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Glossary

(ABS)	Acrylonitrile Butadiene Styrene
(ACS3)	Advanced Composite Solar Sail System
(AE)	Aerospace Corporation Electron
(AM)	Additive manufacturing
(AMODS)	Autonomous On-orbit Diagnostic System
(AP)	Aerospace Corporation Proton
(CAM)	Computer Aided Manufacturing
(CFRP)	Carbon Fiber Reinforced Polymers
(CNC)	Computerized Numerical Control
(COBRA)	Compact On-Board Robotic Articulator
(COTS)	Commercial-off-the-shelf
(CSLI)	CubeSat Launch Initiative
(CTD)	Composite Technology Deployment
(CTE)	Coefficient of Thermal Expansion
(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
(MOSFETs)	Metal Oxide Semiconductor Field Effect Transistors
(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
(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
(TID)	Total Ionizing Dose
(TRAC)	Triangle Rollable and Collapsible
(TRL)	Technology Readiness Level
(ULA)	United Launch Alliance

6.0 Structure, Mechanisms, and Materials

6.1 Introduction

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.

Additive manufacturing (AM) has increased custom structural solutions for SmallSats and demonstrated high throughput of complex structures. Materials that were once out of reach of AM are now readily available in higher end systems. 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, and 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 becomes 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.

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 instruments 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.

Small satellite mechanisms have advanced with deployable structures, actuators, and switches. Deployable structures enable large structural applications with minimal volume requirements. Actuator and switch mechanisms expand the capabilities of small satellites with motion and deployment applications. These mechanisms enable increased small satellite capabilities beyond original structural volume constraints.

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

6.2.1 CubeSat Standard

Two general approaches are common for primary structures, often called frames or chassis, 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.

Table 6-1: CubeSat Standard Structure Dimensions

Type	Dimension (mm)	Average Weight (kg)
1U	100 x 100 x 113.5	0.118
1.5U	100 x 100 x 170.2	0.142
2U	100 x 100 x 227	0.220
3U	100 x 100 x 340.5	0.352
6U	100 x 226.3 x 366	0.916
12U	226.3 x 226.3 x 366	1.84

The CubeSat standard structure has evolved with increasing use over many years. The CubeSat standard structures, also referred to as canisterized satellites, include 1U, 1.5U, 2U, 3U, 6U, and 12U. Table 6-1 shows the nominal weight limits and dimensions of each CubeSat structure from the CubeSat Design Specification document. There is an extra volume (XL) option available for

3U, 6U, and 12U CubeSats; this additional volume, commonly referred to as the "tuna can" volume, is associated with an individual dispenser type. This cylindrical XL additional space allows for structural extensions of the CubeSat that can be used for various components. Steamjet Space has developed Steam Thruster, a tuna can-sized electrochemical thruster specifically designed for CubeSats. The 3U CubeSat Elfin mission used this tuna can space for antenna deployment. Shields mission also fit a radiator within its tuna can volume. Figure 6.1 shows this optional volume and location on the CubeSat.

There are several companies that provide CubeSat primary structures. Most are machined from aluminum alloy 6061 or 7075 and are designed with several mounting locations for components to allow flexibility in spacecraft configuration. The SmallSat community has witnessed an increase in CubeSat standard configuration over the last 10 years from 1U to 3U, to include 6U and 12U. This was due to a higher demand for more science on a smaller platform, and by the need for more volume to design more complex CubeSats that can handle greater responsibility. Table 6-2 lists several commercial primary CubeSat structures. Of the offerings included here, 1U, 3U and 6U frames are most prevalent, however 12U frames are becoming more widely available as there are now more dispensers for the 12U CubeSat structure. Figure 6.2 shows some commercial examples of 3U, 6U and 12U CubeSat structures.

8U and 16U CubeSat Structure

Following the trend of larger CubeSat structures that is driven by the needs of the SmallSat market, several companies are now offering CubeSat structures not officially recognized by the CubeSat standard such as the 8U and 16U. Customized dispensers are available that will host these larger volumes.

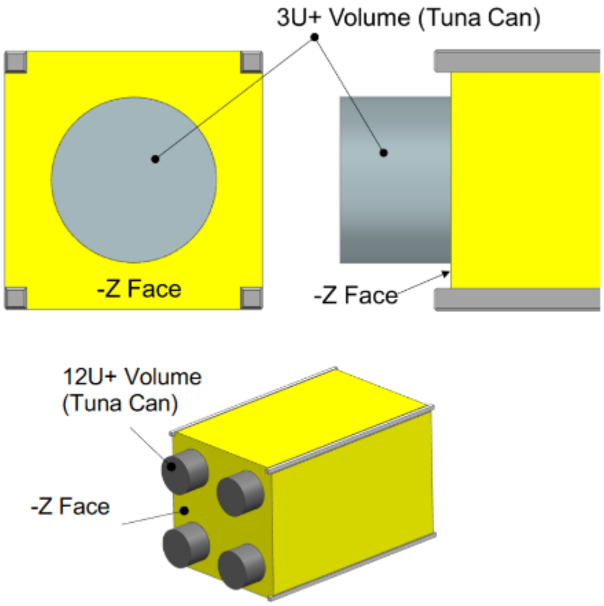


Figure 6.1: Optional Extra Volume shown on 3U and 12U –Z Face (also known as a "Tuna Can"). Credit: Cal Poly CubeSat Laboratory.

