabric, Aluminium, Cadmium Plating, Brass, Velcro, Mylar (Polyester), Gold Plating, Beryllium PAM-D • Conventional quench, Titanium alloys, reinforced plastics, aluminium alloys and temper steels
Cylinder with Cones	• 2000/7000 series Aluminium for Tanks • Silicon, Lithium, Manganese, Magnesium	• Aluminium honeycomb core for fairings (Cone), sandwiched with either graphite epoxy/ aluminium factsheets

2.3 Manufacturing methods

Manufacturing methods used to produce the orbital objects are also collected and stored in the database. This is important information for understanding the initial state of the material and the fixings used. Examples are presented in Table 3 for both rockets and payload. Sources include: ArianeGroup (2021), Nichols (2019), Northrop Grumman (2021) and Sun et al, (2017).

Table 3: Example of material and manufacturing information on objects shaped as a "cylinder with nozzle(s)" for a rocket and cylinder-shaped payload objects.

Shape	Main Materials	Additional Materials	Manufacturing methods
Cylinder with Nozzle(s)	2000/7000 series Aluminium for Tanks Silicon, Lithium, Manganese, Magnesium	• Titanium Alloy • Alloy steel, copper alloys, stainless steels, aluminium alloys, titanium alloys, cobalt-base alloys and nickel-base alloys for injectors • Aluminium alloys, low-alloy steel, stainless steel, pure nickel, nickel-base alloys, cobalt base alloys, titanium alloys, copper alloys, niobium alloys, carbon-carbon, ceramic matrix composites, glass-phenolic, beryllium, and refractory metals for combustion chambers and nozzles • Tubular designs have used nickel 200, stainless steels 316 and 347, Inconel 600, X750, and A286 • Carbon-carbon composites for Nozzles	Normal Welding/ Friction Stir Welding (Mid 1990s onwards)
Cylinder (payload)	Aluminium Alloys, particularly aluminium-coated polyimide Kevlar for shielding	• Silicon Solar Panels (20th Century) OR Gallium Arsenide (9) • Titanium or Aluminium Alloy in Propulsion Tank • Quarts in OSR • Composite Structures in Tower • Graphite and Teflon for lubrication	Hand-drilling and hand -potting of inserts, automation and robots used in modern satellites Bespoke customisation and craft production methods, newer satellites are assembled from supplier parts/ systems

2.4 Accumulation of object types

In order to estimate how many objects are of a certain type or perhaps how much material is present of a certain type (e.g. a particular grade of aluminium), it is useful to be able to pull out of the database, objects which are rich in that material. Due to the extremely large number of objects, 5 random examples were chosen for each shape, with 3 random examples each for each shape variation (e.g.

Box + 1 Panel, Box + 2 Panel etc). It is random to ensure that it is a fair judgement of the probable Object type, therefore allowing for different examples to be looked at with no bias.

Table 4: Example of using the database to extract debris objects of a certain shape class. This can include linking debris fragments of the same original object. From the objects accumulated per class, estimates can be made on the probable type of object.

Shape	***Random Examples***	***Amount of each example***	***Probable Object Type***
Sphere & Cone	1. PAM-D 2. Star 37B (Thor-Burner II) 3. KM-P (Mu-3S-II) 4. Mu-4s-4 (Mu 4s) 5. RSA-3-3 (Shaviyt)	1. 54 2. 10 3. 5 4. 3 5. 8	Payload Assist Module (67.5%) Stage 3 Rocket (32.5%)

2.5 Quantifying mass

One aspect that is required is an estimate of how much material is available from certain objects. For each class of shape, the object can be subdivided into an approximate surface area and maximum cross-sectional area (Table 5). For objects such a rocket stages, estimates can be made for some of the internal structure with a similar method applied to payloads.

For example, the database can be used to estimate the amount of aluminium alloys 6061 and 7075 in current CubeSat debris objects or the amount of steel in rocket stage debris. In the database in the payload class “Box + 4 panels”, 31 objects have been extracted. These comprise 28 Cubesats and 3 larger in-operation satellites (Eutelsat 115 West A, Sentinel-1A and Sentinel-1B). Estimating in terms of aluminium sheets 1 m by 1 m by 0.01 m, and ignoring the solar panels, it is evaluated that there is an average of 3.7 sheets available from each cubesat and roughly 11700 sheets from the three larger satellites once the latter reach the end of their operational life.

Table 5: Formulae used to provide estimates of the amount of materials in an object, used for aluminium, steel and fiberglass estimations. The estimations are calculated in terms of “1m x 1m x 0.1m sheets” of material, measurement similar to materials sold commercially.

