Chapter Contents

Chapter Glossary

(ABS)	Acrylonitrile Butadiene Styrene
(ACS3)	Advanced Composite Solar Sail project
(AE)	Aerospace Corporation Electron
(AM)	Additive manufacturing
(AMODS)	Autonomous On-orbit Diagnostic System
(AP)	Aerospace Corporation Proton
(CAM)	Computer Aided Manufacturing
(COBRA)	Compact On-Board Robotic Articulator
(COTS)	Commercial-off-the-Shelf
(CSLI)	CubeSat Launch Initiative
(CTD)	Composite Technology Deployment
(DCB)	Deployable Composite Boom
(DDD)	Displacement Damage Dose
(DLP)	Digital Light Projection
(DOF)	Degrees of Freedom
(EEE)	Electrical, Electronic and Electro-mechanical
(EELV)	Evolved Expendable Launch Vehicle
(ESD)	Electrostatic Discharge
(ESPA)	EELV Secondary Payload Adapter
(FDM)	Fused Deposition Modeling
(FFF)	Fused Filament Fabrication
(FPGAs)	Field Programmable Gate Arrays
(FST)	Flame, Smoke, and Toxicity
(GCD)	Game Changing Development
(GEVS)	General Environmental Verification Standard
(HDT)	Heat Deflection Temperature
(ISS)	International Space Station
(LaRC)	Langley Research Center
(MOSFETs)	Metal Oxide Semiconductor Field Effect Transistors
(NSTAR)	Naval Academy Satellite Team for Autonomous Robotics
(PAEK)	Polyaryletherketone
(PC)	Polycarbonate

(PCB)	Printed Circuit Board
(PEEK)	Polyetheretherketone
(PEI)	Polyetherimide
(PEKK)	Polyetherketoneketone
(PLA)	Polylactic Acid
(PLEO)	Polar Low-Earth Orbit
(PSC)	Planetary Systems Corporation
(RECS)	Robotic Experimental Construction Satellite
(ROC)	Roll Out Composite
(RSat-P)	Repair Satellite-Prototype
(SADA)	Solar Array Drive Actuator
(SEUs)	Single Event Upsets
(SLA)	Stereolithography
(SLS)	Selective Laser Sintering
(SPEs)	Solar Particle Events
(STELOC)	Stable Tubular Extendable Lock-Out Composite
(STMD)	Space Technology Mission Directorate
(TID)	Total Ionizing Dose
(TRAC)	Triangle Rollable and Collapsible
(ULA)	United Launch Alliance

6.0 Structure, Mechanisms, and Materials

6.1 Introduction

Additive manufacturing (AM) has played a large role in the increase of custom structural solutions for SmallSats, and materials that were once out of reach of AM are now readily available in higher end systems and have demonstrated high throughput of complex structures. Once only for secondary structures, AM has seen an expansion in primary structures – especially in small CubeSat or PocketQube buses.

However, for larger CubeSats and Evolved Expendable Launch Vehicle (EELV) Secondary Payload Adapter (ESPA) SmallSats, conventionally machined assemblies constructed from aluminum alloys still have their place for primary structures. Secondary structures, such as solar panels, thermal blankets, and subsystems, are attached to primary structures. They stand on their own and transmit little to no critical structural loads. When a primary structure fails, catastrophic failure of the mission occurs. While failure of a secondary structure typically does not affect the integrity of the spacecraft, it can have a significant impact on the overall mission. These structural categories serve as a good reference but can be hard to distinguish for small spacecraft that are particularly constrained by volume. This is especially true for SmallSats, as the capabilities of these spacecraft may be similar to full size buses, but the volume afforded by dispensers or deployment rings become the constraining factor. Therefore, it is imperative that structural components are as volume efficient as possible. The primary structural components need to serve multiple functions to maximize volume efficiency. Such functions may include thermal management, radiation shielding, pressure containment, and even strain actuation. These are often assigned to secondary structural components in larger spacecraft.

Material selection is of primary importance when considering small spacecraft structures. Requirements for both physical properties (density, thermal expansion, and radiation resistance) and mechanical properties (modulus, strength, and toughness) must be satisfied. The manufacture of a typical structure involves both metallic and non-metallic materials, each offering advantages and disadvantages. Metals tend to be more homogeneous and isotropic, meaning properties are similar at every point and in every direction. Non-metals, such as composites, are inhomogeneous and anisotropic by design, meaning properties can be tailored to directional loads. Recently, resin or photopolymer-based AM has advanced sufficiently to create isotropic parts. In general, the choice of structural materials is governed by the operating environment of the spacecraft, while ensuring adequate margin for launch and operational loading. Deliberations must include more specific issues, such as thermal balance and thermal stress management. Payload or instrument sensitivity to outgassing and thermal displacements must also be considered.

Structural design is not only affected by different subsystems and launch environments, but also the spacecraft application and intended environment. There are different configurations for spin-stabilized and 3-axis stabilized systems, and the instrumentation used places requirements on the structure. Some require mechanisms, such as deployable booms, to create enough distance between a magnetometer and the spacecraft to minimize structural effects on the measurement. The spacecraft exterior and interior material and electronic subsystems need to be understood in the specific mission environment (e.g., in-space charging effects). Mitigation for charge build up is provided in section 6.3.2 Thermoplastics and Photopolymers.

Highly configurable or modular systems may be desirable in quick-turn products, as prototyping and firmware and software development can be extended further into the spacecraft design cycle with flight hardware in the loop. Card slot systems not only provide those benefits, but when paired with certain standards, they can still fulfill the same structural, mechanical, and thermal requirements as the current CubeSat method of "stacking" electronics and payloads.

An overview of radiation effects and some mitigation strategies is included in this chapter because radiation exposure can impact the structural design of small spacecraft. For SmallSats operating out of low-Earth orbit with increased radiation exposure, mission planners may also want to consider risk mitigation strategies associated with specific radiation environments. This includes both interplanetary missions, where solar radiation dominates, and polar low-Earth orbit (PLEO) missions, where solar radiation risk increases over the poles. In addition, as solar maximum approaches in 2025 (1) with an increased number of solar particle events (SPEs), mission planners will need to consider many orbital environments.

The information described below is not intended to be exhaustive but provides an overview of current state-of-the-art technologies and their development status for a particular small spacecraft subsystem. It should be noted that Technology Readiness Level (TRL) designations may vary with changes specific to payload, mission requirements, reliability considerations, and/or the environment in which performance was demonstrated. Readers are highly encouraged to reach out to companies for further information regarding the performance and TRL of described technology. There is no intention of mentioning certain companies and omitting others based on their technologies or relationship with NASA.

6.2 State-of-the-Art – Primary Structures

Two general approaches are common for primary structures in the small spacecraft market: commercial-off-the-shelf (COTS) structures and custom machined or printed components. It is not surprising that most COTS offerings are for the CubeSat market. Often COTS structures can simplify development, but only when the complexity of the mission, subsystems, and payload requirements fall within the design intent of a particular COTS structure. Custom machined structures enable greater flexibility in mission specific system and payload design. The typical commercially available structure has been designed for low-Earth orbit applications and limited mission durations, where shielding requirements are confined to limited radiation protection from the Van Allen Belts.

There are now several companies that provide CubeSat primary structures (often called frames or chassis). Most are machined from aluminum alloy 6061 or 7075 and are designed with several mounting locations for components to allow flexibility in spacecraft configuration. This section highlights several approaches taken by various vendors in the CubeSat market. Of the offerings included in the survey, 1U, 3U and 6U frames are most prevalent, where a 1U is nominally a 10 x 10 x 10 cm structure. However, 12U frames are becoming more widely available. As there are now dispensers for the 12U CubeSat structure, there is an additional standard for CubeSat configurations. This trend has followed the development path of the 6U and 12U CubeSat structure, as 12U dispensers are now available through several launch service providers like NanoRacks and United Launch Alliance (ULA) through the Atlas series.

6.2.1 Monocoque Construction

Monocoque structures are load-bearing skins that have significant heritage on aircraft. On small spacecraft, the intent of this design is several-fold – it maximizes internal volume, it provides more thermal mass for heat sinks or sources, it allows for more mounting points, and it has more surface area to potentially reduce total ionizing dose (TID). Monocoque construction is common, and "extruded" designs are relatively easy to fabricate through CNC machining, waterjet, or laser cutting. The following are two examples of monocoque CubeSat structures.

Pumpkin, Inc.

In the structural monocoque approach taken by Pumpkin for their 1U – 3U spacecraft, loads are carried by the external skin to maximize internal volume. Pumpkin provides several COTS CubeSat structures intended as components of their CubeSat Kit solutions, ranging in size from sub-1U to the larger 6U – 12U SUPERNOVA structures (2). Pumpkin offerings are machined from Al 5052-H32 and can be either solid-wall or skeletonized.