Figure 6.2: Various commercial CubeSat structures. Top Left: NanoAvionics 3U Structure. Credit: NanoAvionics. Top Right: 6U nanosatellite structure. Credit: GomSpace. Lower Left: 12U Structure. Credit: C3S Electronics Development, LLC. Lower Right: 16U structure. Credit: EnduroSat.

Table 6-2: Commercial Primary CubeSat Structures

Manufacturer	Structure (U)
AAC Clyde Space	ZAPHOD 1U, 2U, 3U, 6U, 12U
C3S Electronics Development LLC	3U/3U Plus, 6U, 12U, 16U
Cervos Space	1U, 2U, 3U, 6U
Cosats Satellite Technology	COSTR 1U, 1.5U, 3U, 6U, 8U,12U, 16U
EnduroSat	1U, 1.5U, 3U, 6UXL, 8U 12UXL, 16U
German Orbital Systems	1U, 2U, 3U, 6U, 12U
GomSpace	3U, 6U, 8U, 12U, 16U
Gran Systems	1U, 1.5U, 2U, 3U, 6U, 6UXL
Gumush	n-ART 1U, 2U, 3U
ISISPACE	1U, 2U, 2UXL, 3U, 6U, 8U, 12U, 16U
Ishitoshi Machining	MBF-1U, 3U
NanoAvionics	1U, 2U, 3U, 6U, 12U, 16U
Pumpkin Space Systems	Supernova 1U, 3U, 6U, 12U
NPC Spacemind	SM 1U, 1.5U, 2U, 3U, 6U, 12U
Nara Space Technology	12U, 16U

6.2.2 Custom CubeSat 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.

DiskSat Structure

The Aerospace Corporation is developing a DiskSat (figure 6.3) demonstration flight with support from NASA's Space Technology Mission Directorate (STMD). The DiskSat is a 1-m circular disk, 2.5 cm thick, graphite-epoxy composite sandwich, with a structural mass less than 3 Kg/m^2. The volume is close to 20 liters, which is equivalent to a hypothetical '20U' spacecraft. While the entire volume will not be filled, the increased surface area is useful for power, aperture, thermal management, and for manufacturing simplification. First launch for the demonstration mission is planned for 2024 (2).

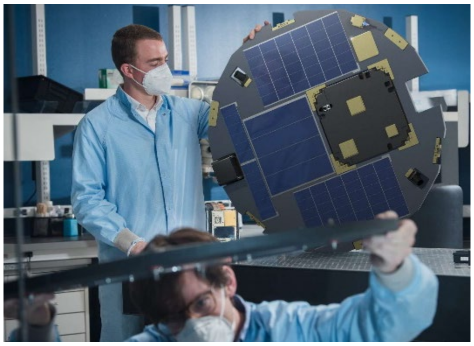


Figure 6.3: DiskSat structure. Courtesy of and reprinted by permission of The Aerospace Corporation.

6.2.3 Primary Structure Standard Dispenser

The box that houses the CubeSats in the launch vehicle is called a dispenser (or deployer), and they dispense (or deploy) the CubeSat into the desired orbit. The CubeSat uses the entire volume of the dispenser to make use of its full capacity. Since the CubeSat adopts a standard size and form factor, CubeSat dispensers have also been standardized with two constraint systems: rail- or tab-type. This allows spacecraft designers and launch service providers to minimize launch integration cost, increase access to space, and sustain frequent launches (3). The CubeSat Design Specification document by the CubeSat Program at Cal Poly was created to provide CubeSat developers baseline requirements that are compatible with as many CubeSat dispensers and launch opportunities as possible to eliminate launch interface failures (4). To view the most updated versions of the CubeSat Design Specification, please visit: http://www.cubesat.org. The CubeSat Design Specification document includes rail systems. The Canisterized Satellite Dispensers (CSD) tab system created by Planetary Systems Corporation (now Rocket Lab) is the most widely available tab dispenser that offers design flexibility for structures that do not require the use of rails. See CSD datasheet for detailed information on tab dispenser (5).

A tab-style canister deployment system uses tabs that are loaded to hold the CubeSat to a wall of the canister which are released upon deployment. The vibrational load during launch passes from the launch vehicle to the canister structure with the pre-loaded CubeSat. A CubeSat using a rail dispenser is lightly loaded on the z-axis. On the x and y axis a thin gap exists between the rail of the dispenser and rails on the CubeSat which can cause vibrational chatter. The vibrational chatter adds to the mechanical load of the CubeSat during testing and launch. For more CubeSat rail vs tab dispensers, please refer to Chapter 10: Launch, Deployment, Integration, and Orbital Services.

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 (6). 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. In response to the demand for larger CubeSats, dispensers for 12U CubeSats are now available through several launch service providers like NanoRacks and United Launch Alliance (ULA) through the Atlas series. There are several European companies providing deployment for 16U platforms that expand the limits of the CubeSat Design Specification. The DSOD, EXOpod, and the Quad Pack are all dispensers that can fit a single 16-unit CubeSat platform or several smaller CubeSats.