Calculating Mass and Volume of 1 sheet of Material:
$m_{material} = \rho_{material} V_s$ where $V_s = l.w.d$
Calculating potential number of sheets in an object:
$N_m = \frac{(m_{object}.dd)}{m_{material}}$ $N_v = \frac{(V_{object}.dd)}{V_s}$ $N_A = \frac{N_m + N_v}{2}$

2.6 Debris mass as a function of cross-sectional area

One type of analysis from the model is the representation of debris mass as a function of cross-sectional area. This allows for the identification of the type of debris in space and can help determine which ones could be useful to capture or deorbit in the future. It can assist the decision making in future Space Debris recycling/ de-orbiting operations and potentially in deciding on the scale for debris removal spacecraft (both in terms of their design to capture debris in a certain size range and how many such satellites should be produced).

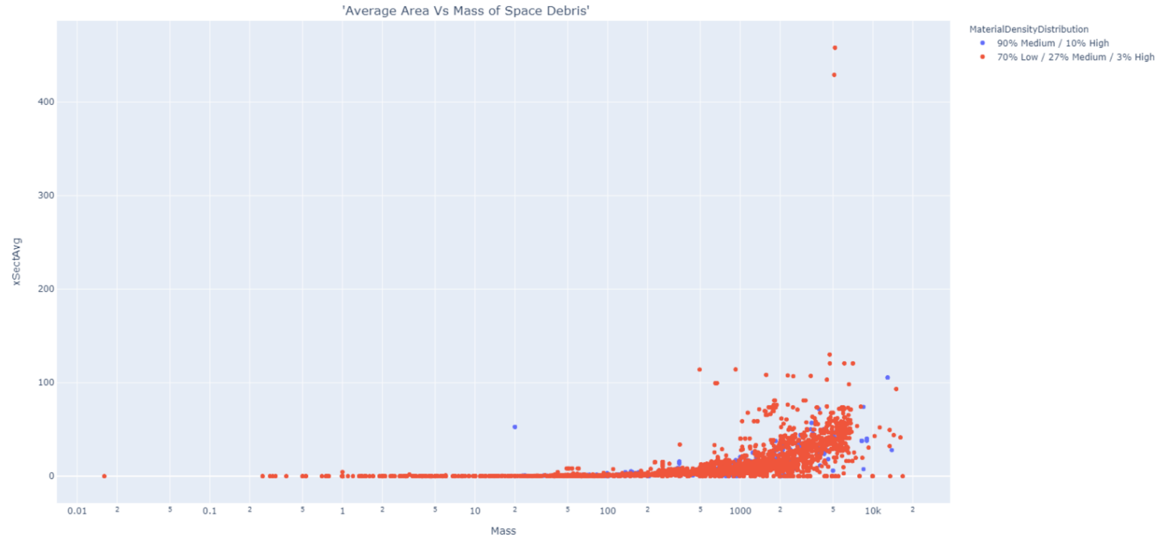

Figure 1 *The number of objects (Payloads and Rocket Bodies) in space. The colours distinguish between low (payload) and medium (rocket) density objects as a function of cross-sectional area.*