Figure 6.1: The 6U Supernova Structure Kit. Credit: Pumpkin, Inc.

Pumpkin has developed the SUPERNOVA, a 6U and 12U structure that features a machined aluminum modular architecture. The 6U structure in figure 6.1 is designed to integrate with the Planetary Systems Corporation (PSC) Canisterized Satellite Dispenser and accommodates the PSC Separation Connector for power and data during integration (2). Configurations for other dispensers are also available.

AAC Clyde Space CS CubeSat Structure

AAC Clyde Space offers a monocoque CubeSat structure from 1U to 3U. The 1U chassis has a total mass of 0.155 kg and dimensions of 100 x 100 x 113.5 mm. The 2U structure has a mass of 0.275 kg and dimensions of 100 x 100 x 227 mm. The 3U structure has a mass of 0.394 kg and dimensions of 100 x 100 x 340.5 mm. AAC Clyde Space standardized their components to facilitate spacecraft configuration, as both 1U and 3U structures interface with all standard dispensers, such as NanoRacks (3). The 3U structure is seen in figure 6.2.

Figure 6.2: 3U CS Structure. Credit: AAC Clyde Space.

6.2.2 Modular Frame Designs

Modular frames allow for a flexible internal design for quick turn missions, while still ensuring strict adherence to external dimensions of the CubeSat standard, especially when deployment from a standardized, reusable dispenser is a requirement. Open frames are suitable for low-Earth orbit, as radiation shielding is not provided by the structure. Care must also be taken to design for thermal mass requirements, as modular frames are inherently light. The following subsections contain examples of modular CubeSat frame designs. Table 6-1 lists commercially available CubeSat structures.

NanoAvionics Modular Frame

NanoAvionics has developed what it calls "standardized frames and structural element" that, when assembled, form the primary structure for 1U to 12U spacecraft. A modular 3U structure from NanoAvionics is shown in figure 6.3. These components are intended to be modular, made from 7075 aluminum, and like many COTS CubeSat structures, compliant with the PC/104 form factor (4).

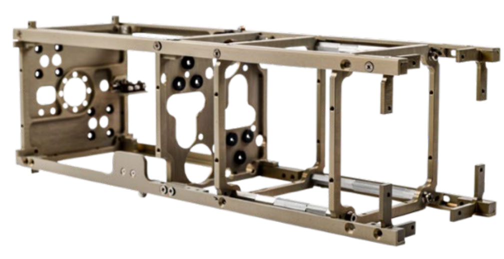


Figure 6.3: NanoAvionics Small Satellite Structures. Credit: NanoAvionics.

Innovative Solutions In SPACE

ISISPACE offers a wide array of CubeSat structures, with the largest being a 16U structure. Several of their 1U, 2U, 3U and 6U structures have been flown in low-Earth orbit (see table 6-1 for more information on these structures). Multiple mounting configurations can be considered to allow a high degree of creative flexibility with the ISISPACE design. Detachable shear panels allow for access to all the spacecraft's electronics and avionics, even after final integration (5).

GomSpace

GomSpace provides full turn-key solutions for small satellite systems. They offer modular nanosatellite structures from 1 – 6U with strong flight heritage. The 6U (figure 6.4) has a 4U payload allocation, mass of 8 kg, and propulsive configuration capabilities. The 3U structure was first deployed from the International Space Station (ISS) in 2015, and two 6U systems were deployed in early 2018 (5).

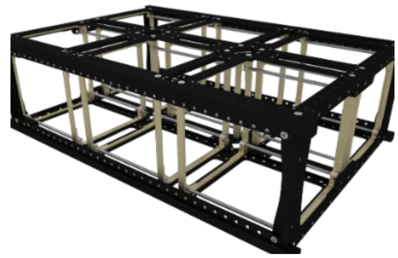


Figure 6.4: 6U nanosatellite structure. Credit: GomSpace.

EnduroSat

EnduroSat provides 1U, 1.5U, 3U, 6U CubeSat structures and material; all EnduroSat structures are made of either Aluminum 6061-T651 or Al 7075. All the listed structures have undergone environmental qualification including vibrational, thermal and TVAC testing while the 1U structure and 3U structure also have flight heritage (6).

Table 6-1: Commercial Modular Frames

Manufacturer	Structure	Dimensions (mm)	Primary Structure Mass (kg)	Material
EnduroSat	1U	100 x 100 x 114	< 0.1	Al 6061 or 7075
	1.5U	100 x 100 x 170.2	0.11	Al 6061 or 7075
	3U	100 x 100 x 340	< 0.29	Al 6061
	6U	100 x 226 x 366	< 1	Al 6061
	1U	100 x 100 x 114	0.1	Al 6061
ISISPACE	2U	100 x 100 x 227	0.16	Al 6061
	3U	100 x 100 x 341	0.24	Al 6061
	6U	100 x 226 x 340.5	0.9	Al 6061
	8U	226 x 226 x 227	1.3	Al 6061
	12U	226.3 x 226 x 341	1.5	Al 6061
	16U	226.3 x 226.3 x 454	1.75	Al 6061
GomSpace	6U	340.5 x 226.3 x 100	1.06	Al 7075
Ishitoshi Machining	1U	100 x 100 x 113.5	0.1	A7075, A6061
NanoAvionics	1U	100 x 100 x 113.5	0.105	Al 7075-T6
	2U	100 x 100 x 227.0	0.208	Al 7075-T6
	3U	100 x 100 x 340.5	0.312	Al 7075-T6
Spacemind	1U	113.5 x 100 x 100	0.0849	Al 6061

	2U	227 x 100 x 100	0.0156	Al 6061
	3U	340.5 x 100 x 100	0.0226	Al 6061
	6U	F: 340.5 x 226.3 x 100 L: 366 x 226.3 x 100	0.055	Al 6061
	12U	340.5 x 226.3 x 226.3	0.143	Al 6061
Sputnik	1U	100 x 100 x 113.5	0.0132	
	3U	100 x 100 x 340.5	0.0455	

6.2.3 Card Slot Systems

Card slot systems for military and space applications are increasingly being employed due to the ease of installation and ability to hot-swap quickly. The card slot system uses a "backplane" PCB that has an array of standardized connectors. In various applications, cards are mechanically supported by a standardized structure on "rails." This is similar to custom desktop personal computers or rack servers that use expansion cards, such as graphics or networking cards using the PCIe standard. As of 2021, very few commercial card slot systems specific to CubeSats have been produced, however the new SpaceVNX standard may change this in the coming years as PC/104 did in the past for CubeSats.

SpaceVNX

For both connectors and structural elements, the VPX standard (VITA 46) was formed in 2009 by Mercury Systems (8). Already supported by dozens of military suppliers, the standard allows for a robust mechanical and electrical connection between the board and expansion card, while still allowing for access to individual systems through interoperability. VPX was modified to create SpaceVNX, ratified in 2017. The SpaceVNX standard (VITA 74) was developed to meet demand for smaller form factors and embedded systems, which is directly compatible with the CubeSat standard. The card slot system was designed for conduction cooling and full contact with structural components to maximize heat transfer. This allows for high-power systems such as large die Field Programmable Gate Arrays (FPGAs) and single board computers. These are important systems engineering considerations, as commercial computing systems with a focus on AI/ML generally have higher thermal dissipation power. More thermal mass in the SpaceVNX structural design also has the benefit of limited radiation shielding. As discussed previously, the backplane system inherent to SpaceVNX allows for hot-swapping of modules and late-load or last-minute software or hardware changes. NASA Goddard's SpaceCube 3.0 data processing system demonstrated the use a custom-designed SpaceVNX connector and backplane system in 2019 (9).

Because SpaceVNX includes a mechanical standard, it can provide a rigid interface to the spacecraft primary structure. The 400-pin backplane connectors are also designed to withstand 0.2 g^2/Hz for 12 hours and the full military temperature range, with 125°C exposure for a minimum of 1,000 hours (10).

Complex Systems & Small Satellites (C3S)

C3S has developed a 3U CubeSat structure (figure 6.5) that uses a backplane printed circuit board (PCB) for bus communication, which provides independent assembly order, simplifies the stack-up tolerances, and uses space-grade interface connectors (7). These benefits include:

- High reliability electronic, structural, and thermal connections
- Access to individual cards and units during integration and testing
- Simplified stack-up tolerances
- Dedicated and independent thermal interfaces for all cards

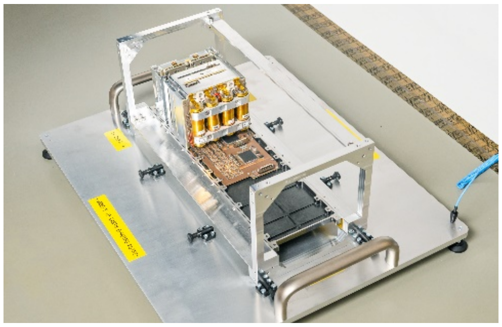


Figure 6.5: C3S 3U CubeSat Structure. Credit: Complex Systems & Small Satellites.