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

Manufacturer	U	Requirements	Available Documents
P-POD by Cal Poly	1U, 3U	Dimensions, Weight, Rail	Follows CubeSat Standard (4)
CSD by Planetary Systems Corp.	1U, 3U, 6U, 12U	Dimensions, Weight, Tab	
Tyvak Railpod III, 6U NLAS, 12U Deployer	3U, 6U, 12U	Dimensions, Weight, Rail	Interface Control Documentation (8)
PSC by Rocket Lab	3U, 6U, 12U	Dimensions, Weight, Tabs	Interface Guide, CAD Drawings (5)
ISIPOD ISISPACE	1U, 2U, 3U, 4U, 6U, 8U, 12U	Dimensions, Weight, Rail	Follows CubeSat Standard (7)
Gran Systems MyPOD Deployer and Test PODs	3U, 6U	Dimensions, Weight, Rail	Website (9)
Dhruva Space CubeSat Deployers DSOD	1U, 3U, 6U, 12U, 16U	Dimensions, Weight, Rail	Website (10)
Exolaunch EXOpod CubeSat Deployer	1U, 2U, 3U, 6U, 8U, 12U, 16U	Dimensions, Weight, Rail	User Manual (11)

6.2.4 CubeSat Structures Construction Methods

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 computerized numerical control (CNC) machining, waterjet, or laser cutting.

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 required. 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.

6.3 State-of-the-Art – Mechanisms

Spacecraft commonly contain onboard devices whose function are based on mechanical movement (i.e.: slide, roll, rotate, separate, unfold, or spin) to either modify part of the spacecraft's geometry or to ensure operational function of a component or instrument. These devices are known as mechanisms, and as spacecraft become more sophisticated with the advances in miniaturization of electronics and systems, their reliance of mechanisms greatly increases.

The domain of spacecraft mechanisms is quite broad as there are many different types in the design and life of a spacecraft that include the moving parts associated in each phase:

- Deployment: dispensing spacecraft into orbit

- Beginning of mission life: deployments of solar arrays, booms, antennas, instrumentation, etc.
- Mission maintenance: sun tracking, pointing antennas and instruments, active doors or shields, gyroscopes and reaction wheels, thrusters, etc.
- End-of-life: deorbiting methods

The technology within the mechanism to perform the movement is accomplished with an actuator. Depending on the actuation method, spacecraft mechanisms are either passively or actively driven. Passive mechanisms do not consume electric energy and provide driving power via spring load, and active mechanisms are motorized to produce driving power for mechanism operation. Most mechanisms can use both passive and active capabilities depending on the application. Table 6-4 provides an overview of common spacecraft mechanisms and examples of technologies used.

The state-of-the-art of small spacecraft mechanisms is quantified on their high reliability, low power, and light weight characteristics, and the common mechanisms listed below are considered state of the art for small spacecraft use. For the purposes of this chapter, the mechanisms focus on deployable extensions, robotic manipulations, release actuation, component pointing, and gimbal mechanisms. Reliability considerations are provided for optimal operational capabilities, as well as a brief explanation of the factors that affect spacecraft mechanisms.

Table 6-4: Type of Spacecraft Mechanisms

Type of Mechanism	Description	Technology Examples
Separation and Release	Reliable stowage and release of spacecraft and deployable components upon an external command (active) or spring-loaded (passive).	Clamp band systems, Frangibolts, release nuts, pin pullers, bolts, burn wire, hinges, and passive spring-loaded switches
Motorized	Allows for rotatory motion of spacecraft components.	Solar Array Drive Assembly, directional antennas, combination of dampeners and absorbers
Attitude Control	Provides pointing accuracy and stability for spacecraft and components.	Reaction (momentum) wheel assembly, gimbals, component pointing, passive methods

6.3.1 Actuators

By classical definition, actuators are devices that convert electrical, thermal, hydraulic, and/or pneumatic energy into mechanical motion when said energy is allowed to flow. Active, or commanded, actuators use onboard data links and electrical transistors to determine the transfer of energy; whereas passive, or reactive, actuators allow the spacecraft environment (including external launch systems) to dictate actuator energy transfer. Table 6-5 provides some commercial actuators.

Specifically, spacecraft actuators are used for a variety of purposes, including:

- Attitude control and gimbaling: to control the orientation of either part (gimbaling), or all (attitude control), of a spacecraft in space. This is important for pointing sensors, instruments, and/or communications antennas in a direction required for their use.
    - Attitude control general types: reaction control thrusters, momentum wheels, control moment gyros, magnetic torquers, aerodynamic control surfaces, solar sails, and gravity gradient stabilizers.

