Make Your Cubesat Overnight and Put it in Any Orbit (Well… almost)

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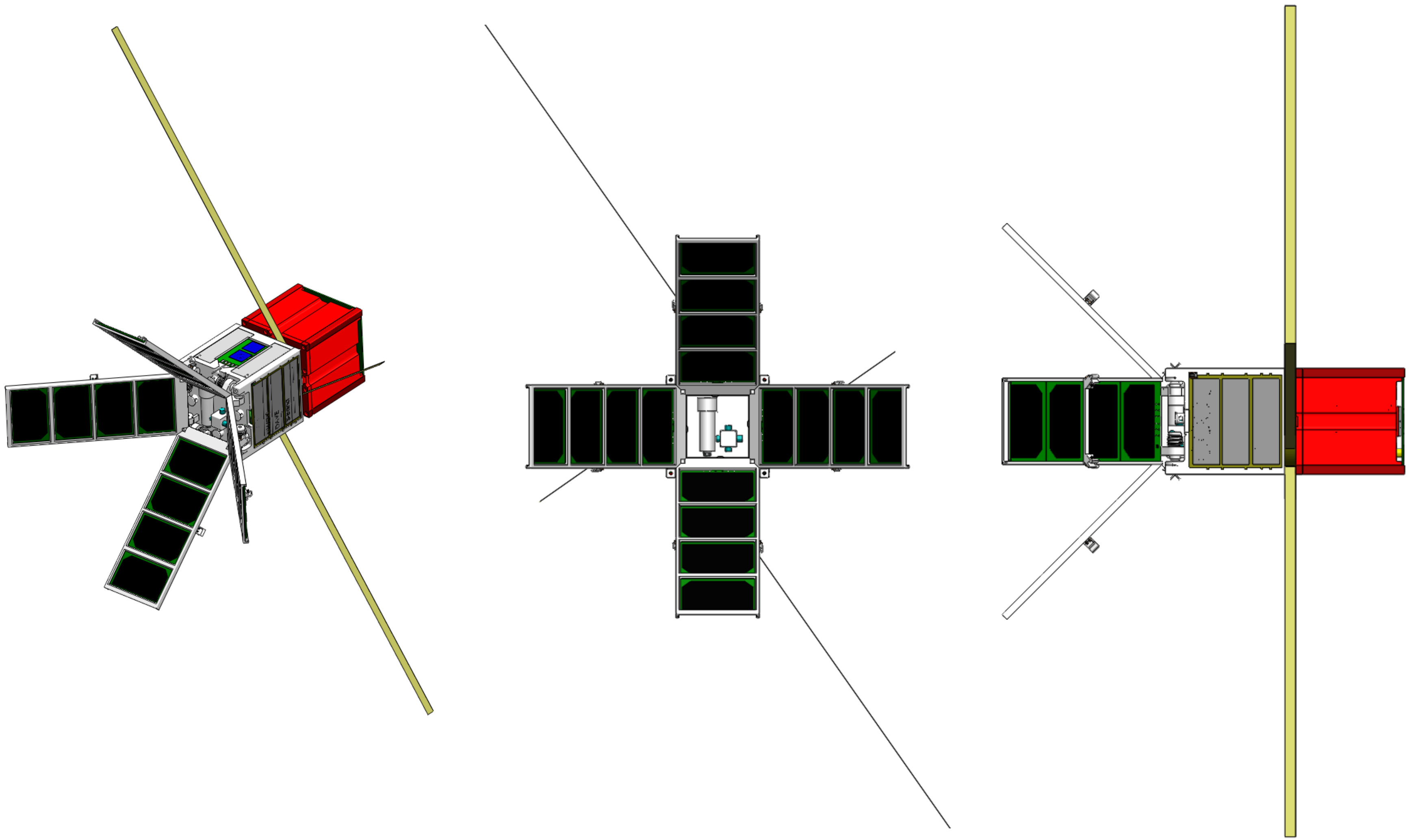
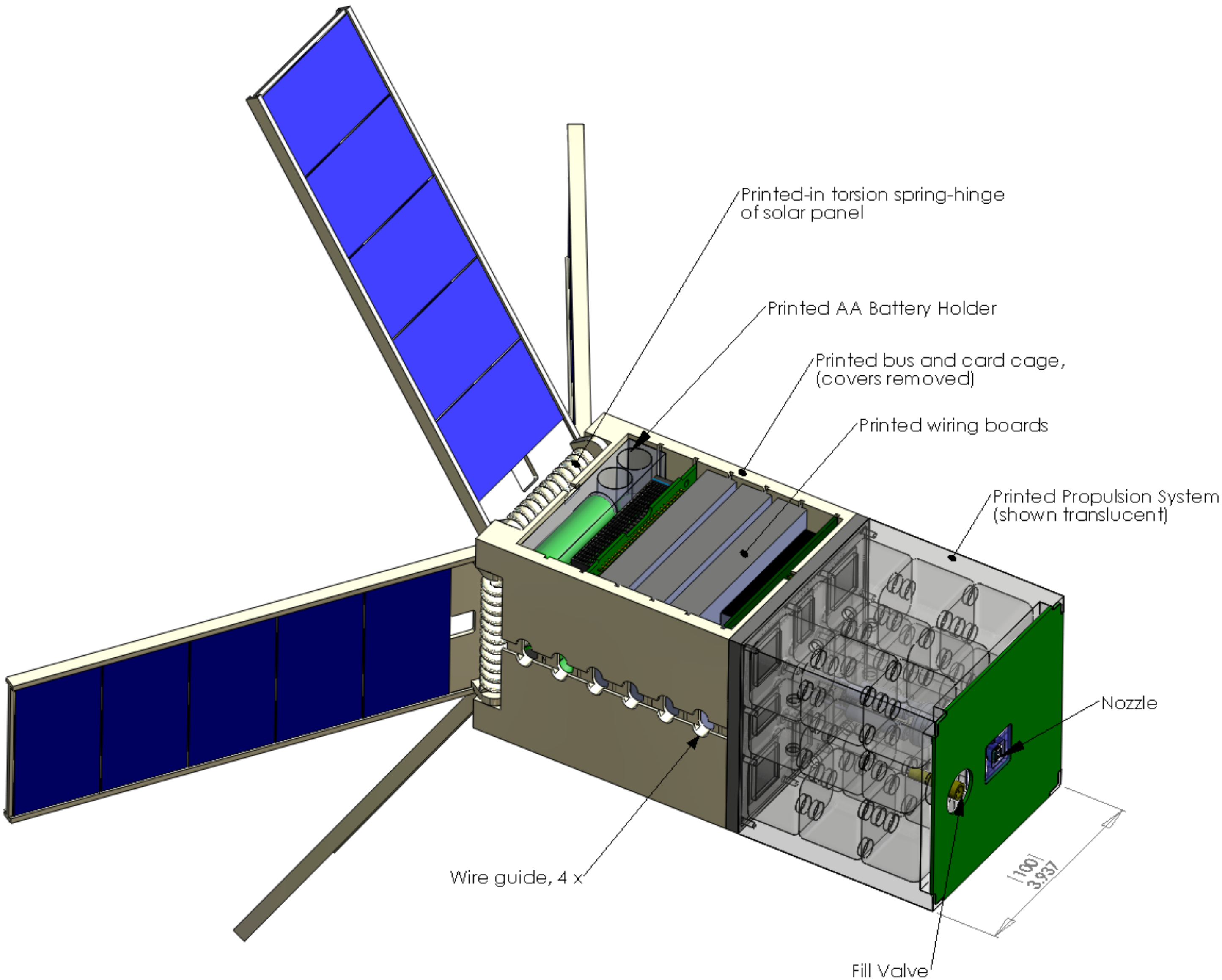
RAMPART Summary



Main Components



The Promise of Cubesats

- Do very cool experiments, very inexpensively, in short time windows

- To fulfill that promise we need to
  - Get them built quickly and inexpensively
    - Faster and cheaper
  - Be in orbit long enough to do something useful
    - Match orbit life to mission life

- However
  - Often take nearly as long to build as microsats
  - Often get very low orbits with a short life and are stuck in that orbit (more so more recently)