6.2.4 Custom Primary Structures

A growing development in building custom small satellites is the use of detailed interface requirement guidelines. These focus on payload designs with the understanding of rideshare safety considerations for mission readiness and deployment methods. Safety considerations include safety switches, such as the "remove before flight" pins and foot switch, and requirements that the spacecraft remain powered-off while stowed in the deployment dispensers. Other safety requirements often entail anodized aluminum rails and specific weight, center of gravity, and external dimensions for a successful canister or dispenser deployment. The required interface documents originate with the rideshare integrator for the specific dispenser being used with the launch vehicle. The launch vehicle provider typically provides the launch vibrational conditions. The NASA CubeSat Launch Initiative (CSLI) requires CubeSat or SmallSat systems be able to withstand the General Environmental Verification Standard (GEVS) vibration environment of approximately 10 G_{rms} over a 2-minute period (11). The NASA CSLI rideshare provides electrical safety recommendations for spacecraft power-off requirements during launch and initial deployment. The detailed dispenser or canister dimensional requirements provide enough information, including CAD drawings in many cases, to enable a custom structural application. Table 6-3 lists some dispenser and canister companies that provide spacecraft physical and material requirements for integration (12-14).

Table 6-3: Spacecraft Physical Dimension and Weight Requirements from Deployers

Manufacturer	U	Requirements	Available Documents
Tyvak Railpod III, 6U NLAS, 12U Deployer	3U, 6U, 12U	Dimensions, Weight, Rail	Interface Control Documentation
Planetary Sciences Corporation	3U, 6U, 12U	Dimensions, Weight, Tabs	Interface Guide, CAD Drawings

ISIPOD ISIS CubeSat Shop	1U, 2U, 3U, 4U, 6U, 8U, 12U, 16U	Dimensions, Weight, Rail	Follows CubeSat Standard

6.2.3 Mechanisms

There are several companies offering mechanisms for small spacecraft. Although not exhaustive, this section will highlight a few devices for release actuation, component pointing, and boom extension, which represent the state-of-the-art for the CubeSat market. Please refer to the Deorbit Systems chapter for deployable mechanisms used for deorbit devices.

Composite Technology Deployment (CTD): Deployable Booms

CTD has developed a composite boom called the Stable Tubular Extendable Lock-Out Composite (STELOC), that is rolled up or folded for stowage and deploys using stored strain energy. The slit-tube boom, shown in figure 6.6 employs an innovative interlocking SlitLock™ edge feature along the tube slit that greatly enhances stability. The boom can be fabricated in many custom diameters and lengths, offers a small stowed volume, and has a near-zero coefficient of thermal expansion (CTE) (15). This technology has flown in low-Earth orbit.

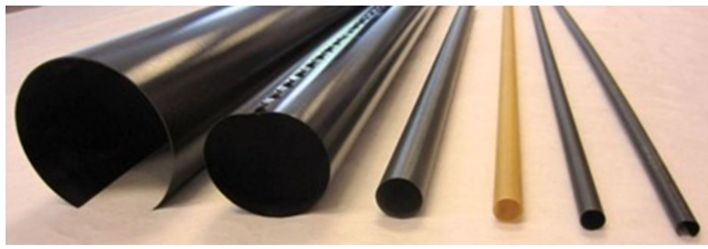


Figure 6.6: CTD's Deployable Composite Booms. Credit: Composite Technology Development.

AlSat-1N: AstroTube Deployable Boom

Oxford Space Systems collaborated with the Algerian Space Agency to develop the AstroTube deployable boom (figure 6.7) that was recently demonstrated in low-Earth orbit on a 3U CubeSat called AlSat-1N. It is the longest retractable boom that has been deployed and retracted on the 3U CubeSat platform. It incorporates a flexible, composite structure for the 1.5 m-long boom element, and a novel deployment mechanism for actuation. When retracted, the boom is housed within a 1U volume and has a total mass of 0.61 kg (16).

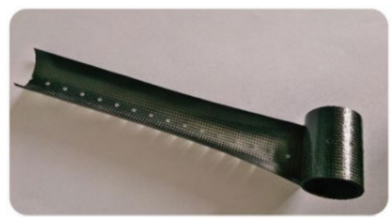


Figure 6.7: The flexible composite member that is employed on the AstroTube. Credit: Oxford Space Systems.

Redwire Space: Deployable Booms and Manipulators

Redwire Space (previously ROCCOR) has developed several different deployable booms that have a wide range of applications on small spacecraft. The Roll Out Composite (ROC) Booms are designed to deploy instruments or provide deployment force and structure to antennas, solar arrays, and other system architectures. These booms are 1 – 5 m in length and are fabricated from fiber reinforced polymer composites and can be tailored to meet a wide range of requirements for stiffness, force output, thermal stability, etc. These booms can also be made either motor driven, or strain energy driven, and some versions have features for harness management. Furthermore, several versions of these booms can be made to retract on-orbit. There are currently three ROC Booms in orbit, with other systems awaiting launch in 2022 (17).

The CubeSat ROC Boom Deployer was developed for magnetometer applications, using a similar high strain composite slit-tube boom, however it is implemented in a different way (17). The CubeSat ROC Boom Deployer is root rolled and motorized while the ROC-FALL system is tiprolled and passively deployed. The CubeSat ROC Boom Deployer is awaiting a launch opportunity to reach TRL 7.

Redwire Space's family of robotic manipulators provide a wide range of capabilities, including 5 to 7 DOF, 1 to 4 m reach, and 8 to 65 kg mass, supporting a variety of orbital and lunar surface applications. The robotic arms are built from a suite of modular interchangeable elements, enabling variable reach, torque applications, configuration, and grappling capabilities. This technology is primarily for ESPA class satellites.

NASA: Deployable Composite Boom (DCB)

NASA Langley Research Center (LaRC) has developed DCBs through the Space Technology Mission Directorate (STMD) Game Changing Development (GCD) program and a joint effort with the German Aerospace Center. DCBs have high bending and torsional stiffness, packaging efficiency, thermal stability, and a low weight of less than 25% compared to metallic booms (18). The Advanced Composite Solar Sail project (ACS3) will demonstrate DCB technology for solar sailing applications. The DCB/ACS3 7 m boom technology is extensible to 16.5 m deployable boom lengths (figure 6.8).

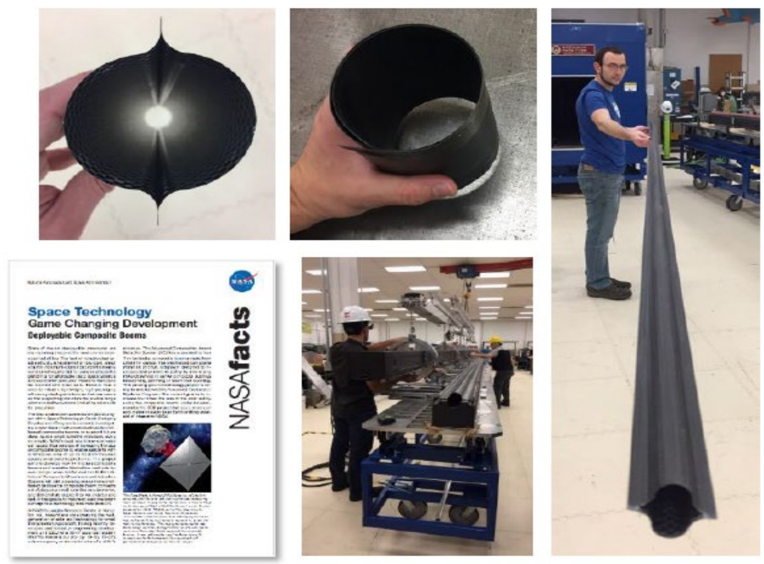


Figure 6.8: NASA Deployable Composite Boom (DCB) Technology. Credit: NASA.

RSat-P and RECS: Robotic Arms

Repair Satellite-Prototype (RSat-P) is a 3U CubeSat that is part of the Autonomous On-orbit Diagnostic System (AMODS) built by the US Naval Academy Satellite lab to demonstrate capabilities for on-orbit repair systems (19). RSat-P uses two 60 cm extendable robotic arms with the ability to maneuver around a satellite to provide images and other diagnostic information to a ground team. RSAT-P launched with the ELaNaXIX Mission in December 2018 and was lost during initial deployment. The robotic development has continued with the Naval Academy Satellite Team for Autonomous Robotics (NSTAR) Robotic Experimental Construction Satellite (RECS), a 3U CubeSat, which will demonstrate the robotic arm capabilities in the ISS microgravity environment in late 2021 (20). The RECS robotic arms were built using 3D Windform print technology. Figure 6.9 shows the robotic arms from RSAT CubeSat heritage that are being developed further for RECS.