  - Gimbal general types: single-axis, dual-axis, and triple-axis system.
- Propulsion: supporting attitude control system operations, maneuvering to a new orbit, or reducing orbital velocity to begin atmospheric reentry.
  - General types: chemical rocket engines (which can be the same as the upper stage launch vehicle engines), reaction control thrusters, and electric propulsion systems. These systems typically require actuated valves to operate.
- Deployment, docking and separation: extend and unfold solar panels, antennas, and other spacecraft components requiring unpacking to function.
  - Deployment general types: hinge-&-spring based, linear-actuator-&-scissor-frame based, roll-out systems, and inflatable structures.
  - Docking general types: probe-and-drogue, peripheral, and soft-capture systems.
  - Separation general types: spring-powered or gas-powered systems.
- Thermal control: manage all or part of the spacecraft's temperature. This is important for protecting internal components from extreme temperatures.
  - General types: louvers, heat pipes, thermoelectric/Peltier devices, and pumped thermal fluid systems.

Mechanical actuation methods/techniques that are found in many of the above systems include:

- Electric & electromagnetic: AC/DC motor, piezoelectric ceramics, and push/pull & rotary solenoids (including solenoid valves), and microelectromechanical systems (MEMS).
- Thermal & thermoelectric: Shape memory alloys (SMA), phase-change liquids/solids (paraffin wax, liquid metals), thermofluidic gas systems, thermal bimorph structures, harmonic drive micro actuators (HMAs), thermal knife cutters, and magnesium alloy band systems.

Figure 6.4: (top left) SADM 1500. Credit: Comat. (right) TiNi Aerospace Frangibolt Actuator and (right) ML50 microlatch. Credit: Ensign-Bickford Aerospace & Defense.

Table 6-5: Commercial Actuators

Manufacturer	Product	Mass (Kg)	Size (mm)	Power Consumption	Actuation method	Ref
Ensign-Bickford Aerospace & Defense Company	TiNi™ FD04 Frangibolt	0.007	13.72x10.16	15 W @ 9 VD	SMA	(13)
Ensign-Bickford Aerospace & Defense Company	TiNi™ ML50	0.015		-	SMA	(14)
Moog	Type 2 Side-Drive Solar Array Drive Mechanism (SADM)	5	234x278.6	15	-	(15)
Honeybee and MMA Design	Solar Array Drive Actuator (SADA)	3.1	127x210	-	Stepper Motor	(16)
Comat Space	Solar Array Drive Mechanism - 400	0.465	83x62x46	4	Geared motor	(17)
Comat Space	Solar Array Drive Mechanism - 1500	3.5	201x132	13	Geared motor	(18)
DHV Technology	MicroSADA-10	<0.25	100x100x100	-	Stepper motor	(19)
DHV Technology	MicroSADA-18	<0.95	226x80x18	-	Stepper motor	(19)
DCUBED	Micro Pin Puller (uD3PP)	0.08	25.5x25.5 x 25.5	-	SMA	(20)
DCUBED	Nano Pin Puller (nD3PP)	0.025	17x17x17	-	SMA	(20)
DCUBED	Micro Release Nut (uD3RN)	0.078	25x25x25	-	SMA	(21)
Beyond Gravity	Separation Nut PSM 3/8B	0.23	58.5x36x56	-	-	(22)
Revolv Space	Solar Array Rotary Actuator (SARA)	<0.35	97x97x23	1 W (average)	-	(23)
Nimesis Technology	Triggy	0.004-0.271	*	*	SMA	(24)

Data unknown is represented by -
* See reference

6.3.2 Deployable Structures

Space deployable mechanisms are structures folded into a compact configuration and deployed into a larger predetermined shape. The development of deployable structures on spacecraft is appealing to enable greater mission performance. Once deployed, the structures reconfigure, changing shape and size from folding and unfolding. Common spacecraft deployables include antennas, radiators, solar panels, gravity assists, and other science instruments. Small spacecraft are great candidates for using deployable structures to raise the functionality of a smaller platform. However, there are limited designs for compact, lightweight, low power deployable structures that can be folded or rolled up for launch and then self-deployed in space to support these kinds of systems on small satellites.

There are different types of deployment mechanisms to ensure the deployed structure effectively expands to the desired configuration in-orbit: folding, sleeve, truss, and inflatable. Deployable solar arrays are a common folded-type of passive deployment mechanism achieved by connecting the spring and hinge to increase solar energy for the spacecraft. Please refer to the *Power* chapter for deployable solar panels and arrays. The sleeve-type deployment mechanism is implemented using a rolling or sliding screw conveyor and is commonly seen on SmallSats for various antennas (24). Inflatable deployment structures are light-weight film material typically used for larger deployed structures, like solar sails. Please refer to the *Deorbit Systems* chapter for deployable mechanisms used for deorbit devices.

Figure 6.5: GPX-2 CAD image with gravity gradient boom deployed. Credit: NASA.

For SmallSat applications, it is common that deployable components are on a boom – a cantilever arm ejected from the spacecraft – that can perform various tasks once deployed. See figure 6.5 for NASA's GPX-2 CubeSat mission with a Redwire Space deployable boom to create gravity gradient stabilization as an example. SmallSat deployable structures are common and are associated with high reliability. Engineers have started developing deployables with different materials to decrease the stowage area, mass, and power. Table 6-6 lists a selection of commercially available deployable booms.