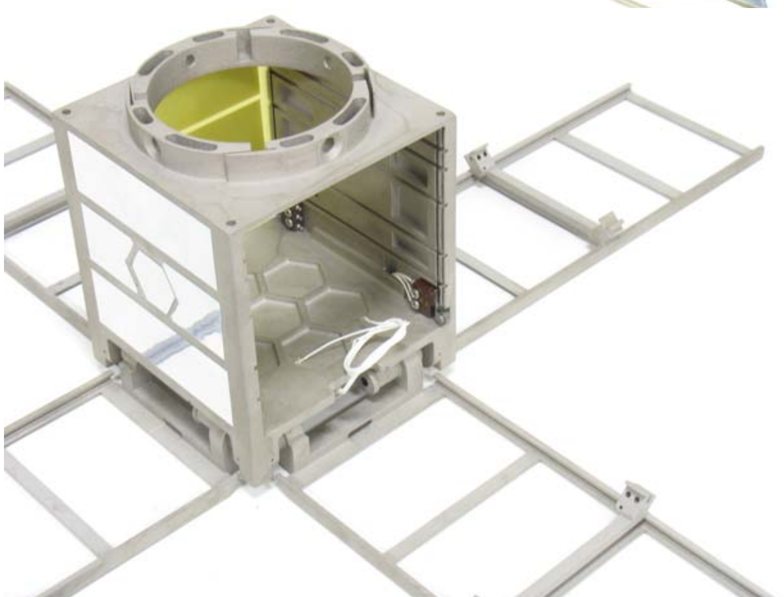
Two developments are changing the game

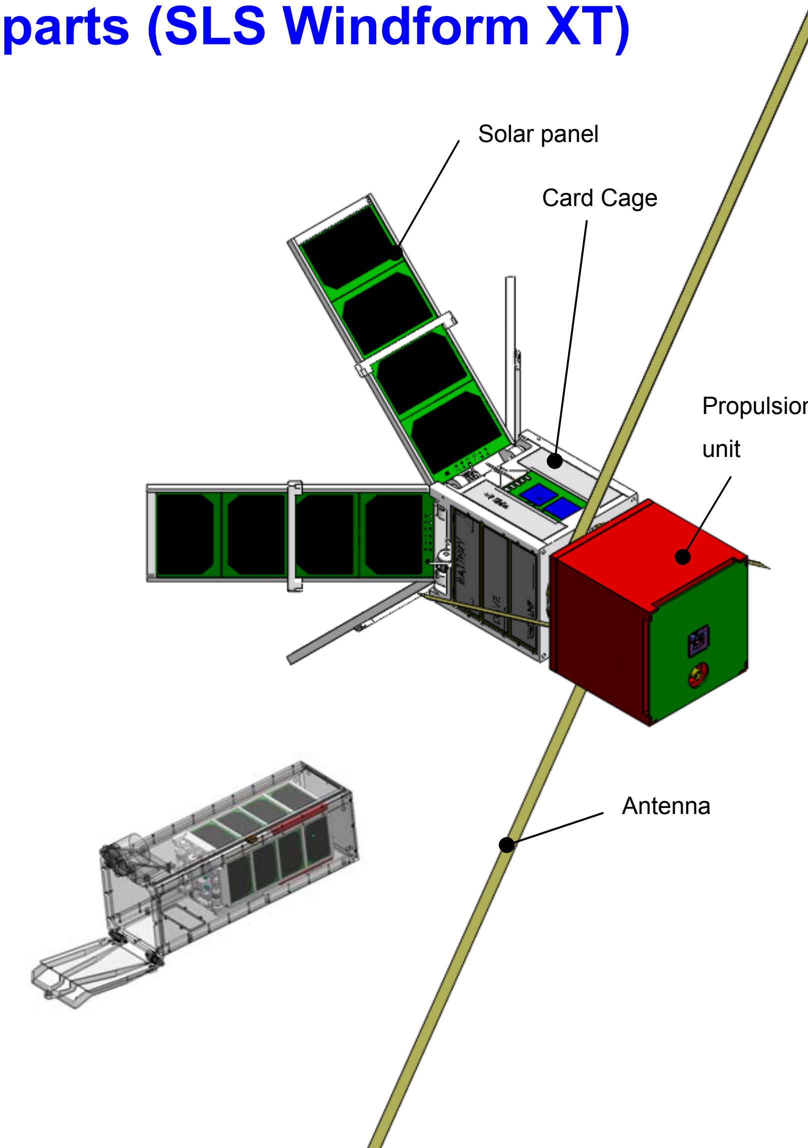
- 3D printing for production
  - The ability to make mechanical pieces by creating a CAD drawing, feeding it into a machine, and have a part a few hours later

- Capable propulsion
  - Simple, safe, effective warm gas propulsion with enough capability to change the orbit in useful ways

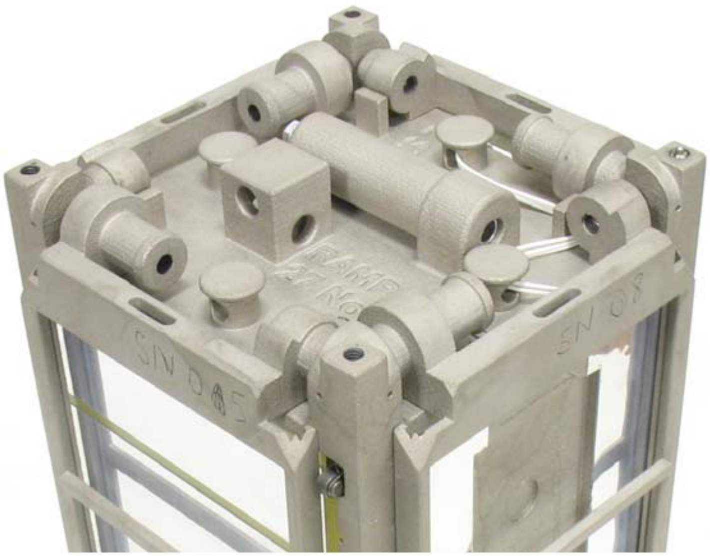
3D Printing for Flight- Real Results

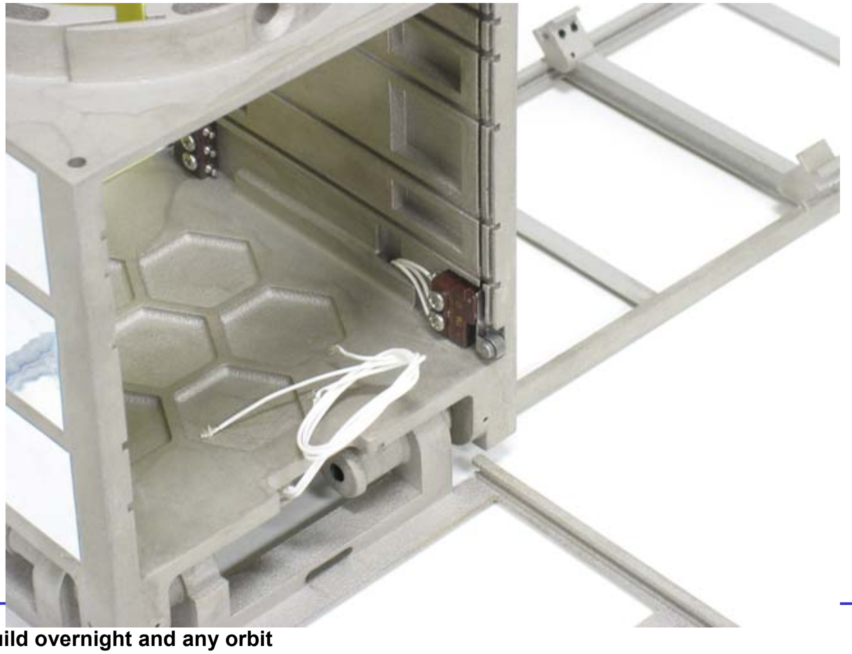
– **RAMPART Cubesat out of printed parts (SLS Windform XT)**





The Current Design





Printed Material and Method

- Used on Rampart Solar panels, card cage, battery and propulsion unit
- Printing Process: Selective Laser Sintering (SLS) by CRP
- Material: Windform XT
  - Nylon with Carbon microfibers
  - http://www.windform.it/sito/en/windform-xt-2-0-polyamide-based-material-carbon-filled.html
- Surface Finish: Nickel Plate, 0.001 thick, best commercial practices
- Meets Outgassing Requirements
  - TML [%] <1.0%, CVCM [%] <0.10

PROPERTIES WINDFORM® XT	Test Method	SI Unity	Windform® XT
GENERAL PROPERTIES			
Density (20° C)		g/cm³	1,101
Colour			DARK
THERMAL PROPERTIES			
Melting Point	ASTM D 3418	°C	179,33
HDT, 1.82 Mpa	ASTM D 648	°C	175,4
Vicat 10N	ASTM D 1252	°C	178,1
MECHANICAL PROPERTIES			
Tensile Strength	UNI EN ISO 527-1(97) UNI EN ISO 527-2(97)	Mpa	77,85
Tensile Modulus	UNI EN ISO 527-1(97) UNI EN ISO 527-2(97)	Mpa	7320,8
Elongation at break	UNI EN ISO 527-1(97) UNI EN ISO 527-2(97)	%	2,6
Flexural Strength	UNI EN ISO 14125: 2000	Mpa	131,52
Flexural Modulus	UNI EN ISO 14125: 2000	Mpa	6248,5
Impact Stength - Charpy Unnotched (23°C)	ASTM D 256 - UNI EN ISO 179:1998	KJ/m²	32,4
Impact Stength - Charpy Notched (23°C)	ASTM D 256 - UNI EN ISO 179:1998	KJ/m²	4,73
Impact Stength - Charpy Notched -30°C	ASTM D 256 - UNI EN ISO 179:1998	KJ/m²	4,66
SURFACE FINISH			
After SLS Process		Ra µm	6,0
After finishing		Ra µm	1,8
PROPERTIES PER DENSITY UNIT			
UTS per density unit		Mpa g/cm³	70,71
Tensile modulus per density unit		Mpa g/cm³	6649,2

Note: These are all indicative values, data were generated from the testing of parts produced with the Windform® XT materials under optimal processing conditions.