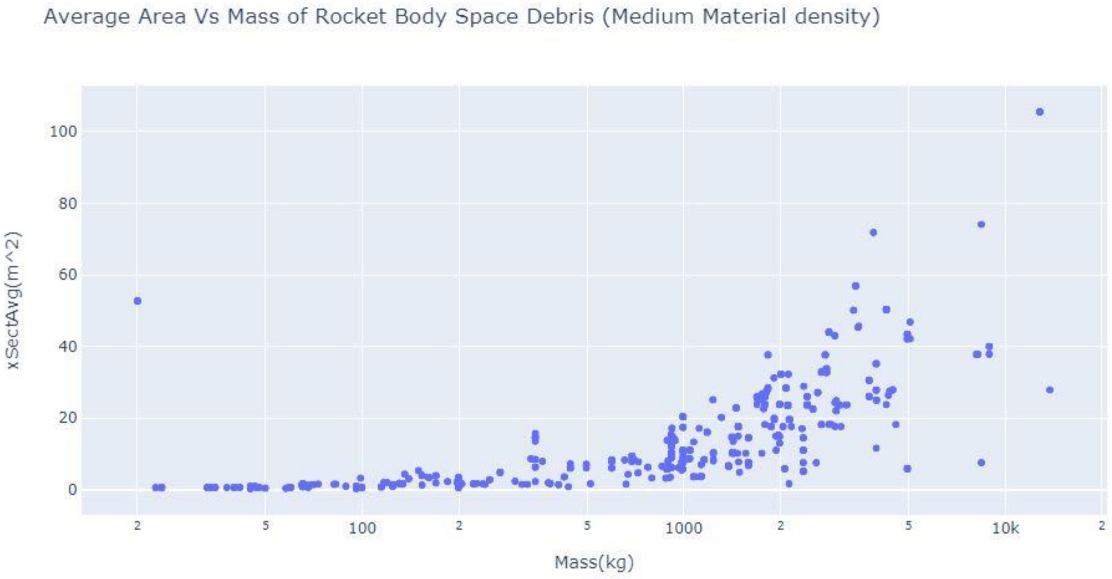

Figure 2 *The amount of rocket bodies currently in space, that potentially have medium-density materials to be harvested (e.g. Aluminium). It is a graph of Cross-sectional area against Mass, therefore indicating the size and masses of rocket bodies, giving an idea of which ones could be priority (e.g. harvest larger and heavier rocket bodies).*

In Figure 1, both rocket and payload objects are shown (22,236 objects have dimensional information available), whereas in Figure 2 only the rocket items are displayed. This can be further reduced into specific types of rocket debris and/or specific alloy compositions. The average area values come from DISCOSweb.

2.7 Material density distribution.

In future, some missions may target certain types of objects for collection and/or removal. In the case of collection, material density distribution of debris as a function of where in the vicinity of Earth's orbit this debris lies would be useful, allowing a greater collection target to be obtained from a particular mission. Figure 3 represents the orbital objects currently in Low Earth orbit, distinguished by rocket type (red) and payload type (green). The Earth is considered here as a completely transparent object so distance from the User is not plotted here. The data is obtained as a 3D rotating object (rather than the flat view seen below) and can be displayed for any date that is required, although extrapolating the information further in the future increases the uncertainty of the objects' positions.

The point cloud data image (Figure 3) is generated using the 3LE location data from Space-track. This data is collated with data from DISCOSWeb using the COSPAR IDs. The data is processed to extract some useful features (as discussed in previous sections) and filtered to highlight these features. It is then visualized using open 3D. The objects tracked by Space-Track and DISCOSWeb are a mixture of satellites, rockets, parts of satellites, parts of rockets, and debris. The full list of object categories is: Rocket Body, Rocket Mission Related Object. Rocket Fragmentation Debris. Rocket Debris, Payload Payload Mission Related Object, Payload Fragmentation Debris, Payload Debris, Other Mission Related Object. Other Debris. And Unknown. The objects are at altitudes from 6378 to 8378 km (LEO), and up to 100,000 km (GEO).

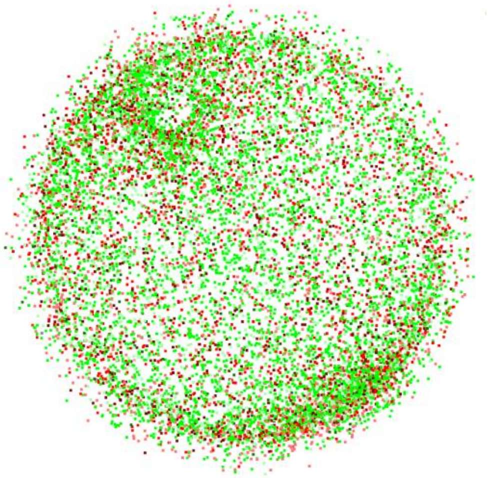

Figure 3 Representation of orbital debris as a function of type. A red dot denotes a rocket object, and a green dot represents a payload object.

A more specific search of the database can be used to identify and plot objects of a certain size, or a certain time in orbit or a particular aspect of the material composition. For example, Figure 4 shows objects with a decided quantity of steel. The deeper the colour, the higher the percentage of steel. Figure 5 denotes objects by the highest material composition.