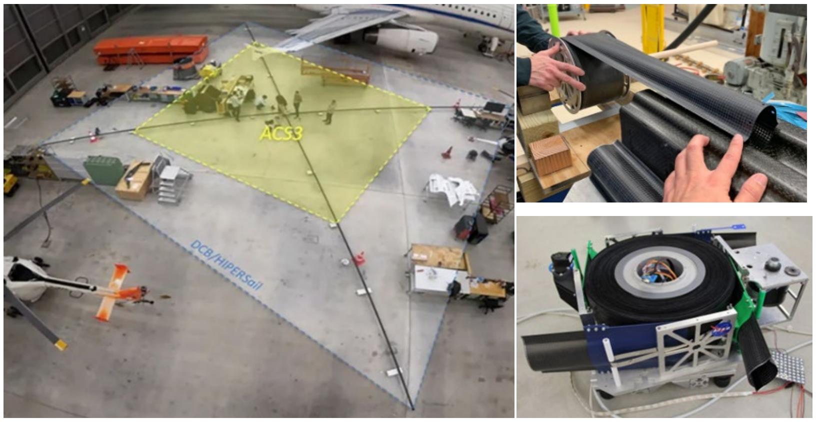


Figure 6.6: NASA Deployable Composite Boom (DCB) Technology. Credit: NASA.

NASA Langley Research Center (LaRC) has developed Deployable Composite Booms (DCB) through the Space Technology Mission Directorate (STMD) Game Changing Development (GCD) program and a joint effort with the German Aerospace Center, see figure 6.6. DCBs have high bending and torsional stiffness, packaging efficiency, thermal stability, and 25% less weight than metallic booms (25). The Advanced Composite Solar Sail System (ACS3) project will demonstrate DCB technology for solar sailing applications with an anticipated 2024 launch. The DCB/ACS3 7-m boom technology is extensible to 16.5 m deployable boom lengths (26).

Engineers have started using origami – the art of paper folding – as a strategy of deployable structure design. Origami structures are flexible in their deployment direction so that they can be easily collapsed along the same path they are deployed. One advantage of origami-inspired mechanisms is potentially faster and cheaper prototyping. Instead of relying on laser cutting or 3D-printing, prototyping of origami-inspired mechanisms can be accomplished using inexpensive materials like paper before moving to other more expensive materials. Many resources and patterns already exist that detail how designs can be created and modified or adapted for engineering purposes (27). Solar panels and arrays, solar sails, and sunshades are examples of ongoing origami engineered SmallSat components.

Table 6-6: Commercial Deployable Booms

Manufacturer	Product	Reference
Composite Technology Development	Stable Tubular Extendable Lock-Out Composite (STELOC)	(28)
Oxford Space Systems	AstroTube deployable boom	(29)
Redwire Space	Roll Out Composite (ROC) booms	(30)
Redwire Space	CubeSat ROC Boom Deployer	(31)
Redwire Space	ROC-FALL system	(31)
Magellan Aerospace	Deployable Boom	(32)
Rolatube Technology	Deployable Composite Booms	(33)

6.3.3 Robotic Manipulator

The need for in-space servicing is receiving more attention from the SmallSat community with the increasing demand of more complex SmallSat with greater capability and longer mission life. These types of challenges are being solved with robotic manipulations that can perform intricate actions in space. Tasks such as repairing defunct satellites, in-orbit assembly, satellite servicing, debris capture, spacecraft system up-keep, construction, and repair are important advances for future space operations; these challenges are currently expensive and risky to perform. Current robotic solutions for in-space construction and repair involve humans and use very large, expensive, custom-built robotic arms with limited capabilities, such as the Canadian Arm. As NASA’s Artemis program prepares for astronaut presence in lunar and deep space missions on the Lunar Gateway, there is a greater need for more advanced and maneuverable space robotic systems. The use of these sophisticated robotic systems on a SmallSat are more alluring than traditional larger platforms as SmallSats present a more cost-effective and agile solution. A more agile robotic system can be stowed in small space and deployed to perform several tasks automatically or semi-automatically.

This section provides an overview of the continuous work occurring to further develop robotic systems on SmallSats. Table 6-7 lists a non-exhaustive list of the ongoing work. This type of SmallSat mechanism is maturing with research and development at government, academia, and commercial entities (34). For example, the Naval Academy Satellite Team for Autonomous Robotics (NSTAR) has developed an autonomous 3U CubeSat robotic arm system called the Robotic Experimental Construction Satellite (RECS) to be tested on the ISS. RECS was launched November 2022 (35).

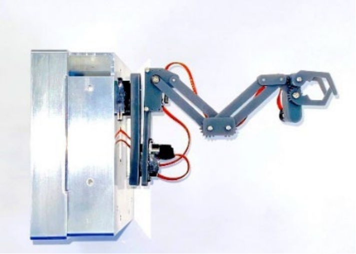


Figure 6.7: SLAC 1 Robotic Arm Credits: Sierra Lobo.