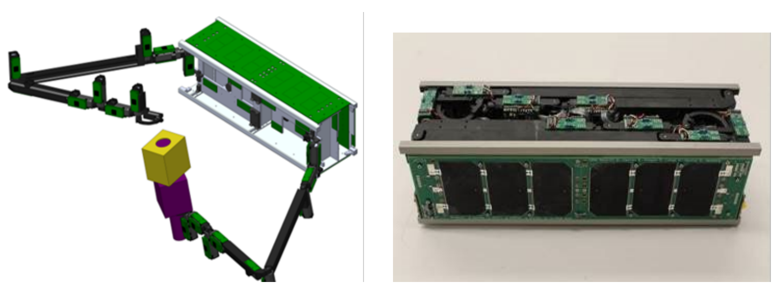


Figure 6.9: Robotic Experimental Construction Satellite (RECS). Credit: The Naval Academy.

Tethers Unlimited, Inc.: 3 DOF Gimbal Mechanism

Tethers Unlimited offers a three degrees of freedom (3DOF) gimbal mechanism called the Compact On-Board Robotic Articulator (COBRA) that has two available configurations. A few of the varying specifications are found in table 6-4, and the HPX configuration is shown in figure 6.10. This mechanism provides accurate and continuous pointing for sensors and thrusters (21).

Five COBRA gimbals have been deployed on-orbit over the past year, providing precision pointing for optical and high frequency RF satellite crosslinks on private small spacecraft missions.

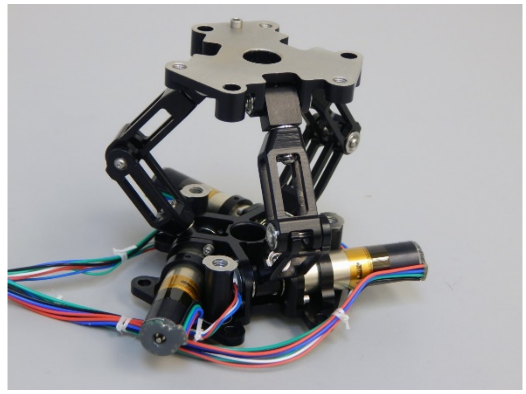


Figure 6.10: COBRA-HPX. Credit: Tethers Unlimited, Inc.

The KRAKEN robotic arm is modular, with high-dexterity (up to 7 DOF) and will enable CubeSats to perform challenging missions, such as in-orbit assembly, satellite servicing, and debris capture. The standard configuration is a 1 m arm that can stow in a 190 x 270 x 360 mm volume with a mass of 5 kg. The TRL for this system is 6, assuming a low-Earth orbit environment (22).

Table 6-4: Tethers Unlimited COBRA Specifications

	COBRA-UHPX	COBRA-HPX
Mass (kg) (with launch locks)	0.491	0.276
Stowed diameter footprint (mm)	165	113
Deployed Height (excl. launch locks)	85.5	73.5
Operating Temperature Range (°C)	-35 to +70	-35 to +70
Power Consumption	Load Dependent	2.4 W
Payload Capacity	0.5 kg in 1G	1.2 kg in zero-G
Actuator	22 mm BLDC Motor	12 mm Stepper Motor
TRL in LEO	9	9

The COBRA-Bee carpal-wrist mechanism was developed for the NASA Astrobee-- a small, free-flying robot that assists astronauts aboard the ISS. The COBRA-Bee gimbal can enable Astrobee to precisely point and position sensors, grippers, and other tools (23). COBRA-Bee is a small-scale, tightly integrated COTS product, that can provide precise multi-purpose pointing and positioning with an interface to support third-party sensors, end-effectors, and tools.

Honeybee: Solar Panel Drive Actuator

Honeybee, in cooperation with MMA, has developed a CubeSat Solar Array Drive Actuator (SADA) that accommodates ±180° single-axis rotation for solar array pointing, can transfer 100 W of power from a pair of deployed panels, and features an auto sun-tracking capability (14). Honeybee also offers the unit in a slip-ring configuration for continuous rotation. Table 6-5 highlights a few key specifications for this actuator. As of 2021, the SADA is in high-rate production for the OneWeb satellite internet constellation (24).

Table 6-5: Honeybee CubeSat SADA Specifications	
Mass (slip ring option)	0.18 kg
Backlash	< 3°
Operating Temperature Range (°C)	-30 to +85
Size	100 x 100 x 6.5 mm
Radiation Tolerance	10 kRad
Wire Wrap (7 channels per wing)	@ 1.4 A per channel
Slip Ring (10 channels per wing)	@ 0.5 A per channel
TRL	9
Reference Mission(s)	OneWeb

Ensign-Bickford Aerospace & Defense

EBAD's TiNi™ product line has a full array of small and reusable non-pyrotechnic actuators suitable for SmallSats. In particular, the Mini Frangibolt® and MicroLatch are suitable for CubeSat deployers or other high loading mechanical release mechanisms.

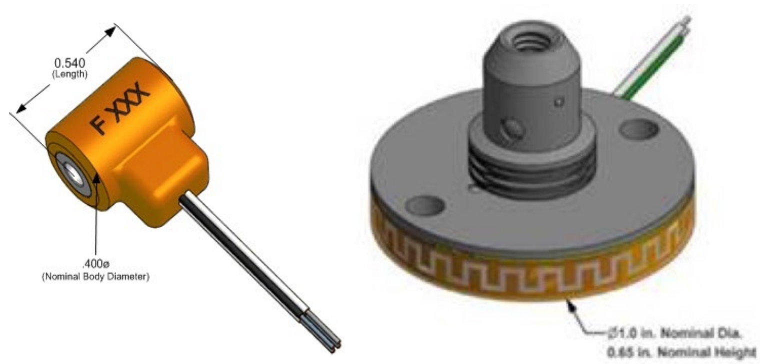


Figure 6.11: (left) TiNi Aerospace Frangibolt Actuator and (right) ML50 microlatch. Credit: Ensign-Bickford Aerospace & Defense.

The Frangibolt operates by applying power to a Copper-Aluminum-Nickel memory shape alloy cylinder which generates force to fracture a custom notched #4 fastener in tension. The Frangibolt is intended to be reusable by re-compressing the actuator using a custom tool and replacing the notched fastener (25), and it has operated in low-Earth orbit on Pumpkin™ CubeSat buses. The ML50 Micro Latch is designed to release loads up to 50 lbf (222.4 N) and is capable of supporting forces up to 100 lbf (445 N) during maximum launch conditions. A standard interface uses a 4 – 40 thread to attach a bolt or stud to the releasable coupling nut. Field resetting of the device is done simply by ensuring no more power is being sent to the device, placing the coupler back on the device, and hand pressing it until the coupler engages with the ball locks (25). Figure 6.11 shows a model of the FD04 Frangibolt actuator and a picture of the ML50 microlatch, and table 6-6 describes a few key specifications of both mechanisms.

Table 6-6: Ensign-Bickford Aerospace & Defense Release Mechanisms			
TiNi™ FD04 Frangibolt Actuator		**TiNi™ ML50 Specifications**	
Mass (kg)	0.007	**Mass (kg)**	0.015
Power C	15 W @ 9 VD	**Power/Operational Current**	1.5 A to 3.75 A
Operating Temperature Range (°C)	-50 to +80	**Operating Temperature Range (°C)**	-50°C to +60
Size	13.72 x 10.16 mm	**Max Release Load**	222.4 N
Holding Capacity	667 N	**Max Torque**	106 N mm
Function Time Typically	20 sec @ 9 VDC	**Function Time Typically**	120 ms @ 1.75A (23°C)
Life	50 cycles MIN	**Life**	50 cycles MIN
TRL	9	**TRL**	9

6.3 State-of-the-Art – Additive Manufacturing (AM)

Additive manufacturing processes for primary spacecraft structures have long been proposed; only recently such methodologies have been adopted for flight. However, it is important to note that AM has become common for smallsat secondary structural elements for many years. Typically, the advantage of AM is to free the designer from constraints imposed by standard manufacturing processes and allow for monolithic structural elements with complex geometry. In practice, additive manufacturing has a separate design space and design process, which has seen tighter integration into computer-aided design, computer-aided manufacturing, and modal and structural analysis packages in the past few years. Such tools can enable quicker turnaround times for smallsat development. This is instrumental in mass optimization, the potential for using AM materials in radiation shielding, and high-throughput, high-quality manufacturing. As the AM field is rapidly evolving, this section makes a best attempt to cover as many materials and printers as possible that are potentially applicable to SmallSat development.

6.3.1 Applicability of TRL to Polymer AM

While AM systems and platforms might be considered mature and of high TRL, the TRL of AM parts configured for spaceflight depends on the material, the configuration of the actual part, the manufacturing process of the material, the postprocessing of the manufactured part, the testing and qualification process, and many other factors. For example, nylon fabricated with a fused filament fabrication (FFF) system will have different bulk structural properties from nylon fabricated with a selective laser sintering system.