<u>**Standard Technical Details for Accuracy versus Tolerance:**</u>

For parts up to 6" (150 mm) the standard tolerance is: +/- 0.012 inch (0,3 mm)

For parts more then 6" (150 mm) the standard tolerance is: +/- 0.002 inch per inch (0.05 mm per 25 mm)

CRP Technologies

WINDFORM

Manufacturing Current State

- Printing
  - 6 weeks, could have been 1 week
- Plating
  - 3 weeks, could have been 1 week

Note:

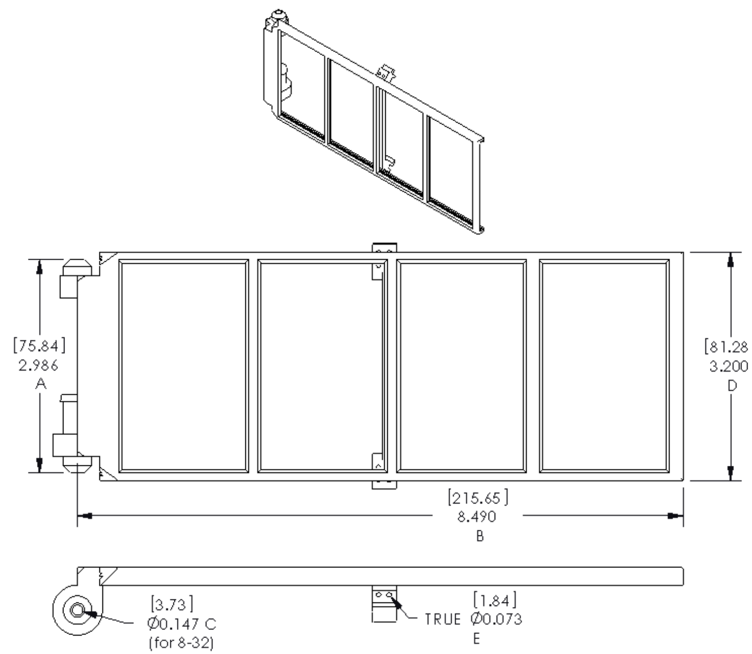
- Printed parts and plating donated on RAMPART
  - Our schedule was not a priority
- Estimated total cost to print and plate a 2U satellite ~$3,000

Precision of Printed Parts (SLS Windform XT)

- Printed parts have errors about 5 times greater than machined parts
  - Machined part typically has an error less than 0.005 inches on an 8.0 inch feature size
  - Greatest error on solar panels was 0.023 inches on an 8.49 inch feature size

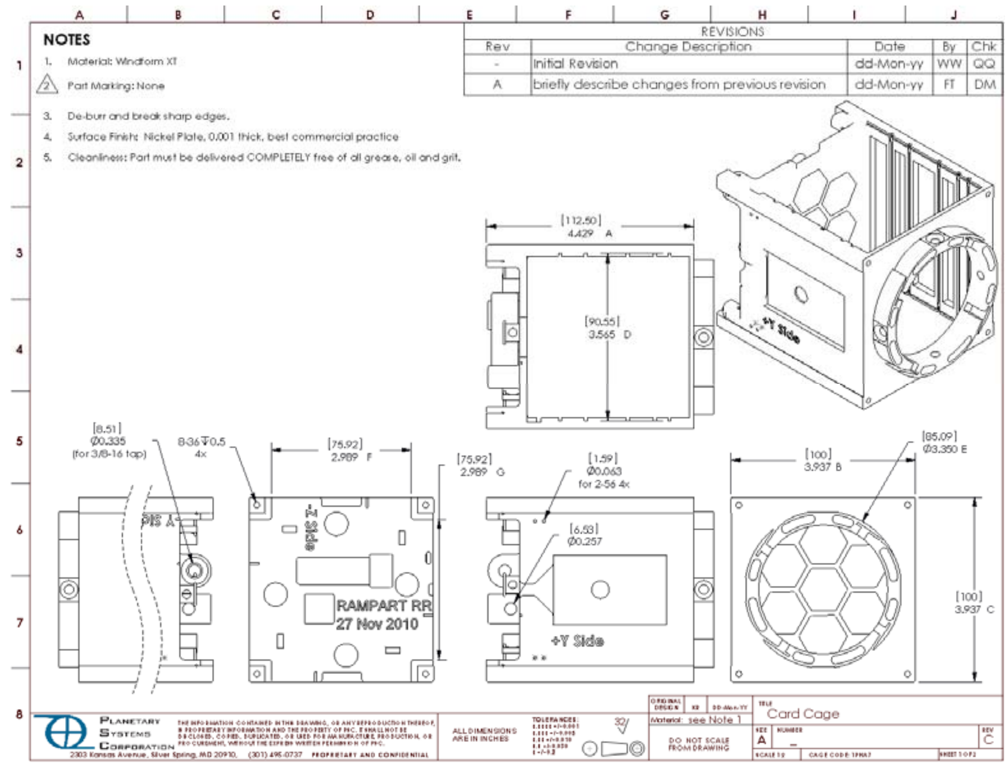
Example: Printed Solar Panel Inspection

Serial Number	Feature Size [inch]					Mass [g]
	A	B	C	D	E	
1	2.994	8.468	0.140	3.206	0.073	23.8
2	2.992	8.476	0.140	3.215	0.073	23.6
3	2.987	8.472	0.140	3.209	0.073	24.0
4	2.990	8.469	0.140	3.206	0.073	24.0
5	2.996	8.476	0.140	3.211	0.073	23.9
6	2.997	8.476	0.140	3.212	0.073	23.8
7	2.993	8.467	0.140	3.210	0.071	23.5
8	2.996	8.474	0.140	3.216	0.073	24.0
Mean	2.993	8.472	0.140	3.211	0.073	23.8
Max	2.997	8.476	0.140	3.216	0.073	24.0
Min	2.987	8.467	0.140	3.206	0.071	23.5
3 x Standard deviation	0.010	0.011	0.000	0.011	0.002	0.573
Should be	2.986	8.490	0.147	3.200	0.073	23.6
Greatest error	0.011	0.023	0.007	0.016	0.002	0.4
Mean Error [%]	0.239	-0.209	-4.762	0.332	-0.342	0.953
3 x Stdev error [%]	0.341	0.135	0.000	0.347	2.906	2.426
Greatest error [%]	0.368	0.271	4.762	0.500	2.740	1.695



Advantage of SLS Windform XT

- Made quickly and cheaply
- Unlike machined parts:
  - Quantity of unique features does not influence cost
  - Designers need not consider how machining is completed or features created
    - » Printed parts are to mechanical engineers what printed wiring boards are to electrical
    - » Features can be inexpensively added
- Card Cage incorporates many features in one part
  - Load Cell
  - Hysteresis rods
  - Six cards
  - Five Antennas
  - Solar cell experiment
  - Snap in solar panel and covers
  - Wire guides

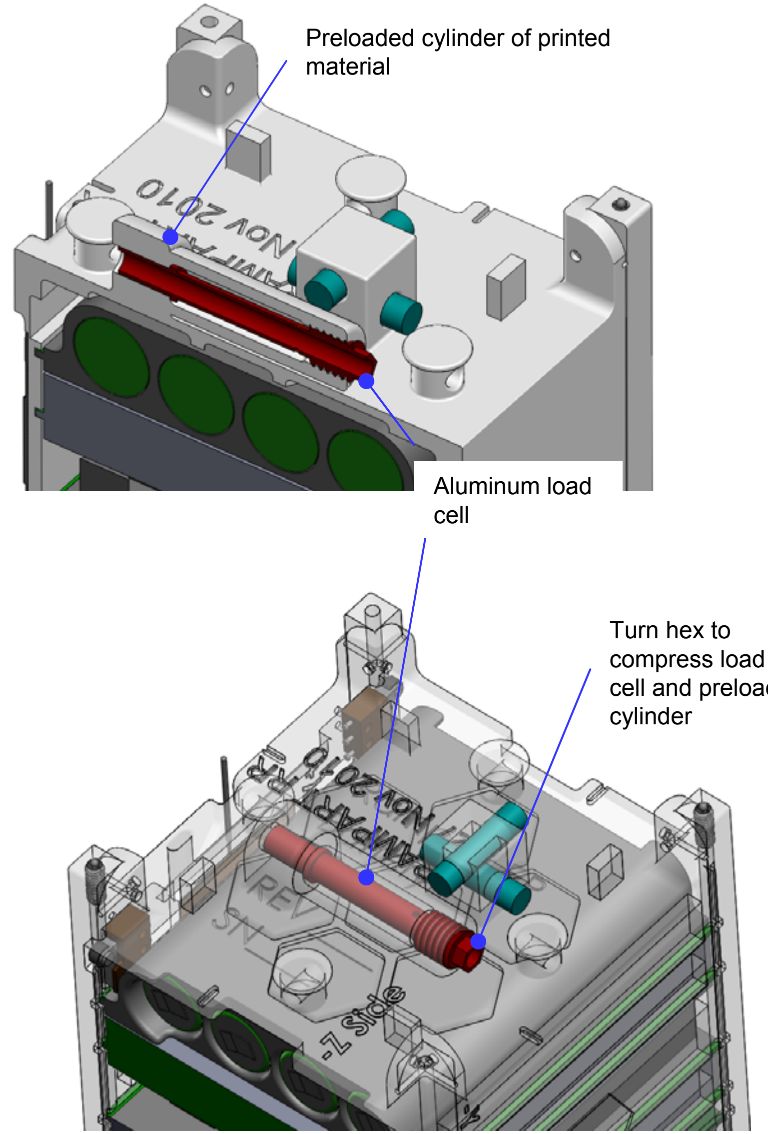


Disadvantages of Current Printing Methods

- Printed parts have dimensional errors about 5 times greater than machined parts
- SLS Resolution limits makes features smaller than 0.03 inches difficult to achieve
- Threading cannot be printed-in
  - Tapped threads are tight leading to high running torque on fasteners
- Nickel plating is rough like 280 grit sandpaper
- Mechanisms made from printed parts (deployable solar panels) require sanding, filing or a tuning feature
  - Integral mechanism are possible to avoid this issue….
- Printed Plastic is weaker than metal and has much higher Coefficient of thermal expansion (CTE)
- Aspect ratios **D/d** > 30 can warp by 100% of **d**
  - Ribs are needed to decrease aspect ratio