Table 6-7: Robotic Arms for Small Spacecraft

Manufacturer	Product	Mass (kg)	Extendable length (mm)	Stowed Envelope (mm)	DOF	Power Consumption (W)	Actuator method	Form Factor
U.S. Naval Academy	3U CubeSat with two robotic arms	4	600	300x100x100	6 plus "claw" end-effector actuation	-	Stepper motor	RECS 3U (Nov 2022)
Redwire Space	-	-	1 to 4 m reach	-	5 to 7	8 to 65	-	ESPA class satellites
Sierra Lobo	Sierra Lobo Arm (SLAC 1)	-	100x100x100	30x50x65	3	1.5	-	-

Data unknown is represented by -

6.3.4 Reliability Considerations

Mechanisms add capabilities and complexities to small satellite design. Additional integration and testing are required. NASA Reliability and Maintainability Standard (36) describes maintainability, and “test as you fly,” in addition to multiple other mitigation strategies and considerations. For mechanisms, it is important to test the full sub-system and system integration for power consumption and sub-system dependencies. Mechanisms have lifetimes, so it is important to have a maintainable mechanism and to understand the lifetime of the mechanism from test to flight. Because mechanisms add complexity and a single point failure risk in some instances, such as attitude control or solar panel pointing, directional antenna control, or one-time sub-system deployment switches, it is important to focus on reliability strategies. Mechanisms have contributed to over 10% of reported small satellite failures (37). Adding a mechanism to enable a mission increases risk.

The space environment adds to reliability considerations for operational considerations in vacuum, plasma, and/or thermal environments. For the reliability of mechanisms, there are multiple steps that contribute to risk mitigation. Sarafin et al. describes a multi-step approach for a reliable mechanism from design simplicity, margin, supplier selection, to test (38). The steps include guidance for torque margin for rotating parts, such as solar panel and antenna pointing motors (38)(39)(40). During ground testing of mechanisms, it is important to understand the mechanism lifetime, so that the component performs throughout the planned mission duration. Materials considerations contribute to mechanism reliability in the space environment, such as lubricant use and material coatings to avoid corrosion and welding of dissimilar materials (39)(40)(41). Because mechanisms are critical for advanced spacecraft capabilities for power, communications, and science/research instruments, it is important to add mechanism margin and tests to the spacecraft development and/or sub-system and system integration.

6.4 State-of-the-Art – Additive Manufacturing

Additive manufacturing (AM) processes for primary spacecraft structures have long been proposed but only recently have such methodologies been adopted for flight. AM has been 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, and have been instrumental in mass optimization, using AM materials in radiation shielding, and enabling 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.

6.4.1 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 LEO 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.

6.4.2 Inspection and Testing

When new materials and/or processes are used, testing must be performed to minimize risk and bridge the gap between TRL levels. In particular, the only way to validate a tailored structure, component, or material 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.

6.4.3 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 associated manufacturing processes have improved to the point where microfluidics experiments may be additively manufactured, with the microfluidics channels and growth chambers 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 cure the entire layer nearly instantly; 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, although, as of this writing, they have yet to gain widespread acceptance for space applications. One reason for this is AM methods cannot yet produce surfaces as smooth as machined metals, which is often a requirement for parts with tight tolerances. However, some thermoplastics are machinable, such as Nylon or polyetherimide (PEI). Like the manufacture of cast iron parts, machining to a final, high tolerance specification may allow these thermoplastics to gain further 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 through availability of technical specifications and potential applicability. For various types of AM solutions, readers are encouraged to use these sections as a rough guide for currently available commercial filaments. Additionally, the material tables will be expanded as more data is obtained on the following materials.

Surface discharge, or electrostatic discharge (ESD), is a result of in-space charging effects and is caused by interactions between the in-flight plasma environment and spacecraft materials and electronic subsystems (42). The field buildup and ESD can negatively affect the spacecraft and there are design precautions which must be considered depending on the spacecraft's operational environment. 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 (42).

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 off gassing 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)	ESD Risk* (Ω-cm)
Prusament PLA	55	12 kJ/m^2	57	N/A	215	50-60	1.24	No
Verbatim PLA	50	16 kJ/m^2	63	N/A	210	50-60	1.24	No
ColorFabb PLA-PHA (43)	N/A	30 kJ/m^2	61	89	210	50-60	1.24	No
Stratasys PLA (44)	51	27 kJ/m^2	26	84	N/A	N/A	1.264	No, 10^{15}
3DXSTAT™ ESD-PLA	55	N/A	55	95	210	23-60	1.26	Yes, 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 (45). 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)	ESD Risk (Ω-cm)
Stratasys ABS-CF10	100	20-51 J/m	21	29-69	N/A	N/A	1.0972	Marginal 10^4-10^9
Stratasys ABS-ESD7	105	36.2 J/m	35	44	N/A	N/A	1.07	Marginal 10^4-10^9
3DXSTAT™ ESD-ABS	97	N/A	58	80	230	110	1.09	Yes, 10^6-10^9
Verbatim ABS	106 (ISO 306)	21 J/m	47	78	240-260	90	1.05	No