In other words, a TRL might be assignable to a component created through a particular manufacturing process with a specific material. If a particular component manufactured with nylon on an FFF system was flown to low-Earth orbit successfully, the TRL for this component would be 7. If this component was subsequently flown on another mission manufactured with Antero 840 PEEK also on an FFF system, the TRL would still be 7. Documentation of the manufacturing process is important to properly account for TRL. This section focuses on polymer AM and does not address metal AM for SmallSats.

Inspection and Testing

When new materials and/or processes are used, testing shall be performed to minimize risk by lowering the gap between jumps in TRL. In particular, the only way to validate what the structure, component, or material is being tailored for is through testing, especially if more freedom is allocated to research and development. For new material types, if there is latitude afforded in upfront research and development, mechanical, modal, and thermal tests should be performed to compare against a known, proven structural design.

6.3.2 Thermoplastics and Photopolymers

With the expansion of available open-source AM platforms in the last decade, thermoplastics and photopolymer materials have rapidly gained traction and acceptance in many applications ranging from mechanical validation and fit-checking to engineering-grade, low-rate production products. Photopolymer or “thermoset” resins, and the associated manufacturing processes, have improved to the point where microfluidics experiments may be additively manufactured, where microfluidics channels and growth chambers are directly manufactured as one piece, as opposed to the more traditional microfluidics approach of machining a plastic block.

As of publication, there are three primary methods of conducting AM for plastics: FFF, which uses thermoplastics in either a spool or pellet form; stereolithography (SLA), which uses photopolymer resin; and selective laser sintering (SLS), which uses a fine powder. Within SLA, there are two methods of curing resin: digital light projection (DLP), which uses a very high-resolution LED matrix – a monochrome display – to nearly instantly cure the entire layer; and polyjets, which deposit resin from a line array of jets, much like an inkjet printer with a large print head.

Certain thermoplastics are quickly gaining acceptance for high-reliability parts and applications on Earth; though, as of writing, this has yet to be seen in widespread acceptance in any space application. A factor in this is the lack of ability to produce surfaces as smooth as machined metals, in which the latter is required for parts with tight tolerances. However, some thermoplastics are machinable, such as Nylon or polyetherimide (PEI). Similar to the manufacture of cast iron parts, machining to a final, high tolerance specification may allow these thermoplastics to further gain more acceptance.

Except for some large-format AM centers, almost all thermoplastics are manufactured in spools, and may or may not be packaged for proprietary solutions. For SLA, almost all resins are used specifically for commercial solutions and AM centers. Additionally, some manufacturers may mix in additives to enhance material properties or ease the printing process. Because of this, the following sections on each material include a table of materials for both open-source and commercial solutions, and selected properties of interest. Availability of recommended nozzle and bed temperature is indicative of the ability to be printed on an open-source machine, except otherwise noted in the material description. Materials are not picked according to preference but picked through availability of technical specifications and potential applicability. Readers are encouraged to use these sections as a rough guide for commercially available filaments at the time of writing for either type of AM solutions. Additionally, the material tables will be expanded as more data is obtained on the following materials.

Surface discharges, or electrostatic discharge (ESD), is a result of in-space charging effects and are caused by interactions between the in-flight plasma environment and spacecraft materials and electronic subsystems (26). The field buildup and ESD can negatively affect the spacecraft and there are design precautions that must be taken depending on the environment in which the spacecraft will be operating. Per ESD guidelines from NASA Spacecraft Charging Handbook 4002A, dielectric materials above 10^{12} Ohm (Ω) cm should be avoided because charge accumulation occurs regardless. Please refer to the NASA Handbook 4002A, 5.2.1.5 Material Selection for more information. Historically, ESD due to faulty grounding has been a leading cause of spacecraft or subsystem failures (26). Volume resistivity and dielectric constant are two material properties used to determine charge dissipation for the evaluation of electrostatic discharge risk in the space environment (26). Please refer to NASA Handbook 4002A, Appendix D.7 "Dielectric Constant, Time Constant" page 138 for determining the leakage time constant.

Polylactic Acid (PLA)

PLA is the most common filament used in AM and table 6-7 lists several PLA filaments. It exhibits very low shrinkage and is extremely easy to print because it does not require a heated bed or build chamber and requires a relatively low extruder (nozzle) temperature. It also has low offgassing during printing, important in open-frame AM systems in rapid prototyping environments such as lab settings. Unless the application has a very short-term exposure to harsh conditions, and if the conditions are well characterized and controlled, it is not recommended to use PLA for an application beyond TRL 3-4. For laboratory settings in controlled environments not subject to excessive mechanical forces, ESD-compatible filaments are available.

Table 6-7: Polylactic Acid Filaments

Filament Name (Citation)	ISO 75/ASTM D648 Deflection Temp (°C)	ISO 179-1 Hardness (kJ/m^2) or Izod D256-10A (J/m)	ISO 527-1/ASTM D638 ZX Tensile strength (MPa)	ASTM D790/ISO 178 Flexural strength (MPa)	Nozzle Temp (°C)	Bed Temp (°C)	Density (g/cc)	Volume Resistivity (Ω-cm)
Prusament PLA	55	12 kJ/m^2	57	N/A	215	50-60	1.24	--
Verbatim PLA	50	16 kJ/m^2	63	N/A	210	50-60	1.24	--
ColorFabb PLA-PHA (27)	N/A	30 kJ/m^2	61	89	210	50-60	1.24	--
Stratasys PLA (28)	51	27 kJ/m^2	26	84	N/A	N/A	1.264	10^{15}
3DXSTAT™ ESD-PLA	55	N/A	55	95	210	23-60	1.26	10^6-10^9

Acrylonitrile Butadiene Styrene (ABS)

ABS has traditionally been the choice for higher strength, lightweight prints from the Fused Deposition Modeling (FDM) process in the open-source community. It is generally temperature resistant and UV resistant, but turns yellow and eventually becomes more brittle over time when exposed to sunlight. It is a marginally difficult filament to print, especially in open-frame systems. High temperature gradients during printing may cause warping as parts get larger. Enclosed AM systems with heated chambers print ABS well. Additionally, ABS shrinks 1 to 2 percent of its printed size upon cooling – the shrinkage varies from manufacturer to manufacturer. ABS has flown as the complete structure for KickSat-2, a FemtoSat deployer for chip-scale satellites (68). The single-use, short mission duration, and intricate dispenser frame made a conventionally machined deployer mass- and cost-prohibitive. Table 6-8 lists some examples of ABS filaments.

Table 6-8: ABS Filaments

Filament Name	ISO 75/ASTM D648 Deflection Temp (°C)	ISO 179-1 Hardness (kJ/m^2) or Izod D256-10A (J/m)	ISO 527-1/ASTM D638 Tensile strength (MPa)	ASTM D790/ISO 178 Flexural strength (MPa)	Nozzle Temp (°C)	Bed Temp (°C)	Density (g/cc)	Volume Resistivity (Ω-cm)
Stratasys ABS-CF10	100	20-51 J/m	21	29-69	N/A	N/A	1.0972	10^4-10^9
Stratasys ABS-ESD7	105	36.2 J/m	35	44	N/A	N/A	1.07	10^4-10^9
3DXSTAT™ ESD-ABS	97	N/A	58	80	230	110	1.09	10^6-10^9
Verbatim ABS	106 (ISO 306)	21 J/m	47	78	240-260	90	1.05	--

Nylon

Versatile and tough, there are multiple formulations for nylon that allow for a very wide range of applications and material properties. In general, nylon is more difficult to manufacture than ABS on open-source FFF systems due to the need for an enclosure for thermal stability and additional bed preparation due to the need for higher adhesion. Secondary structural pieces have been flown through the TechEdSat program using Markforged Onyx carbon fiber filaments. Table 6-9 lists some examples of nylon filaments.