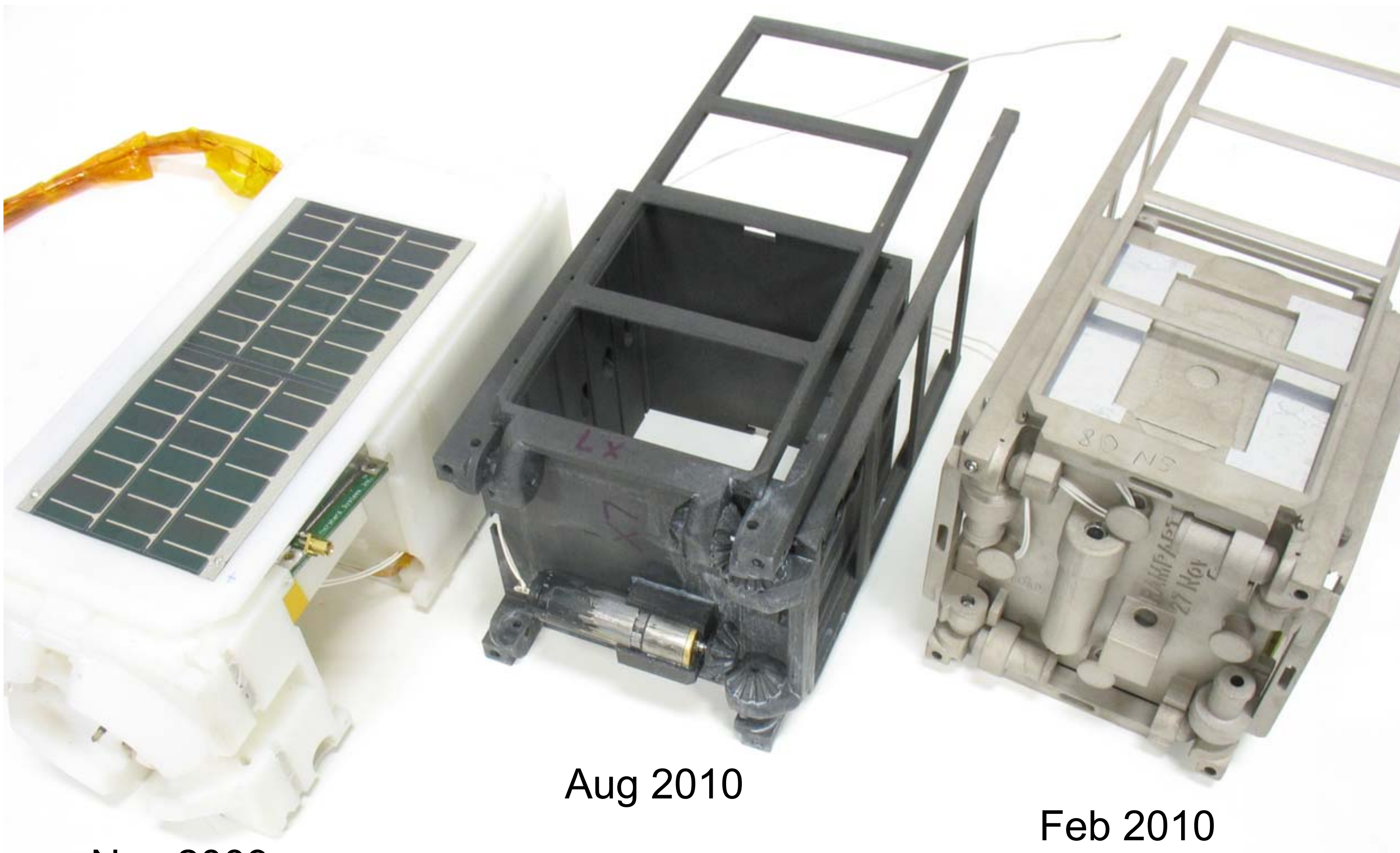
Mission Assurance and Printed Parts

- Thermal vacuum
  - Pressure: <10-5 torr
  - Temperature: -34 to +70 C
  - Cycles: 27
  - Solar array deployment after 27th cycle at temperature extreme
- Random vibration
  - 14.1 Grms, 3 minutes/axis
  - Solar array deployment after excitation
- Load cell to monitor the strain of a preloaded cylinder on orbit
  - Thermal cycling, and radiation may cause degradation of material properties and creep
  - May be compared to terrestrial measurements



Development Advantages

- Short build cycles allowed rapid change and integration of new ideas
  - Three different solar panel release system tested



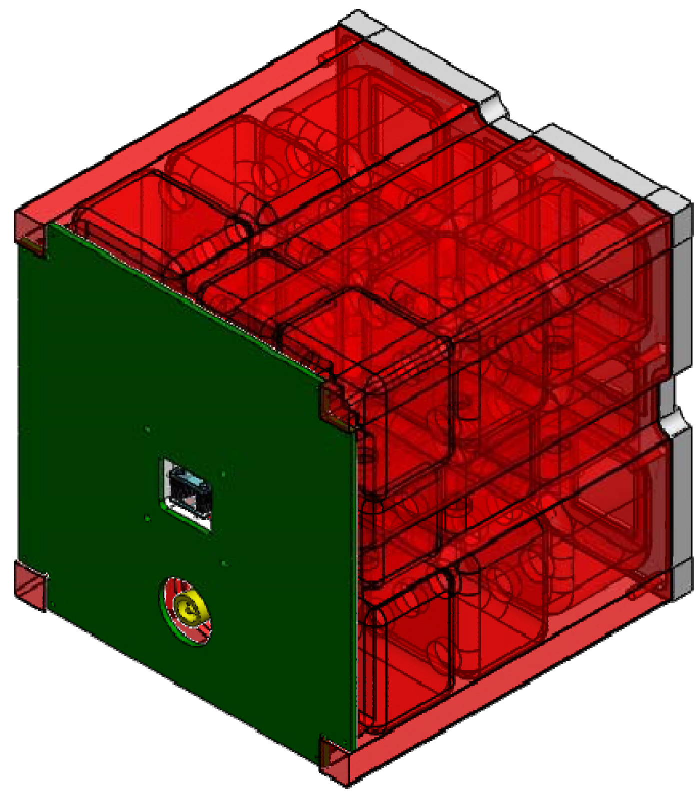
Future Performance

- More features to accommodate wiring harness
- Receive assembly-ready parts two weeks after order
- Complete mechanical assembly in 1 day

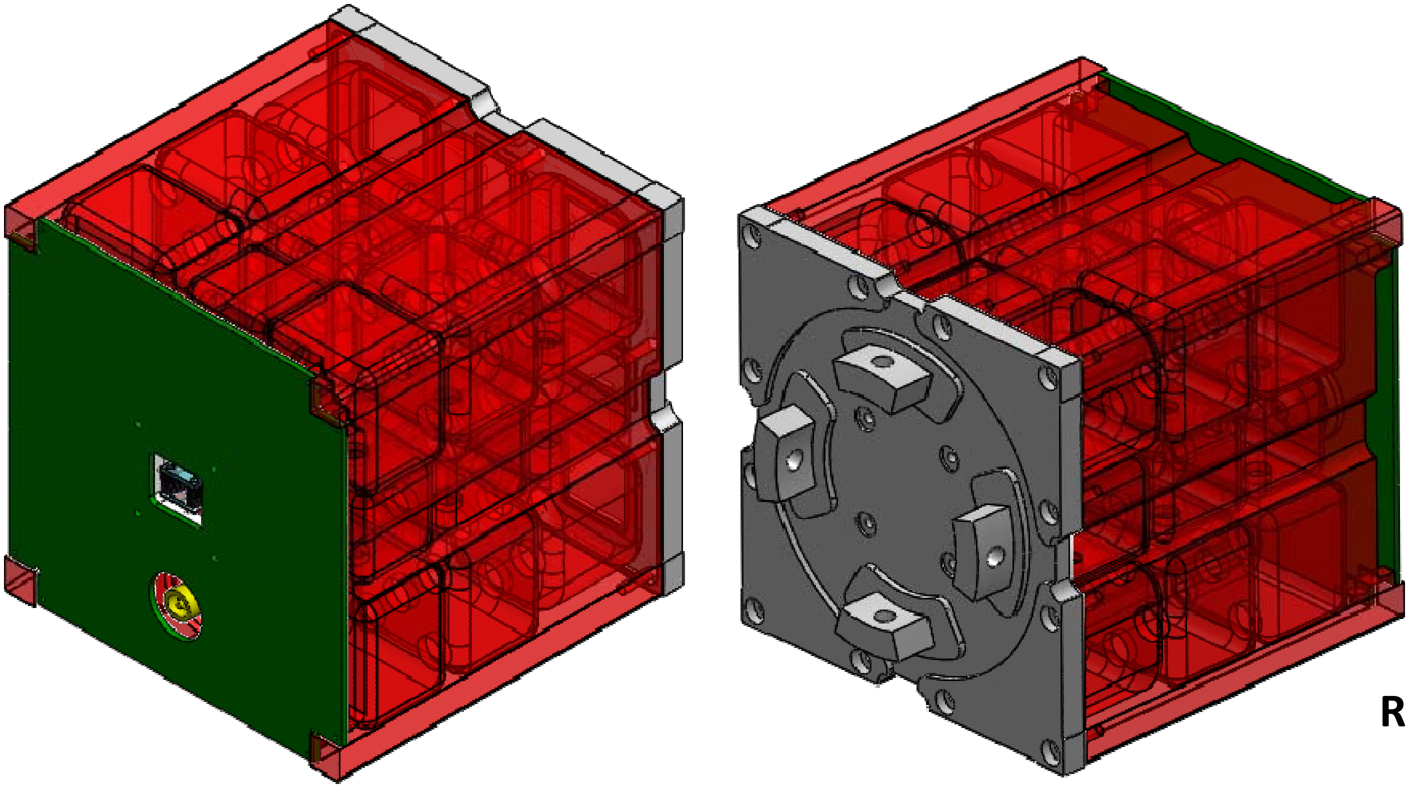
Second Enabler - Propulsion

- RAMPART warm gas printed propulsion
  - Construction
  - 3D printed performance