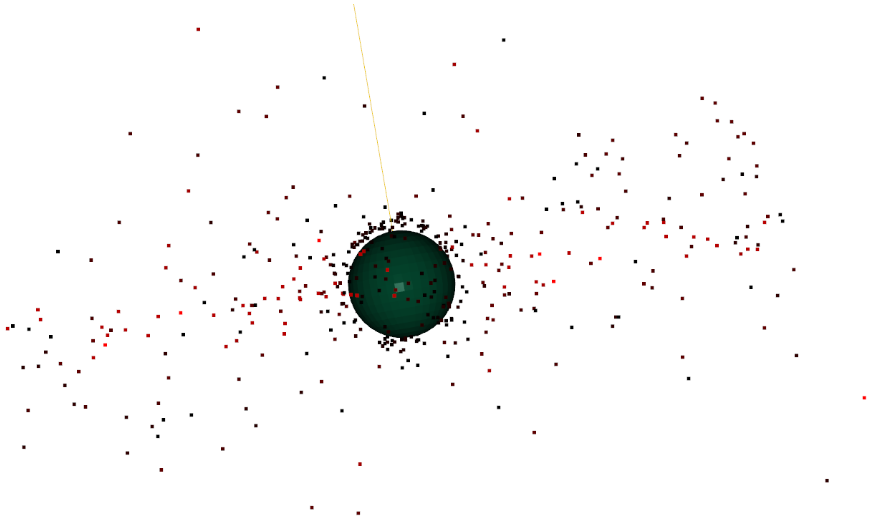

Figure 4. Orbital objects in LEO and GEO displayed as a function of percentage composition of steel

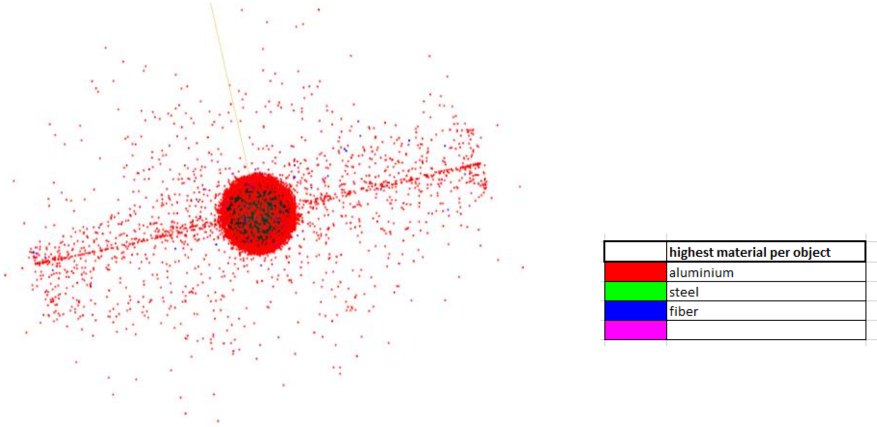

Figure 5 Representation of LEO and GEO objects as a function of the material with the highest composition (of each object). The yellow line perpendicular to the object disc is towards north.

In terms of extrapolating in time, the accuracy of the propagated TLE data depend on the limitations in the sgp4 model and introduced by atmospheric drag (for LEO) (Aida et al, 2013, and Smith, 2019). The time that an object has been in space and its orbit is used in calculations to determine how much radiation a debris object would have accumulated.

4. Conclusions

The database and its software for extraction and visualisations provide the foundations of further classifying Space Debris for future applications. The intention is that the database is updated and improved to ensure it keeps up with new Space Objects and provides greater insight into the dangers, opportunities and the future uses of space debris.

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6. References

Aida, S. & Kirschner, M., 2013, *Accuracy Assessment of SGP4 Orbit Information Conversion Into Osculating Elements*, https://conference.sdo.esoc.esa.int/proceedings/sdc6/paper/41/SDC6-paper41.pdf (last accessed 24.06.2021)

ArianeGroup, 2021, *Bipropellant Tanks*, https://www.space-propulsion.com/spacecraft-propulsion/bipropellant-tanks/index.html#:~:text=Portfolio%20of%20space%20qualified%20titanium,198%20litres%20to%202100%20litres.&text=Some%20bipropellant%20tanks%20are%20also%20qualified%20for%20use%20with%20hydrazine%20propellant (last accessed 17.06.2021)

AstriaGraph, 2021, http://sites.utexas.edu/moriba/astriagraph/ (last accessed 17.06.2021)

Bhat, B.N., 2018, *Aerospace Materials and Applications*, Progress in Astronautics & Aeronautics, AIAA, pp 277, doi.org/10.2514/4.104893

Chapline, G., 2013, *Materials & Manufacturing*, Engineering Innovation, NASA Johnson Space Centre, https://www.nasa.gov/centers/johnson/pdf/584729main_Wings-ch4c-pgs200-225.pdf, (last accessed 17.06.2021)

DISCOSweb, https://discosweb.esoc.esa.int/, last accessed 15.02.2021]

ESA, 2017a, *Space debris, the ESA approach,* Fletcher, K. (Ed.), https://esamultimedia.esa.int/multimedia/publications/BR-336/offline/download.pdf (last accessed 17.06.2021)

ESA, 2017b, *Space debris by the numbers*, https://www.esa.int/Safety_Security/Space_Debris/Space_debris_by_the_numbers (last accessed 17.06.2021)