Table 6-9: Nylon Filaments

Filament Name (Citation)	ISO 75/ASTM D648 Deflection Temp (°C)	ISO 179-1 Hardness (kJ/m^2) or Izod D256-10A (J/m)	ISO 527-1/ASTM D638 ZX Tensile strength (MPa)	ASTM D790/ISO 178 Flexural strength (MPa)	Nozzle Temp (°C)	Bed Temp (°C)	Density (g/cc)	Volume Resistivity (Ω-cm)
Taulman3D Alloy 910 (29)	82	N/A	56	N/A	250-255	30-65	N/A	--
Taulman3D Alloy 910 HDT (29)	112	N/A	56	N/A	285-300	55	N/A	--
Taulman3D Nylon 680 Food Grade (30)	N/A	N/A	47	N/A	250-255	30-65	N/A	--
Markforged Onyx ESD 316)	138	44 J/m	52	83	N/A	N/A	1.2	10^5-10^7
3DXTECH CARBONX™ HTN+CF (32)	240	N/A	87	95	295	130	1.24	10^9
Stratasys Nylon 12 (33)	92-95	71-138 J/m	33-42	55-57	N/A	N/A	1.01	10^{13}

Polycarbonate (PC)

Also known as Lexan™, this thermoplastic has some of the highest impact resistance, tensile strength, and temperature resistance available for most open source-based AM systems. After manufacturing, it is dimensionally stable and very stiff. However, it is difficult to print on open-frame, open-source AM systems due to very high warping especially when printing large components. Very high bed and nozzle temperatures are required, and poor adhesion to the bed is a typical issue. It is also highly hygroscopic; if possible, filament should be baked out before printing, or should be kept in a dedicated dry box while printing. Certain filaments, like the Prusament PC Blend, have additives to mitigate some of the difficulties of printing PC. If PC is desired for a smallsat structure, it should be printed on a commercial AM system. Table 6-10 lists some polycarbonate filaments.

Table 6-10: Polycarbonate Filaments								
Filament Name (Citation)	ISO 75/ASTM D648 Deflection Temp (°C)	ISO 179-1 Hardness (kJ/m^2) or Izod D256-10A (J/m)	ISO 527-1/ASTM D638 ZX Tensile strength (MPa)	ASTM D790/ISO 178 Flexural strength (MPa)	Nozzle Temp (°C)	Bed Temp (°C)	Density (g/cc)	Volume Resistivity (Ω-cm)
Prusament PC Blend (34)	113	No break for ISO 179	63	88-94	275	110	1.22	--
Prusament PC Blend Carbon Fiber (35)	114	35 kJ/m^2	55-65	85-106	285	110	1.16	--
Stratasys PC (36)	143	27-77 J/m	60	75	N/A	N/A	1.20	--

Windform

Manufactured by CRP USA, these proprietary materials are classified as a carbon fiber reinforced polymer originally designed for the automotive racing industry. They are unique in that these composites are manufactured through SLS (43). This results in higher dimensional stability and more isotropic properties than FFF. Windform XT 1.0 and 2.0 have been used on CubeSat and PocketQube platforms and have flight heritage through KySat-2 launched on ELaNa IV, and TANCREDO-1, launched through the ISS via JEM in 2017 (37). Table 6-11 lists CRP Windform filaments.

Table 6-11: CRP Windform								
Filament Name (Citation)	ISO 75/ASTM D648 Deflection Temp (°C)	ISO 179-1 Hardness (kJ/m^2) or Izod D256-10A (J/m)	ISO 527-1/ASTM D638 ZX Tensile strength (MPa)	ASTM D790/ISO 178 Flexural strength (MPa)	Manufacturing process	Bed Temp (°C)	Density (g/cc)	Volume Resistivity (Ω-cm)

Windform XT 2.0 (38)	173	4.72 kJ/m^2	84	133	N/A, SLS	N/A, SLS	1.097	10^8
Windform RS (39)	181	10.8 kJ/m^2	48-85	139	SLS	SLS	1.10	10^8

Polyetherimide

PEI, also known by the Saudia SABIC trade name Ultem™, is a very tough thermoplastic resin with high thermal and chemical stability. It is inherently flame-resistant and can be machined. Some formulations of PEI are FAA-approved for flame, smoke, and toxicity (FST), and may also have ESD formulations. PEI is also known for extremely low offgassing, crucial in optical and sensitive scientific packages. PEI is a common bed material for higher end open-source FFF systems due to its adhesive properties with other thermoplastics at higher temperatures. PEI has similar characteristics to polyetheretherketone (PEEK). Due to these similarities, PEI is only practically printable on commercial FFF systems. Table 6-12 lists some PEI filaments.

Table 6-12: PEI Filaments

Filament Name (Citation)	ISO 75/ASTM D648 Deflection Temp (°C)	ISO 179-1 Hardness (kJ/m^2) or Izod D256-10A (J/m)	ISO 527-1/ASTM D638 ZX Tensile strength (MPa)	ASTM D790/ISO 178 Flexural strength (MPa)	Nozzle Temp (°C)	Bed Temp (°C)	Density (g/cc)	Volume Resistivity (Ω-cm)
THERMAX™ Ultem™ 9085	158	N/A	63	90	275	115	1.34	--
3DXSTAT™ Ultem™ 1010 CF-ESD (40)	205	N/A	62	115	395	150	1.34	10^7-10^9
Stratasys Ultem™ 1010 CG (41)	212	22-27 J/m	81	82-128	N/A	N/A	1.29	10^{14}
Stratasys Ultem™ 9085 (41)	153	39-88 J/m	69	80-98	N/A	N/A	1.27	10^{15}
Zortrax Z-PEI 9085 (42)	186	N/A	54	90	N/A	N/A	1.34	--

PAEK

Polyetheretherketone (PEEK) and polyetherketoneketone (PEKK) – in the polyaryletherketone (PAEK) family – are the highest performing thermoplastics developed as of writing. With certain additives and matrix materials, they can rival the strength of stainless steel and withstand over 200°C continuously in some formulations, after annealing. PEEK/PEKK are naturally flame-retardant; they are accepted for use in aviation ducting. They also achieve extremely low offgassing in operation, which makes these thermoplastics good candidates for compatibility with optical components in space. Due to the extreme conditions required for manufacturing and the very high filament cost, these materials are only practically available for printing in extremely robust commercial FFF systems with sealed and heated chambers. PEEK has heritage on long-term, external ISS experiments, and structural elements on the Juno spacecraft, making it suitable for extreme radiation environments (42). Table 6-13 lists some PAEK-based filaments.

Table 6-13: PAEK-based Filaments

Filament Name (Citation)	ISO 75/ASTM D648 Deflection Temp (°C)	ISO 179-1 Hardness (kJ/m²) or Izod D256-10A (J/m)	ISO 527-1/ASTM D638 ZX Tensile strength (MPa)	ASTM D790/ISO 178 Flexural strength (MPa)	Nozzle Temp (°C)	Bed Temp (°C)	Density (g/cc)	Volume Resistivity (Ω-cm)
3DXSTAT™ ESD-PEEK (44)	140	N/A	105	141	380-400	150	1.32	10^7-10^9
3DXSTAT™ ESD-PEKK	185	N/A	109	135	375	140	1.34	10^7-10^9
CarbonX™ CF PEKK-Aerospace	285	N/A	126	178	390	140	1.33	10^7
Stratasys Antero 840 (45)	150	28-43 J/m	95	87-139	N/A	N/A	1.27	10^4-10^9
Zortrax Z-PEEK (42)	160	N/A	100	130	N/A	N/A	1.30	--

Photopolymers

Otherwise known as “thermosets,” these materials are liquid polymers cured by an optical and thermal process. Compared to other AM processes, photopolymers and their manufacturing processes allow for superior isotropic material properties, very high resolution, and the ability to manufacture optical quality parts. Some formulations, especially from 3D Systems and Stratasys, are designed for extreme temperature resistance and strength, desirable in aerospace applications. In some cases, the listed heat deflection temperature (HDT) may be superior to those of PAEK. As previously discussed, there are three major methods of curing photopolymers, one of which is proprietary. Many photopolymers are specifically paired for commercial systems. As a result, the following table includes the commercial system associated with the photopolymer.

Some of the photopolymers listed below have several additional characteristics not listable in this table, including, but not limited to, elasticity, tear strength, optical clarity, water absorption, and medical grade certifications. Such characteristics may be useful for biological experiments in future SmallSats. Please consult the products' specific websites and datasheets for additional information. Additionally, photopolymers have the advantage of being able to be mixed, in-situ, as the object is being manufactured. This allows for continuously varying material properties throughout the object. Table 6-14 lists some photopolymers.

Table 6-14: Photopolymers

Photopolymer Name (Citation)	ISO 75/ASTM D648 HDT (°C)	ISO 179-1/ASTM D256-10A (J/m)	ISO 527-1/ASTM D638 Tensile (MPa)	ASTM D790 Flexural (MPa)	Density (g/cc) at 25°C	ESD Risk (Ω-cm)	Manufacturing and/or Machine Type
Accura Bluestone (46)	267-284	13-17	66-68	124-154	1.78	ND	3D Systems ProX 800
VisiJet M2S-HT250 (47)	250	10	51	83	1.15	ND	3DS MJP 2500 Plus
DSM Somos® Watershed XC	50	25	50	69	1.12	ND	Stratasys V650 Flex SL
Henkel LOCTITE® IND402 A70 Flex (48, 49)	N/A	N/A	5.5	N/A	1.068	ND	Several
Henkel LOCTITE® 3D 3843 (48)	80	54	60	81	N/A	ND	DLP SLA types only

6.3.3 AM Design Optimization

Design optimization is an integral part of manufacturing validation and testing. As previously discussed for AM, validation, testing, and optimization encompass all materials and manufacturing processes. Software platforms, especially those that integrate toolpathing generation, computer aided manufacturing (CAM), load analysis, and fill generation, help speed up this process. The inherent advantage of AM to allow monolithic structural elements implies a much-expanded design space compared to subtractive manufacturing. Software has kept up with the pace of manufacturing advances and incorporates tools to assist with AM designs.