- Orbit change capability
  - In plane maneuvers
  - Out of plan maneuvers



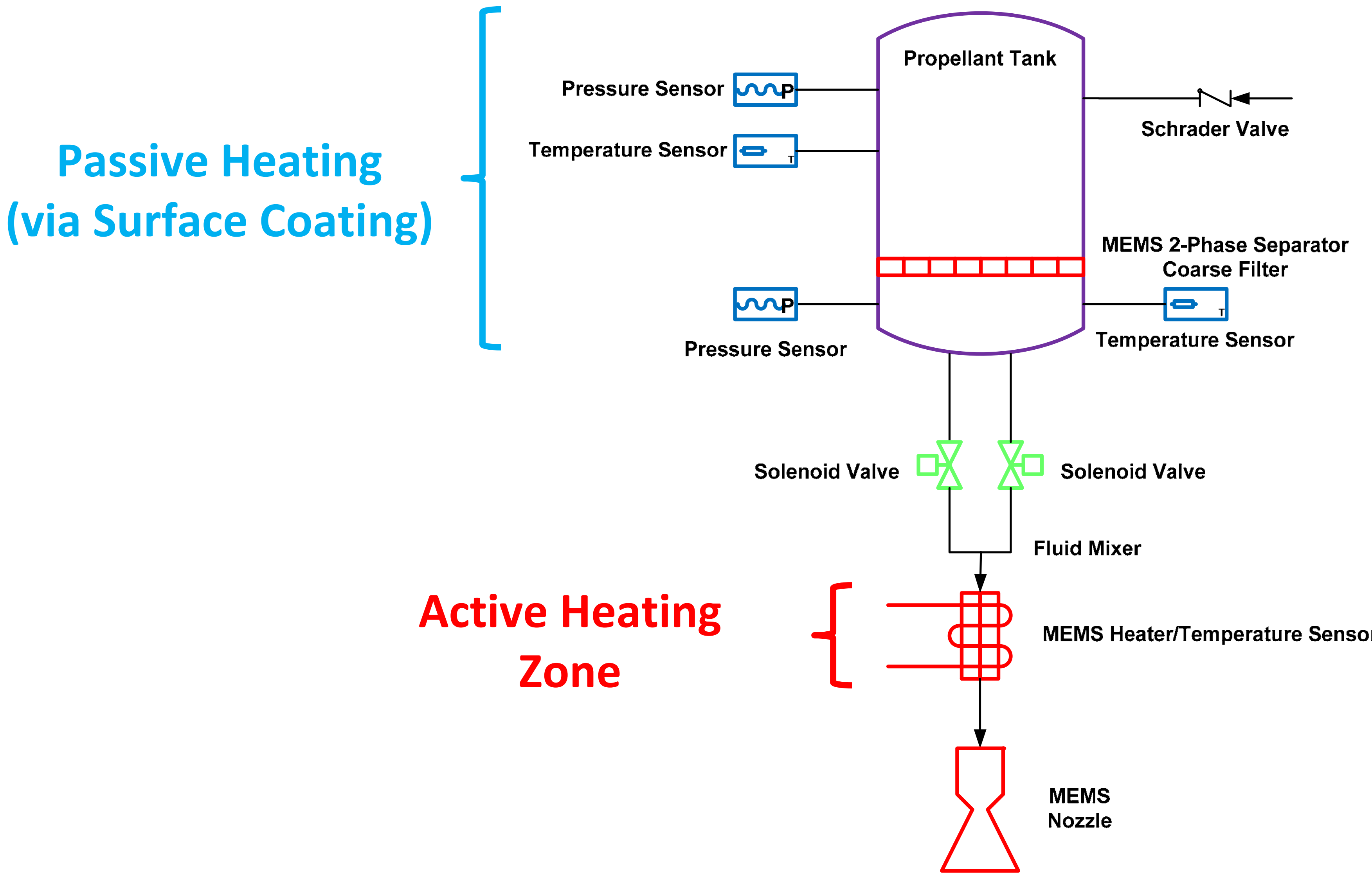
RAMPART Propulsion System



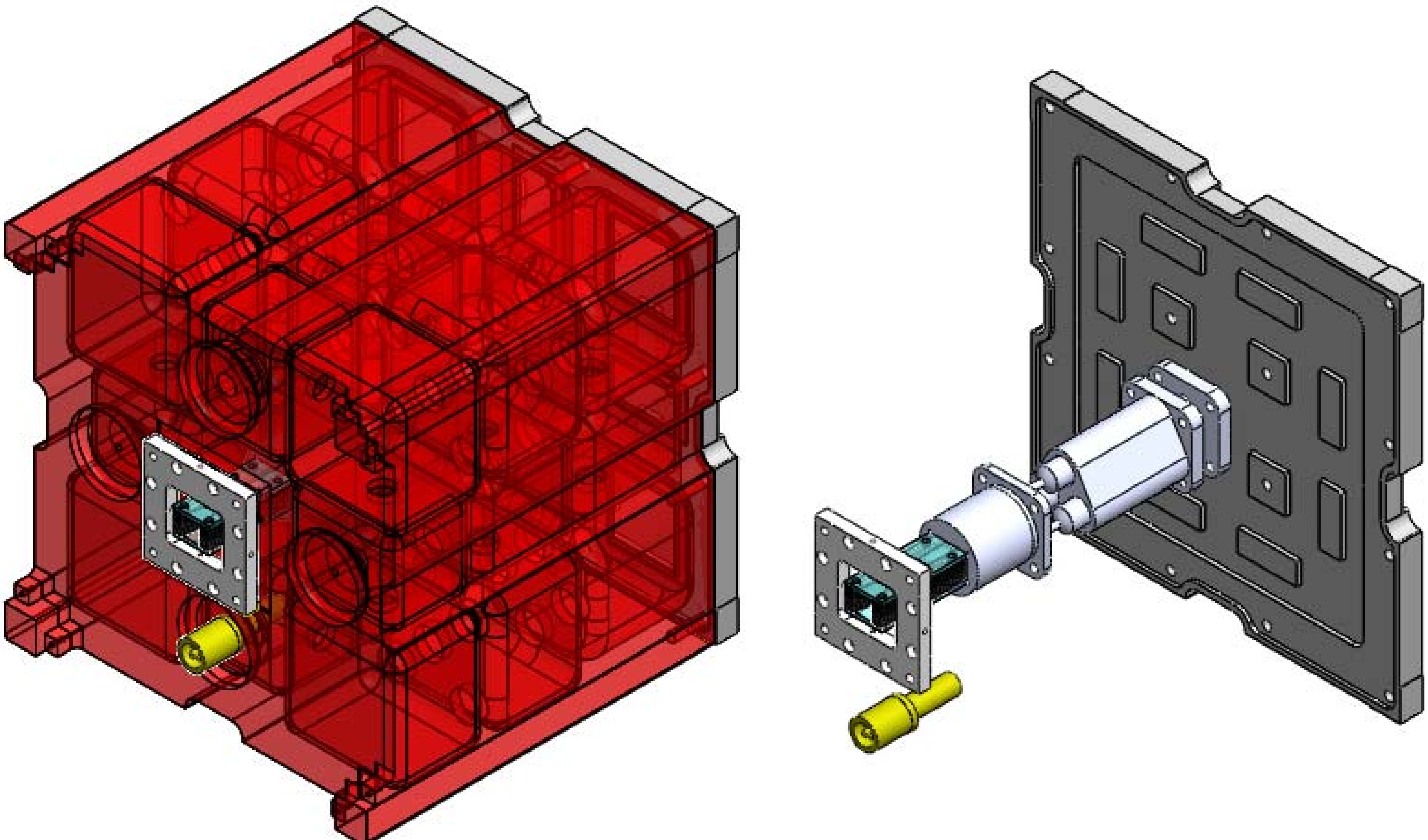
Rule of Thumb-Every 100km Holmann transfer at LEO requires 50-60m/s ΔV

Dimension: 10cm x 10cm x 11.35cm (4.47")
Empty Weight: 450 grams
Fueled Weight: 1100 grams (with R-134a propellant)
Nominal Propellant Volume: 500 cm^2
Design Mission ΔV: 300m/s
Design Performance: 90s Isp, 0.5N 30 second pulse duration