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 because it requires an enclosure for thermal stability and additional bed preparation 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)	ESD Risk (Ω-cm)
Taulman3D Alloy 910 (46)	82	N/A	56	N/A	250-255	30-65	N/A	Unk
Taulman3D Alloy 910 HDT (46)	112	N/A	56	N/A	285-300	55	N/A	Unk
Taulman3D Nylon 680 Food Grade (47)	N/A	N/A	47	N/A	250-255	30-65	N/A	No
Markforged Onyx ESD (48)	138	44 J/m	52	83	N/A	N/A	1.2	Yes, 10^5-10^7
3DXTECH CARBONX™ HTN+CF (49)	240	N/A	87	95	295	130	1.24	Marginal 10^9
Stratasys Nylon 12 (50)	92-95	71-138 J/m	33-42	55-57	N/A	N/A	1.01	No, 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, the 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)	ESD Risk (Ω-cm)
Prusament PC Blend (51)	113	No break for ISO 179	63	88-94	275	110	1.22	No
Prusament PC Blend Carbon Fiber (51)	114	35 kJ/m^2	55-65	85-106	285	110	1.16	No
Stratasys PC (52)	143	27-77 J/m	60	75	N/A	N/A	1.20	No

Windform

Manufactured by CRP Technology, 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 (53). 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 (54). Table 6-11 lists CRP Windform filaments. The NASA GPX-2 Windform XT 2.0 structure launched in July 2022 and is operational.

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)	ESD Risk (Ω-cm)
Windform XT 2.0	173	4.72 kJ/m^2	84	133	N/A, SLS	N/A, SLS	1.097	Yes, 10^8
Windform RS (56)	181	10.8 kJ/m^2	48-85	139	SLS	SLS	1.10	Yes, 10^8

Polyetherimide

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 off gassing, crucial for optical components 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)	ESD Risk
THERMAX™ Ultem™ 9085	158	N/A	63	90	275	115	1.34	No
3DXSTAT™ Ultem™ 1010 CF-ESD (57)	205	N/A	62	115	395	150	1.34	Yes, 10^7-10^9
Stratasys Ultem™ 1010 CG(58)	212	22-27 J/m	81	82-128	N/A	N/A	1.29	No, 10^{14}
Stratasys Ultem™ 9085 (59)	153	39-88 J/m	69	80-98	N/A	N/A	1.27	No, 10^{15}
Zortrax Z-PEI 9085 (60)	186	N/A	54	90	N/A	N/A	1.34	No

PAEK

Polyetheretherketone (PEEK) and polyetherketoneketone (PEKK) – in the polyaryletherketone (PAEK) family – are the highest performing thermoplastics developed as of this 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 off gassing 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 (61). 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/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)	ESD Risk (Ω-cm)
3DXSTAT™ ESD-PEEK (62)	140	N/A	105	141	380-400	150	1.32	Yes, 10^7-10^9
3DXSTAT™ ESD-PEKK	185	N/A	109	135	375	140	1.34	Yes, 10^7-10^9
CarbonX™ CF PEKK-Aerospace	285	N/A	126	178	390	140	1.33	Yes, 10^7
Stratasys Antero 840 (63)	150	28-43 J/m	95	87-139	N/A	N/A	1.27	Yes, 10^4-10^9
Zortrax Z-PEEK (64)	160	N/A	100	130	N/A	N/A	1.30	N/A

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 table 6-14 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 (65)	267-284	13-17	66-68	124-154	1.78	ND	3D Systems ProX 800
VisiJet M2S-HT250 (66)	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 (67)	N/A	N/A	5.5	N/A	1.068	ND	Several
Henkel LOCTITE® 3D 3843 (68)	80	54	60	81	N/A	ND	DLP SLA types only

6.4.4 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 help speed up this process, especially those that integrate toolpathing generation, computer aided manufacturing (CAM), load analysis, and fill generation. 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 this 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.

6.5 Radiation Effects and Mitigation Strategies

6.5.1 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 (69). The benefits include reducing the risk of early total ionizing dose electronics failures (70). 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 (71).

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.

6.5.2 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; currently an active area of NASA's Small Business Innovation Research (SBIR) program research and development.

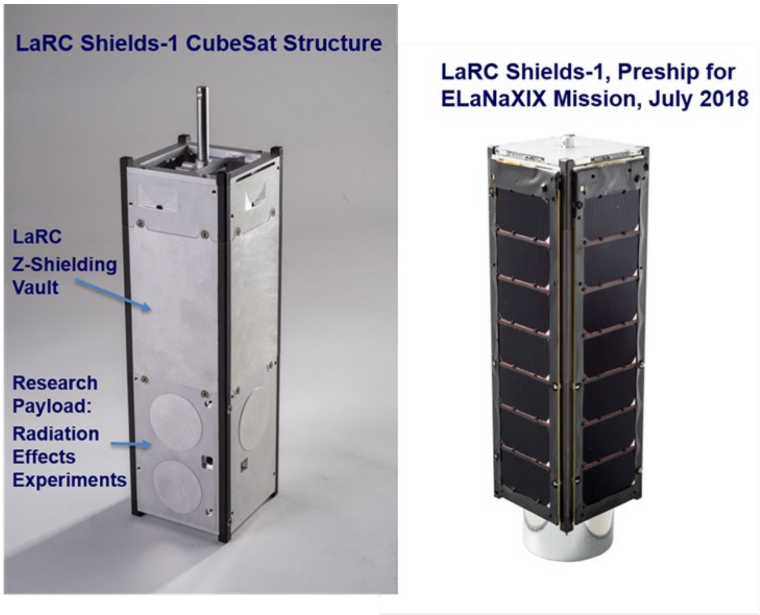
The process to determine exactly how much inherent shielding exists involves using a reverse ray tracing program on the spacecraft solid model from the specific point(s) of interest. After generating the "shielding-per-unit-solid-angle" map of the critical area(s) of the spacecraft, a trade study can 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 (73). 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 6-16) (74). Adding a two-fold increase for the trapped belt radiation uncertainty brings the total radiation near the TID lifetime of many commercial parts (73), 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 (75). The NASA Preferred Reliability Series "Radiation Design Margin Requirements" also recommends a radiation design margin of 2 for reliability (76). Currently, The Aerospace Corporation proton (AP) (63) and The Aerospace Corporation electron (AE) (78)