The manufacturing ecosystem includes software ranging from simple CAM solutions generating toolpaths (G-code) to complete, structural analysis and high-fidelity manufacturing simulations. As of writing, AM has gained significant traction and value in low-TRL demonstrations and physical validation, partly due to the ease of fabrication in typical AM ecosystems. It is beginning to displace traditional machining – "subtractive" manufacturing – as AM systems have matured enough to print advanced thermoplastics, resins, and metals.

Infill Patterns

Due to the flexibility that AM offers, new methods of lightweighting are now possible. "Lightweighting" refers to the reduction of mass of structural elements, without compromising structural integrity. The best examples of well-proven heritage methods of lightweighting are "honeycomb" sandwiched aluminum panels, subtractive machining, and truss structures. However, such methods have certain limitations. Honeycomb panels for example, do not have uniform, or isotropic, properties – they do not exhibit the same stiffness in all directions.

Lightweighting in AM encompasses what is called "infill," or the internal structure of a hollow body or panel. With a minimal increase in mass, an internal structure manufactured with AM can vastly increase the strength of a body. Very recently, the AM community has renewed interest in the use of the gyroid pattern, discovered by NASA researcher Alan Schoen in 1970, due to the ease of generation in AM toolpath programs. Aside from honeycomb and gyroids, several options for infill exist. Different options are offered with different AM-focused software packages.

Digital Materials

Both honeycomb panels and AM parts with infill have a common repetitive unit cell. By repeating this unit cell throughout the interior of a part, or as a structure on its own, a larger structure can be made. Further, by defining properties into this unit cell, information can effectively be encoded into the design, allowing for differing behavior of different parts of the structure. Digital materials can dramatically expand the design space of a structure, allowing for targeted optimization of various properties such as mass to strength ratios, structural lightweighting, and others. As previously discussed, with certain resin polyjet AM centers, resins can be mixed in real time to form an object that has continuously varying properties.

6.4 Radiation Effects and Mitigation Strategies

6.4.1 Shielding from the Space Environment

Radiation Shielding has been described as a cost-effective way of mitigating the risk of mission failure due to total ionizing dose (TID) and internal charging effects on electronic devices. In space mission analysis and design, the average historical cost for adding shielding to a mission is below 10% of the total cost of the spacecraft (50). The benefits include reducing the risk of early total ionizing dose electronics failures (51). Some of the key CubeSat and SmallSat commercial electronic semiconductor parts include processors, voltage regulators, and memory devices, which are key components in delivering science and technology demonstration data (52).

Shielding the spacecraft is often the simplest method to reduce both a spacecraft's ratio of total ionizing dose to displacement damage dose (TID/DDD) accumulation, and the rate at which single event upsets (SEUs) occur if used appropriately. Shielding involves two basic methods: shielding with the spacecraft's pre-existing mass (including the external skin or chassis, which exists in every case whether desired or not), and spot/sector shielding. This type of shielding, known as passive shielding, is only very effective against lower energy radiation, and is best used against high particle flux environments, including the densest portions of the Van Allen belts, the Jovian magnetosphere, and short-lived solar particle events. In some cases, increased shielding is more detrimental than if none was used, owing to the secondary particles generated by highly penetrating energetic particles. Therefore, it is important to analyze both the thickness and type of materials used to shield all critical parts of the spacecraft. Due to the strong omni-directionality of most forms of particle radiation, spacecraft need to be shielded from the full 4π steradian celestial sphere. This brings the notion of "shielding-per-unit-solid-angle" into the design space, where small holes or gaps in shielding are often only detrimental proportionally to the hole's solid angle as viewed by the concerned electrical, electronic and electro-mechanical (EEE) components. Essentially, completely enclosing critical components should not be considered a firm design constraint when other structural considerations exist.

6.4.2 Inherent Mass Shielding

Inherent mass shielding consists of using the entirety of the pre-existing spacecraft's mass to shield sensitive electronic components that are not heavily dependent on location within the spacecraft. This often includes the main spacecraft bus processors, power switches, etc. Again, the notion of "shielding-per-unit-solid-angle" is invoked here, where a component could be well shielded from its "backside" (2π steradian hemisphere) and weakly shielded from the "front" due to its location near the spacecraft surface. It would only then require additional shielding from its front to meet operational requirements. The classic method employed here is to increase the spacecraft's structural skin thickness to account for the additional shielding required. This is the classic method largely due to its simplicity, where merely a thicker extrusion of material is used for construction. The disadvantage to this method is the material used, very often aluminum, is mass optimized for structural and surface charging concerns and not for shielding either protons/ions or electrons. Recent research has gone into optimizing structural materials for both structural and shielding concerns and is currently an active area of NASA's Small Business Innovation Research (SBIR) program research and development.

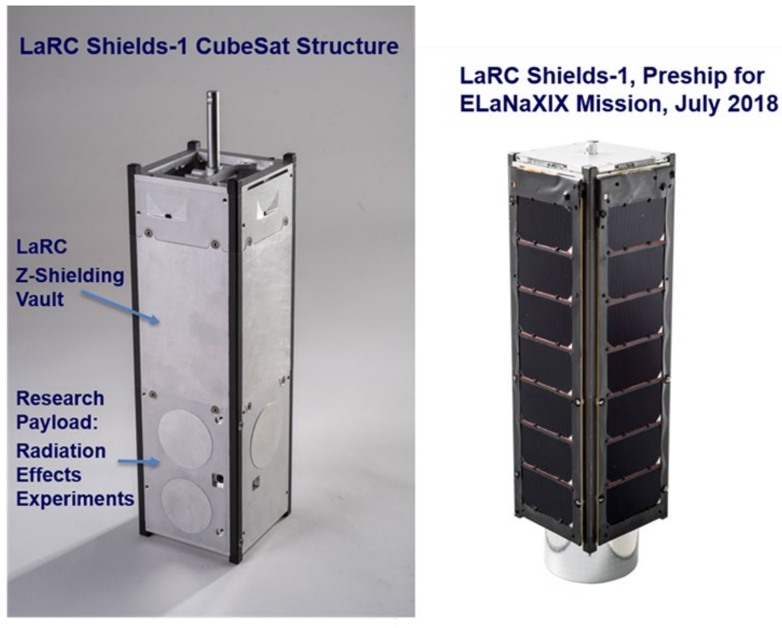
The process to determine exactly how much inherent shielding exists involves using a reverse ray tracing program on the spacecraft solid model from the specific point(s) of interest. After generating the "shielding-per-unit-solid-angle" map of the critical area(s) of the spacecraft, a trade study can be performed on what and where best to involve further additional shielding.

Numerous CubeSat and SmallSat systems use commercial, processors, radios, regulators, memory, and SD cards. Many of these products rely on silicon diodes and metal oxide semiconductor field effect transistors (MOSFETs) in these missions. A comprehensive NASA guidance document on the use of commercial electronic parts was published for the ISS orbit, which is a low-Earth orbit where the predominant radiation source is the South Atlantic Anomaly. The hardness of commercial parts was noted as having a range from 2 – 10 kRad (54). For typical thin CubeSat shielding of 0.20 cm (0.080 in) aluminum, yearly trapped dose is 1383 Rad; with an additional estimated 750 Rad from solar particle events, the total dose increases to 2133 Rad for the ELaNaXIX Mission environment at 85 degrees inclination and 500 km circular orbit (table 6-9) (53). Adding a two-fold increase for the trapped belt radiation uncertainty brings the total radiation near the TID lifetime of many commercial parts (54), even before estimating a SPE TID contribution. The uncertainty of radiation model results of low-earth orbit below 840 km has been estimated as at least two-fold; Van Allen Belt models are empirical and rely on data in the orbital environment (55). The NASA Preferred Reliability Series "Radiation Design Margin Requirements" also recommends a radiation design margin of 2 for reliability (56). Currently, The

Aerospace Corporation proton (AP) (57) and The Aerospace Corporation electron (AE) (58) Models do not have radiation data below 840 km, and radiation estimates are extrapolated for the lower orbits (55). For spacecraft interplanetary trajectories near the sun or Earth, the radiation contributions from SPEs will be higher than low-Earth orbit, where there is some limited SPE radiation protection by the magnetosphere. By reducing the total ionizing dose on commercial parts, the mission lifetimes can be increased by reducing the risk of electronic failures on sensitive semiconductor parts.