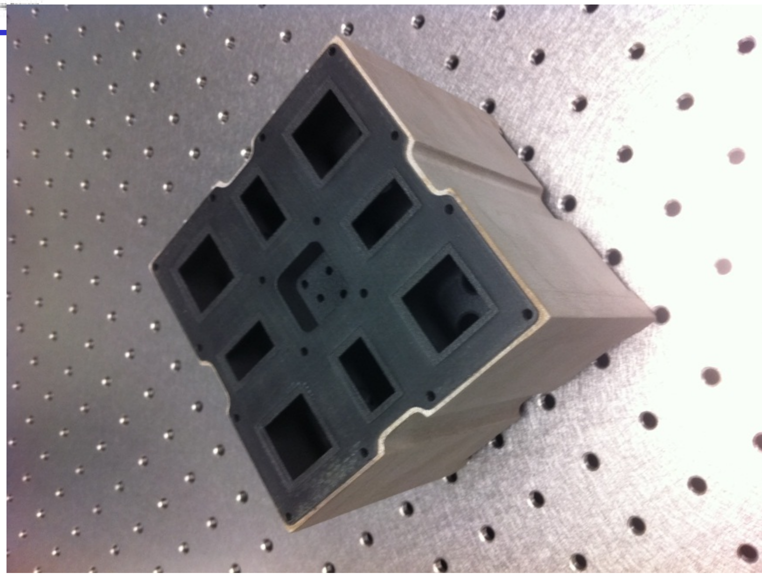
RAMPART Propulsion System

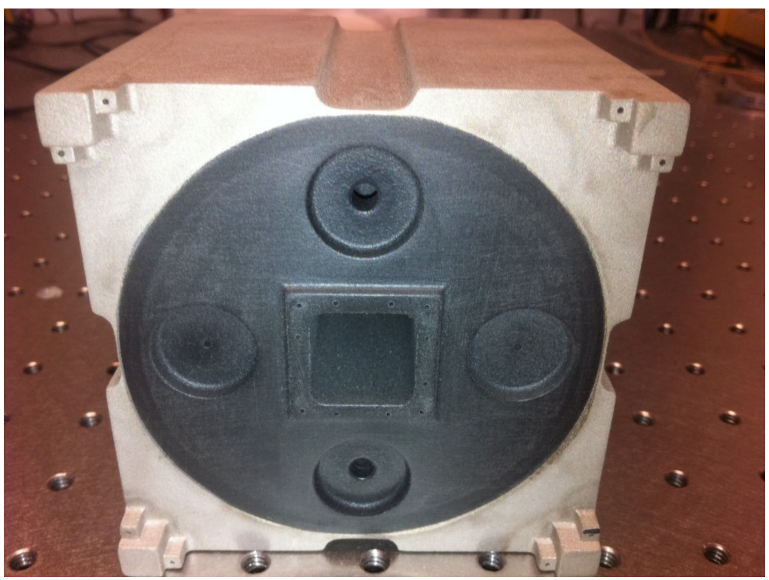


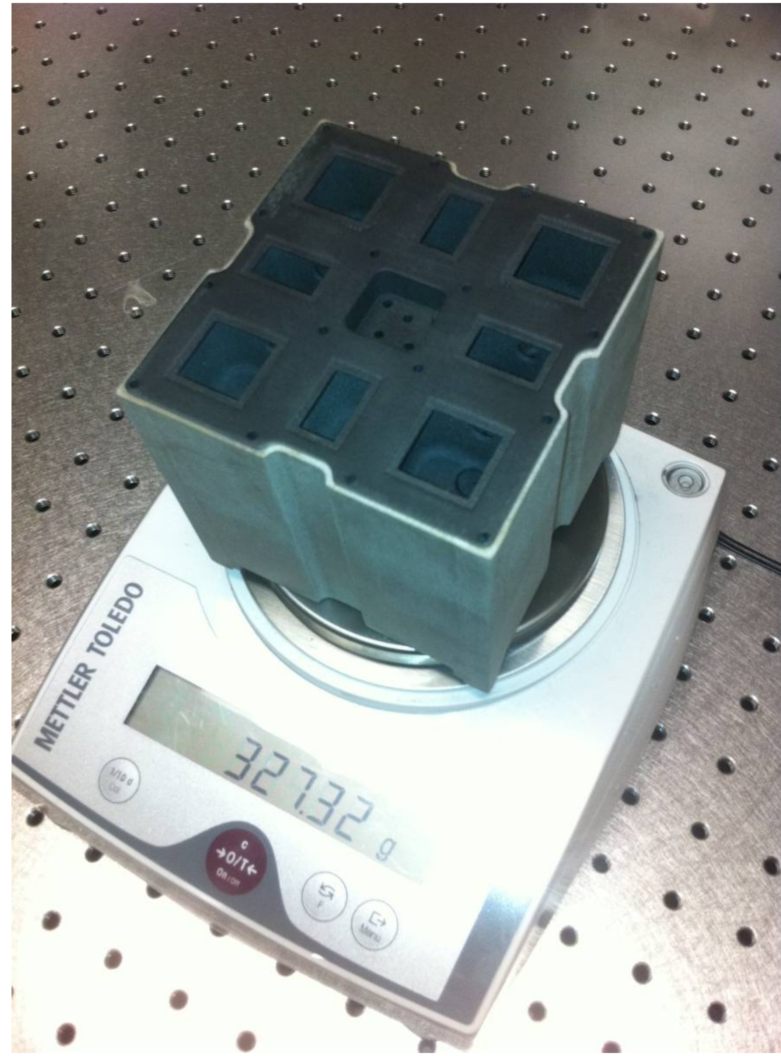
Printed/Non-Printed Parts



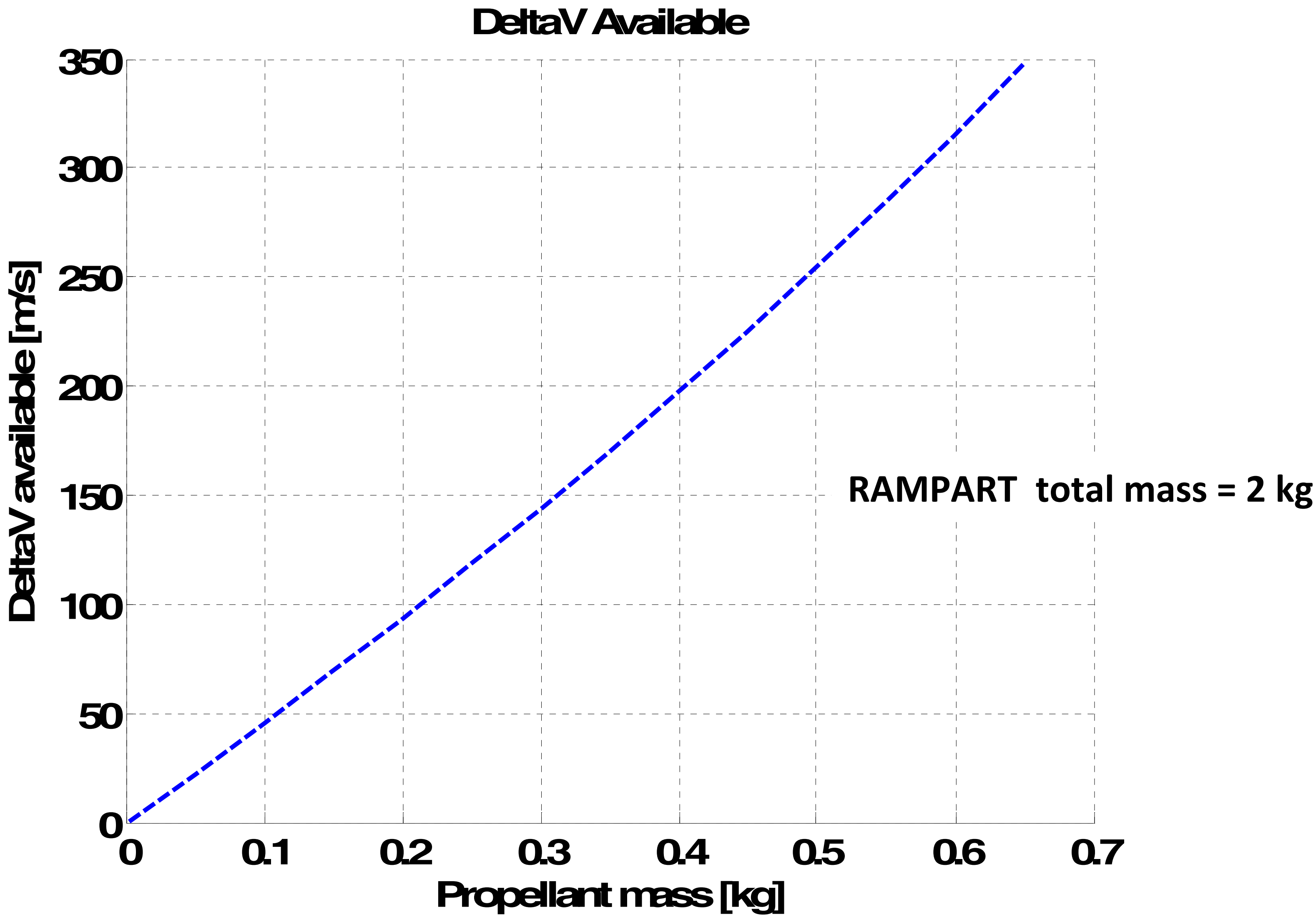
Red: Printed Windform XT Propellant Tank