Models do not have radiation data below 840 km, and radiation estimates are extrapolated for the lower orbits (75). 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.

6.5.3 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 6.14) (79). Preliminary results in table 6-15 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 (74).



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

Figure 6.14: Shields-1 Z-shielding structure and final Preship picture, ELaNaXIX Mission. Credit: NASA.

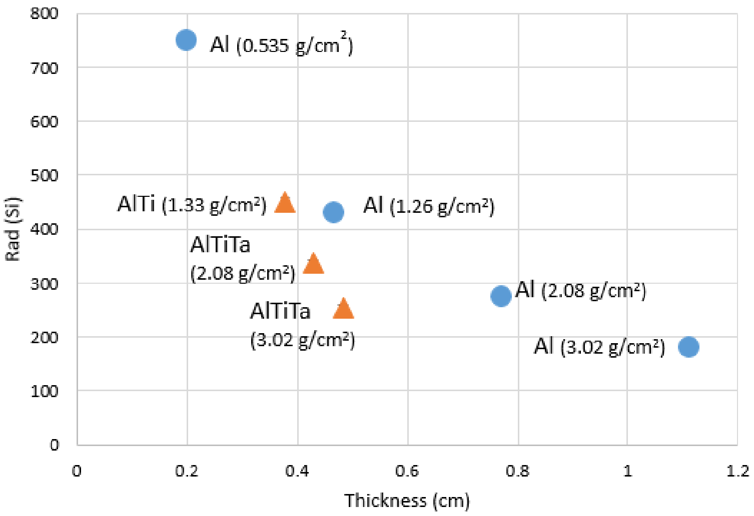


Figure 6.15: SPE Contribution to TID in PLEO, King Sphere Model, ELaNaXIX Shields-1 orbit. Credit: NASA.

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 6.15). NASA has innovated “Methods of Making Z-Shielding” with patents in preparing different structural shieldings (80)(81)(82)(83), from metals to hybrid metal laminates and thin structural radiation shielding, to enable low-volume integrated solutions with CubeSats and SmallSats (84).

Table 6-15: 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

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.*

6.5.4 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).

6.5.5 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 (85), and HumiSeal acrylic coatings (86) 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 (43).

6.5.6 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 6-16) and is currently developing space heritage through the NASA MISSE 9 mission and Shields-1 (86). 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 6-16: 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)

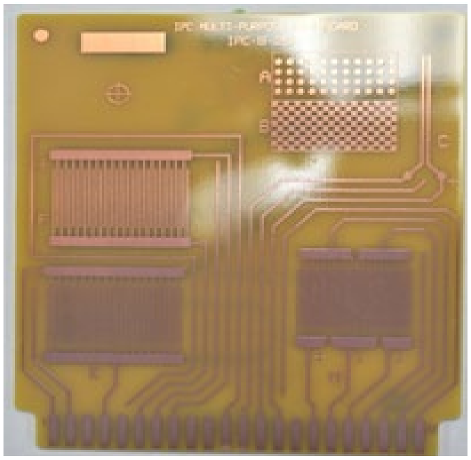


Figure 6.16: Transparent LUNA XP Charge Dissipation Coating on an electronic board. Credit: LUNA Innovations, Inc.

The LUNA XP Charge Dissipation Coating has reduced resistance compared to typical commercial conformal coatings, which reduces surface charging risk on electronic boards. LUNA XP Coating (figure 6.16) 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 (43).

6.6 Summary

This chapter has been updated with the current status of structures, materials, and mechanisms for small satellite missions. Additions include custom structure references with the dimensional and material requirements of integrating deployment systems, new mechanisms technology to reflect the ongoing growth in SmallSat mechanical devices, and more commercially procured deployable booms and larger CubeSat primary structures (12U and 16U), as well as the upcoming DiskSat structure. The radiation environment section, state-of-the-art radiation shielding, and charge dissipation materials have been updated. Reflecting the fast pace of development in additive manufacturing, a selection of available thermoplastics and resin-based materials suitable for different TRL levels have been detailed.

There has been high focus on deployment mechanisms with respect to light weighting and reliability. Small spacecraft subsystems related to antenna booms, gravity gradients, stabilization, sensors, sails, and solar panels are some examples. These technologies are gaining space heritage through operations and more often are being included in mission planning. The growth of these deployment mechanisms increase the capabilities of SmallSat technology and will be a continued focus in the next edition of this report.

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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