ESA (European Space Agency), 2019, *ESA commissions world's first space debris removal,* https://www.esa.int/Safety_Security/Clean_Space/ESA_commissions_world_s_first_space_debris_removal (last accessed 17.06.2021)

FAA, 1999, Trends in satellite manufacturing : changing how the commercial space transportation industry does business : Quarterly Launch Report : special report, https://rosap.ntl.bts.gov/view/dot/15775 (last accessed 17.06.2021)

Henry, C., 2016, *Modernizing Manufacturing: How to Build the Satellite of the Future*, Via Satellite, http://interactive.satellitetoday.com/via/april-2016/modernizing-manufacturing-how-to-build-the-satellite-of-the-future/ (Last accessed 17.06.2021)

JAXA, 2021, *CRD2 Phase I: A JAXA and Astroscale Mission Towards Space Sustainability*, https://sma.jaxa.jp/trismac2021/pdf/2-T1-1.pdf (last accessed 17.06.2021)

NASA, 2017, Cubesat 101 Basic Concepts & Processes for First-Time CubeSat Developers, NASA CubeSat Launch Initiative, https://www.nasa.gov/sites/default/files/atoms/files/nasa_csli_cubesat_101_508.pdf

Nichols, M.R., 2019, *What Materials Keep Satellites Safe in Space?*, RealClearScience, https://www.realclearscience.com/articles/2019/09/23/what_materials_keep_satellites_safe_in_space.html (last accessed 17.06.2021

Northrop Grumman, 2021 *Spacecraft Components*, https://www.northropgrumman.com/space-old/spacecraft-components/#:~:text=Radome%20structures%20are%20made%20of,%2D%20to%20high%2Dtemperature%20applications. (Last accessed 17.06.2021)

NRC, 1995, Orbital Debris, A Technical Assessment, Committee on Space Debris, National Research Council, National Academy Press

OECD, 2020, Space Sustainability. *The Economics of Space Debris in perspective*, OECD Science, Technology & Industry Policy Paper No. 87, https://www.oecd-ilibrary.org/docserver/a339de43-en.pdf?expires=1624818770&id=id&accname=guest&checksum=83B9553DB743AEA0F907223570AD25AE (last accessed 17.06.2021)

Opiela, J.N., 2009, *A study of the material density distribution of space debris*, Advances in Space Research, Volume 43, Issue 7, pp 1058-1064, ISSN 0273-1177, doi.org/10.1016/j.asr.2008.12.013.

RemoveDEBRIS, 2018, https://www.surrey.ac.uk/surrey-space-centre/missions/removedebris (last accessed 17.06.2021)

Smith, A., 2019, Assessment of TLE-based Orbit Determination and Prediction for Cubesats, Omitron Inc. https://core.ac.uk/download/pdf/199183197.pdf (last accessed 24.06.2021)

Smithsonian Air & Space Museum, 2021, *Cradle, Payload Assist Module (PAM-D), Space Shuttle (flown)*, https://airandspace.si.edu/collection-objects/cradle-payload-assist-module-pam-d-space-shuttle-flown/nasm_A19900058000 (last accessed 17.06.2021)

Space-Track, https://www.space-track.org/, (last accessed 17.06.2021)

Spilker, B., 2019, *Metals in Space: How Superalloys changed the rocket Landscape*. https://matmatch.com/blog/metals-in-space-how-superalloys-changed-the-rocket-landscape/m Last accessed 17.06.2021

Sun, Kai & Riedel, Christoph & Wang, Yudong & Urbani, Alessandro & Simeoni, Mirko & Mengali, Sandro & Zalkovskij, Maksim & Bilenberg, B. & De groot, C.H. (Kees) & Muskens, Otto. (2017). *Metasurface Optical Solar Reflectors Using AZO Transparent Conducting Oxides for Radiative Cooling of Spacecraft*. ACS Photonics. 5. 10.1021/acsphotonics.7b00991. https://www.researchgate.net/publication/321378914_Metasurface_Optical_Solar_Reflectors_Using_AZO_Transparent_Conducting_Oxides_for_Radiative_Cooling_of_Spacecraft (last accessed 17.06.2021)

Thiokol Propulsion, 2011, *Rocket Basics, A Guide to Solid Propellant Rocketry*, http://www.aeroconsystems.com/tips/Thiokol_basics.pdf (last accessed 17.06.2021)

UKSA, 2021, *Active Debris Removal: Call for study proposals*, https://www.gov.uk/government/publications/active-debris-removal-call-for-study-proposals (last accessed 17.06.2021)