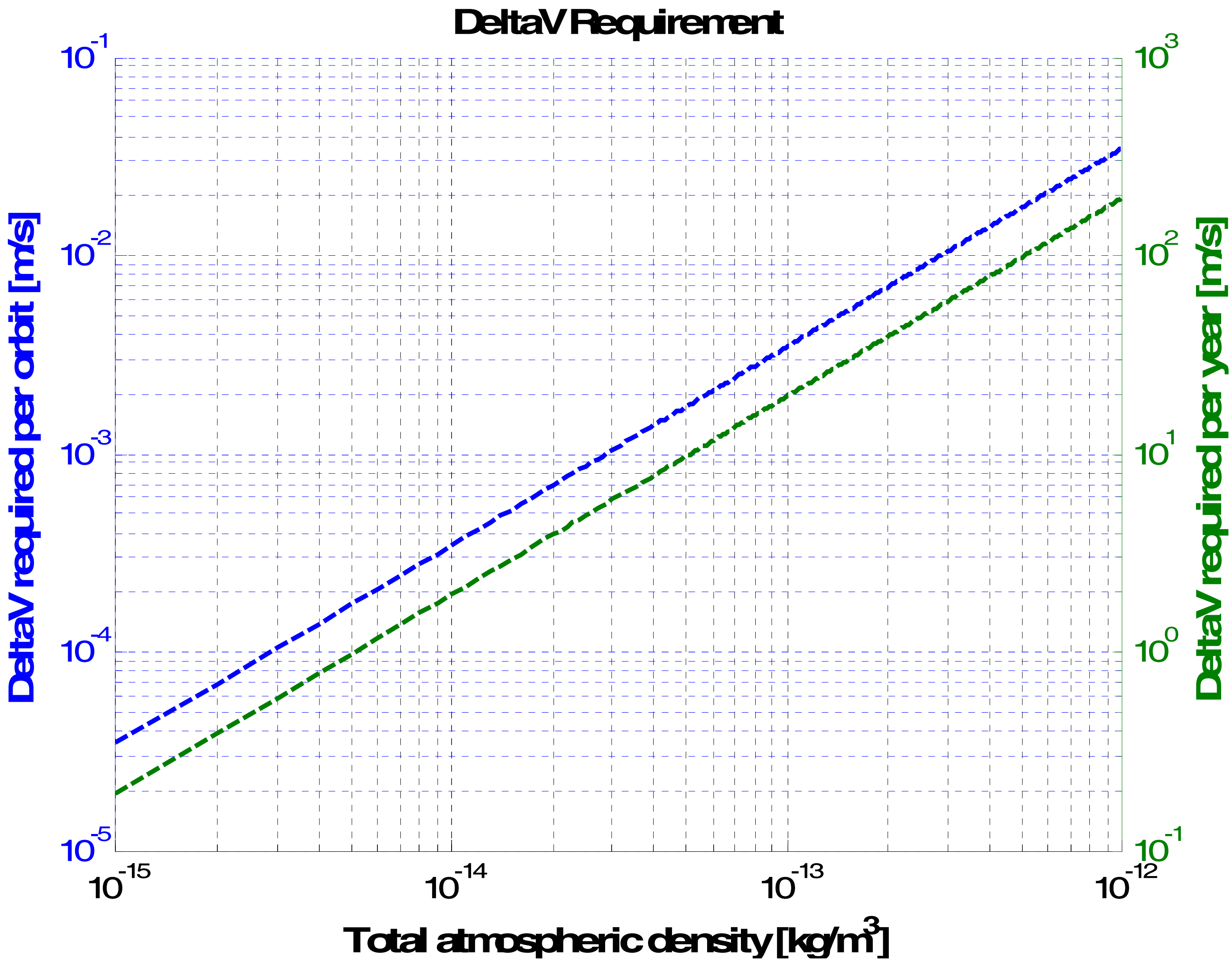



METTLER TOLEDO
327.32 g

RAMPART Delta-V Performance

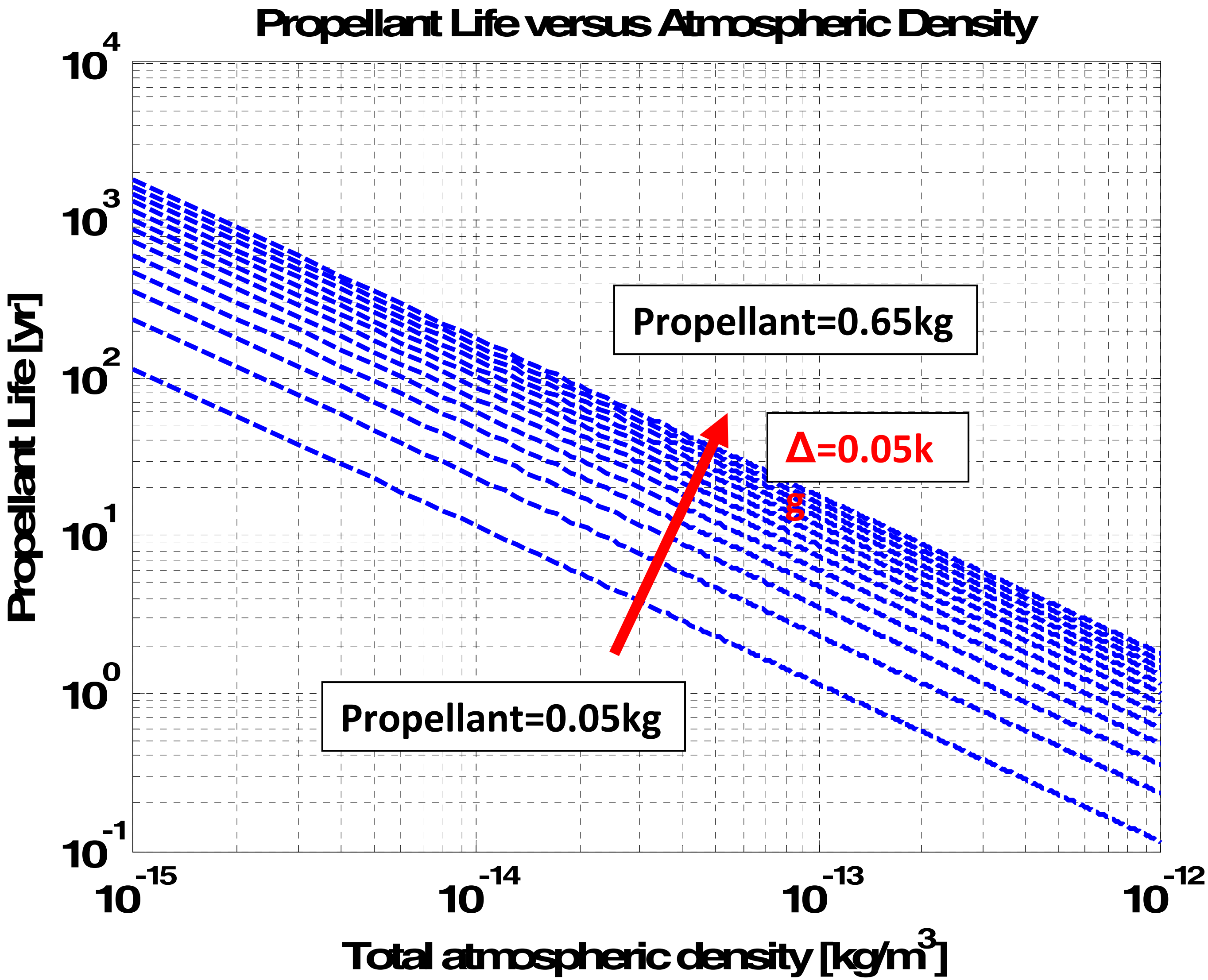


RAMPART Drag Make-Up (Propellant Life)