6.4.3 Shields-1 Mission, Radiation Shielding for CubeSat Structural Design

Shields-1 has operated in polar low-Earth orbit and was launched through the ELaNaXIX Mission in December 2018. The Shields-1 mission increased the development level of atomic number (Z) Grade Radiation Shielding with an electronic enclosure (vault) and Z-grade radiation shielding slabs with aluminum baselines experiments (figure 6.15) (59). Preliminary results in table 6-9 show a significant reduction in total ionizing dose in comparison to typical modeled 0.20 cm (0.080 in) aluminum structures sold by commercial CubeSat providers. The 3.02 g cm^{-2} Z-Shielding vault has over 18 times reduction in total ionizing dose compared to modeled 0.20 cm aluminum shielding (53).



Shields-1 structure and Final Preship Picture with LaRC Z-Shielding Vault and Experiment, Solar Panels and Thermal Radiator

Figure 6.15: Shields-1 Z-shielding structure and final Preship picture, ELaNaXIX Mission. Credit: NASA.

Z-shielding enables a low volume shielding solution for CubeSat and SmallSat applications where reduced volume is important. AlTiTa, Z–shielding, at 2.08 g cm^{-2} reduces the dose from a SPE by half when compared to a standard 0.2 cm aluminum structure (figure 6.16). NASA has innovated "Methods of Making Z-Shielding" with patents in preparing different structural shieldings (60-63), from metals to hybrid metal laminates and thin structural radiation shielding, to enable low-volume integrated solutions with CubeSats and SmallSats (64).

Table 6-9. Shields-1 Experimental Total Ionizing Dose Measurements in PLEO

Shielding	Areal Density (g/cm^2)	Thickness (cm)	Trapped Belts TID Total (Rad (Si)/Year)	SPE King Sphere Model, (Rad (Si))
Al	0.535	0.198	1383+/-47 #	750+/-5
Al	1.26	0.465	**90.9 +/-2.7 (SL)**	432 +/- 7

Al	1.69	0.624	**84.3 +/-2.5 (SL)**	345 +/- 9
Al	3.02	1.11	**73.6 +/-3.2 (SL)**	183 +/- 11
AlTi	1.33	0.378	**89.7 +/-2.7 (SL)**	451 +/- 6
AlTiTa20	2.08	0.429	**84.3 +/-2.5 (SL)**	338 +/- 6
AlTiTa40	3.02	0.483	**81.9 +/-3.4 (SL) 75.6+/- 3.2 (Vault)**	253 +/- 6

Table 6-9. Shields-1 Experimental total ionizing dose measurements in PLEO in comparison to typical 0.20 cm aluminum shielding commercially available for CubeSats and SPE additional contributions to dose. ***Bold values*** *Shields-1 experimental results. SL = Slab, Vault = Z-Shielding electronics enclosure. # sphere Space Environment Information System (SPENVIS) Multi-layered Shielding Simulation Software (MULASSIS) AP8 Min AE8 Max modeled results. SPE King Sphere Model SPENVIS MULASSIS modeled results.*

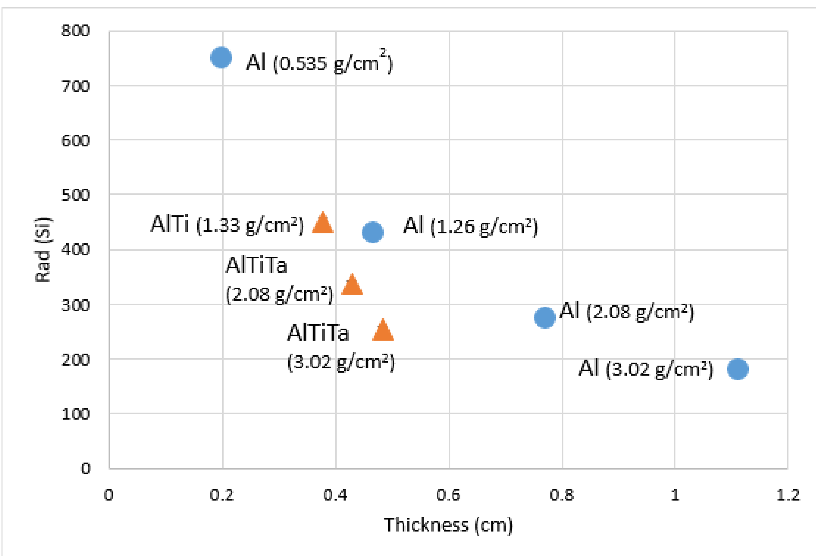


Figure 6.16: SPE Contribution to TID in PLEO, King Sphere Model, ELaNaXIX Shields-1 orbit. Credit: NASA.

6.4.4 Ad Hoc Shielding

There are two types of ad hoc shielding used on spacecraft: spot shielding, where a single board or component is covered in shield material (often conformally), and sector shielding, where only critical areas of the spacecraft have shielding enhancement. These two methods are often used in concert as necessary to further insulate particularly sensitive components without unnecessarily increasing the overall shield mass and/or volume. Ad hoc shielding is more efficient per unit mass than inherent mass shielding because it can be optimized for the spacecraft's intended radiation environment while loosening the structural constraints. The most recent methods include: multiple layer shields with layer-unique elemental atomic numbers which are layered advantageously (often in a low-high-low Z scheme), known as "graded-Z" shielding, and advanced low-Z polymer or composite mixtures doped with high-Z, metallic micro-particles. Low-Z elements are particularly capable at shielding protons and ions while generating little secondary radiation, where high Z elements scatter electrons and photons much more efficiently. Neutron shielding is a unique problem, where optimal shield materials often depend on the particle energies involved. Commercial options include most notably Tethers Unlimited's VSRS system for small spacecraft, which was specifically designed to be manufactured under a 3D printed fused filament fabrication process for conformal coating applications (a method which optimizes volume and minimizes shield gaps).

6.4.5 Charge Dissipation Coating

The addition of conformal coatings over finished electronic boards is another method to mitigate electrostatic discharge on sensitive electronic environments. Arathane, polyurethane coating materials (65), and HumiSeal acrylic coatings (66) have been used to mitigate discharge and provide limited moisture protection for electronic boards. This simple protective coating over sensitive electronic boards supports mission assurance and safety efforts. Charge dissipation films have decreased electrical resistances in comparison to standard electronics and have been described by NASA as a coating that has volume resistivities between 10^8 – 10^{12} ohm-cm. In comparison, typical conformal coatings have volume resistivities from 10^{12} – 10^{15} ohm-cm (26).

6.4.6 LUNA Innovations, Inc. XP Charge Dissipation Coating

The XP Charge Dissipation Coating has volume resistivities in the range of 10^8 – 10^{12} ohm-cm (table 6-9) and is currently developing space heritage through the NASA MISSE 9 mission and Shields-1 (67). The XP Charge Dissipation Coatings were developed through the NASA SBIR program from 2010 to present for extreme electron radiation environments, such as Outer Planets, medium Earth, and geostationary orbits, to mitigate charging effects on electronic boards.

Table 6-10: XP Charge Dissipation Coating and Commercial Conformal Coating Resistivity Comparisons

Material	Volume Resistivity (Ohm-cm)
XP Charge Dissipation Coating	10^8 – 10^{12}, 4.7 x 10^9 at 25°C
Arathane 5750 A/B	9.3 X 10^{15} at 25°C, 2.0 X 10^{13} at 95°C
Humiseal 1B73	5.5 x 10^{14} Ohms (Insulation Resistance per MIL-I-46058C)

Figure 6.17: Transparent LUNA XP Charge Dissipation Coating on an Electronic Board. Credit: LUNA Innovations, Inc.

The LUNA XP Charge Dissipation Coating has reduced resistance compared to typical commercial conformal coatings as shown in table 6-10, which reduces surface charging risk on electronic boards. LUNA XP Coating (figure 6.17) on an electronic board has transparency for visual parts inspection. For extreme radiation environments, a combination of radiation shielding and charge dissipation coating reduces the ionizing radiation that contributes to charging and provides a surface pathway for removing charge to ground (26).

6.5 Summary

The Structures, Materials, and Mechanisms chapter was revised in 2020 to include custom structure references with the dimensional and material requirements of integrating deployment systems. The chapter has been updated with the current status of structures, materials, and mechanisms for small satellite missions. The Mechanisms section has been updated with new technology. In 2020, a radiation environment section was revised with radiation shielding considerations for orbits and solar maximum with references for commercial parts and radiation design margin. State-of-the-art radiation shielding and charge dissipation materials have been updated.

Reflecting the fast pace of developments in additive manufacturing, a new section was added in 2021 with a wide sampling of available thermoplastics and resin-based materials suitable for different TRL levels. To complement additive manufacturing, a new section was added to bring attention to the increasing importance of design optimization.

For feedback solicitation, please email: arc-sst-soa@mail.nasa.gov. Please include a business email so someone may contact you further.

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