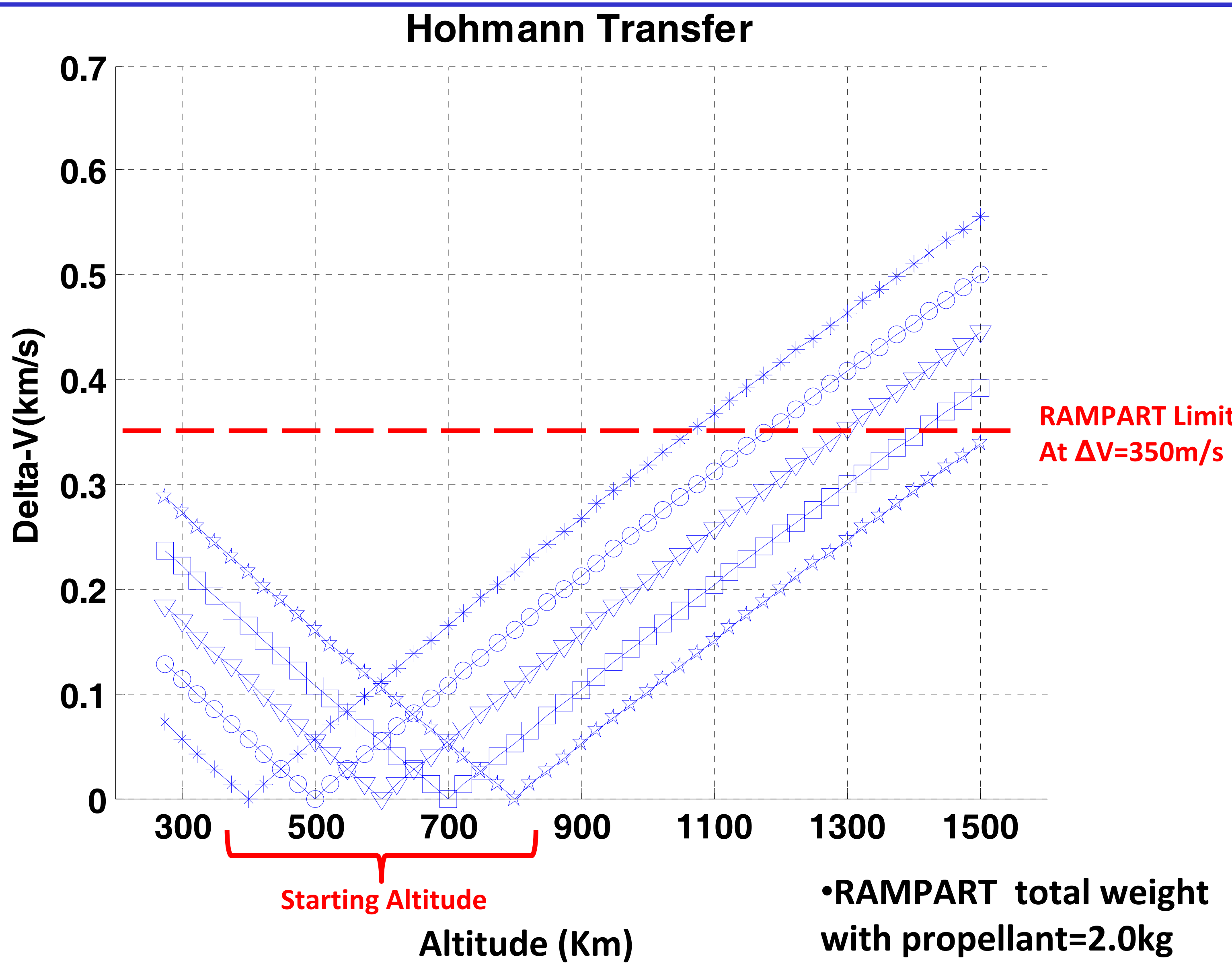
•RAMPART with maximum frontal cross-section (panels deployed; 1.35kg; C_D=2.5)

RAMPART Drag Make-Up (Delta-V Available)



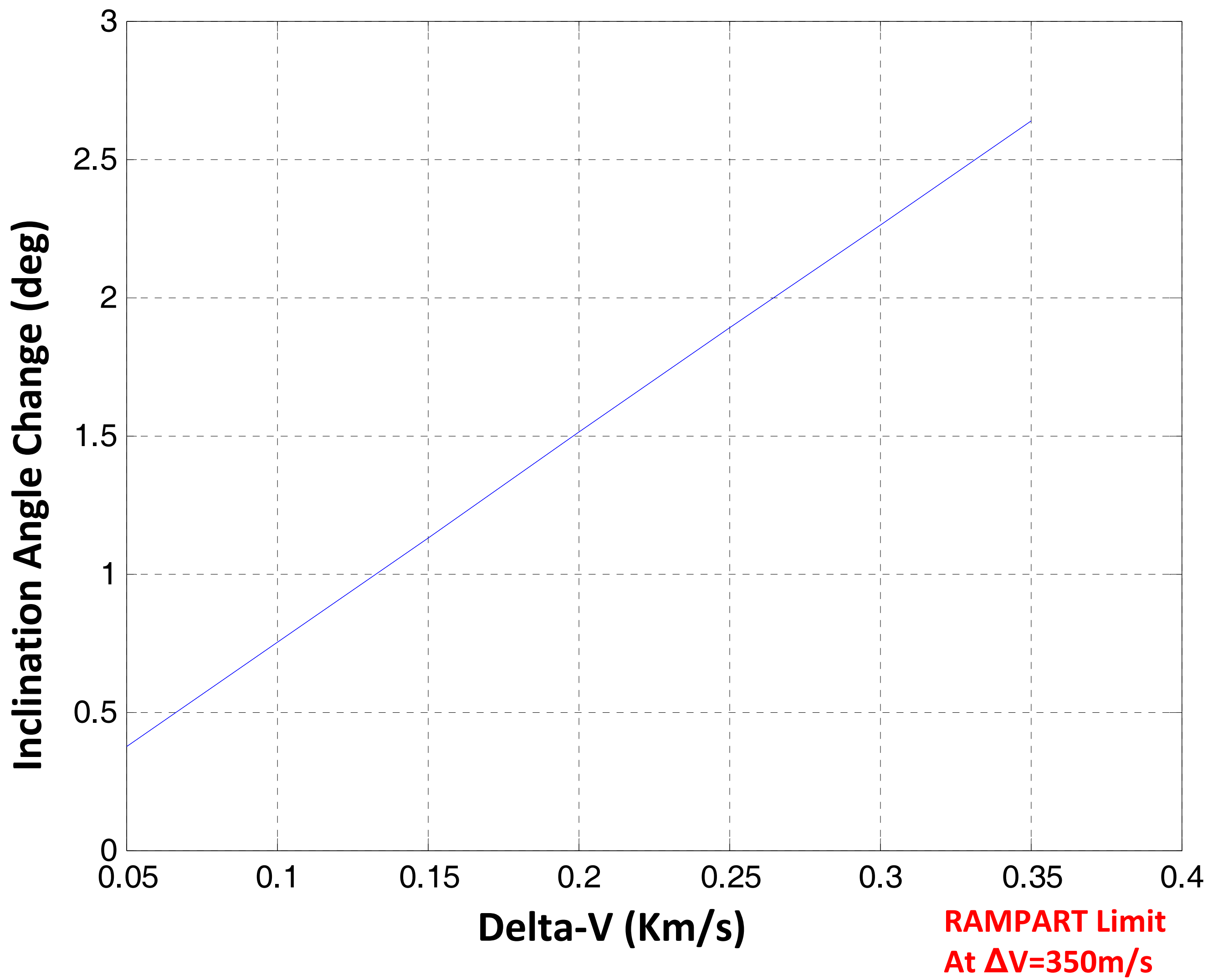
•RAMPART total weight with propellant=2.0kg

In-Plane Orbit Peformance



- RAMPART total weight with propellant=2.0kg

Out-of-plane Performance



- **RAMPART total weight with propellant=2.0kg, 450km circular orbit**

Propulsion Capability Summary

- The hard part to machine – the tank – is dead easy with 3D printing
- The Windform XT material is at least 3X stronger than needed for this tank
- With this simple warm gas system, using about 1U, a 2U orbit can be
  - Raised from 350 to (up to) 1000 circular
  - Raised from 800 to (up to) 1500 circular
  - Raised from 450 to (up to) 1200 elliptical, then the perigee lowered to reduce orbit life
  - Change the plane up to 2.5 degrees to ‘tune’ the orbit
  - Lower apogee at any time to reduce orbit life (de-orbit on demand)
- Limitations
  - Same tolerance limits as with the card cage
    - » Must design the mounts for the end plate, valves, etc. to be tolerant of those dimension errors or do light post-printing machining

Status of that Promise

- Do very cool experiments, very inexpensively, in short time windows
- To fulfill that promise we need to
  - Get them built quickly and inexpensively
    - Make (Print) trial and test structures and mechanisms literally overnight out of plastic and similar materials
      - Can do that over and over again for a few 10's of dollars per print
    - Can do the entire flight structure including complex internal parts in 2 weeks from drawings to completed pieces
    - Final assembly in less than a week including deployed panels and similar features
    - Include complex and multiple features at essentially no extra cost
    - Include external plating for a conductive RF 'skin'
    - Can design to handle the tolerance issues
    - Easily change things like putting pockets in side to mount other items and test overnight

Start to finish in about 1 month now, perhaps 1 week in not too distant future

Status of that Promise

- Be in orbit long enough to do something useful
  - Can move the typical low altitude cubesat orbit to anything up to about 1200 elliptical then reduce orbit life to a few weeks at end of mission
  - Can move that same initial orbit up to about 800 circular and still reduce orbit life to < 20 years at end of mission
  - Warm gas using R134-A is safe and should gain more and more acceptance
    - Pressures are low, propellant volume is small, tank safety factors are large
  - Prop tank structure very easily modified for things like
    - Changing size
    - Points to mount external items
    - Change connection to remainder of spacecraft
    - Accommodate integral antennas
    - Scaled up for use on a 6U
    - Made pretty much any other size or shape for other applications

Can, with safe and cheap propulsion, be in orbit long enough to do useful work, and de-orbit or shorten life when done

Missions Made Possible

- What kinds of missions to these two capabilities enable
  - Rapid response: Build and be ready for launch in a few weeks
  - Long duration exposure to space environment
  - Exposure to radiation effects (may be less expensive than a full set of rad tests on the ground)
  - Wide area communications from higher orbit
  - Spread within orbit plane from a single launch
  - Station keeping
  - Orbit maintenance in highly elliptical with low perigee – for a 'close look' but long orbit life
  - Orbit maintenance in low orbit for longer durations
  - Iterate a mechanical design, launch and test, iterate again
  - Precise drag measurements with releasable spheres into an elliptical orbit – then spread out in that orbit
  - Rapid and cheap production of dozens (hundreds) of structures and mechanisms for swarms – could even be modified for different capabilities
  - Do a mission in one orbit, change the orbit and do a different mission

Wrap Up

Questions