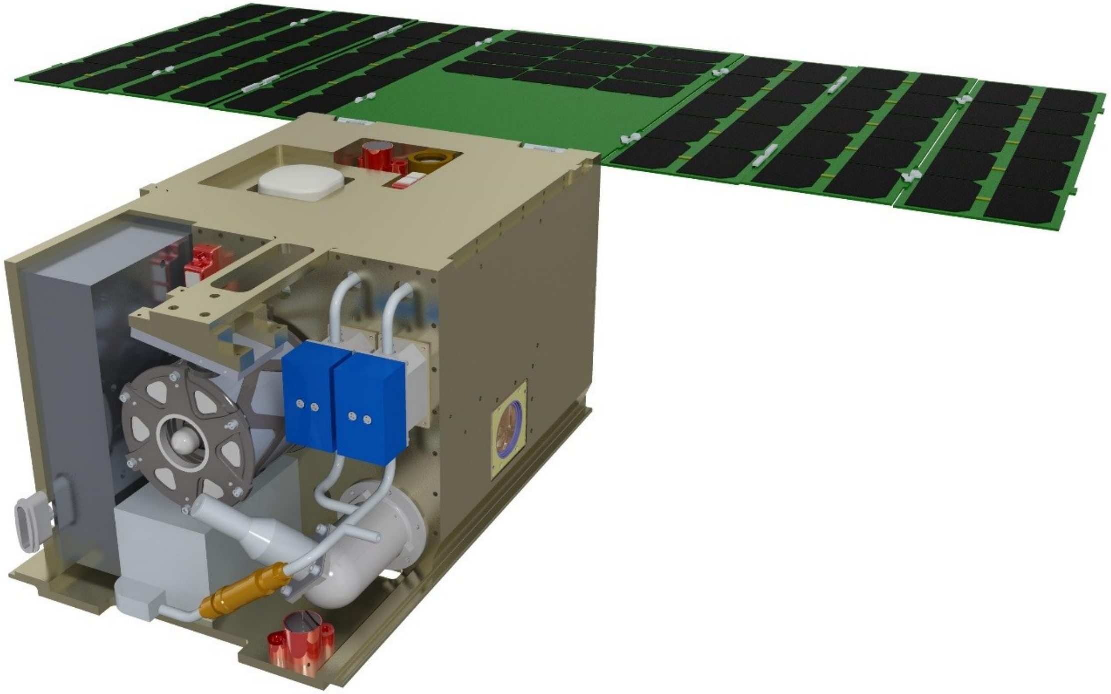
The Iodine Satellite (iSat) Project Development towards Critical Design Review



IEPC-2015-303

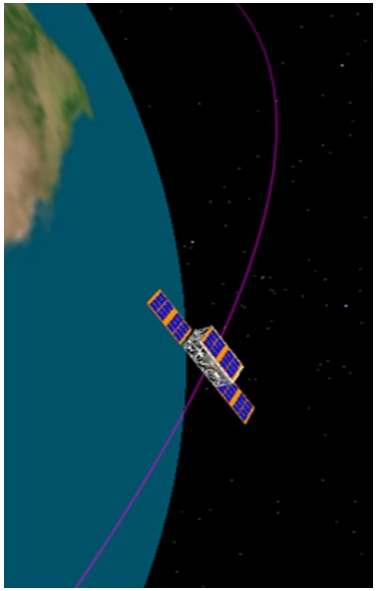
Presented at Joint Conference of 30th International Symposium on Space Technology and Science
34th International Electric Propulsion Conference and 6th Nano-satellite Symposium,
Hyogo-Kobe, Japan
July 4 – 10, 2015

John Dankanich, Derek Calvert, Hani Kamhawi, Tyler Hickman, James Szabo and Lawrence Byrne

iSAT Mission Concept Overview

The iSAT Project is the maturation of iodine Hall technology to enable high ΔV primary propulsion for NanoSats (1-10kg), MicroSats (10-100kg) and MiniSats (100-500kg) with the culmination of a technology flight demonstration.

- NASA Glenn is leading the technology development and is the flight propulsion system lead
    - Busek delivering the qualification and flight system hardware
- NASA MSFC is leading the flight system development and operations

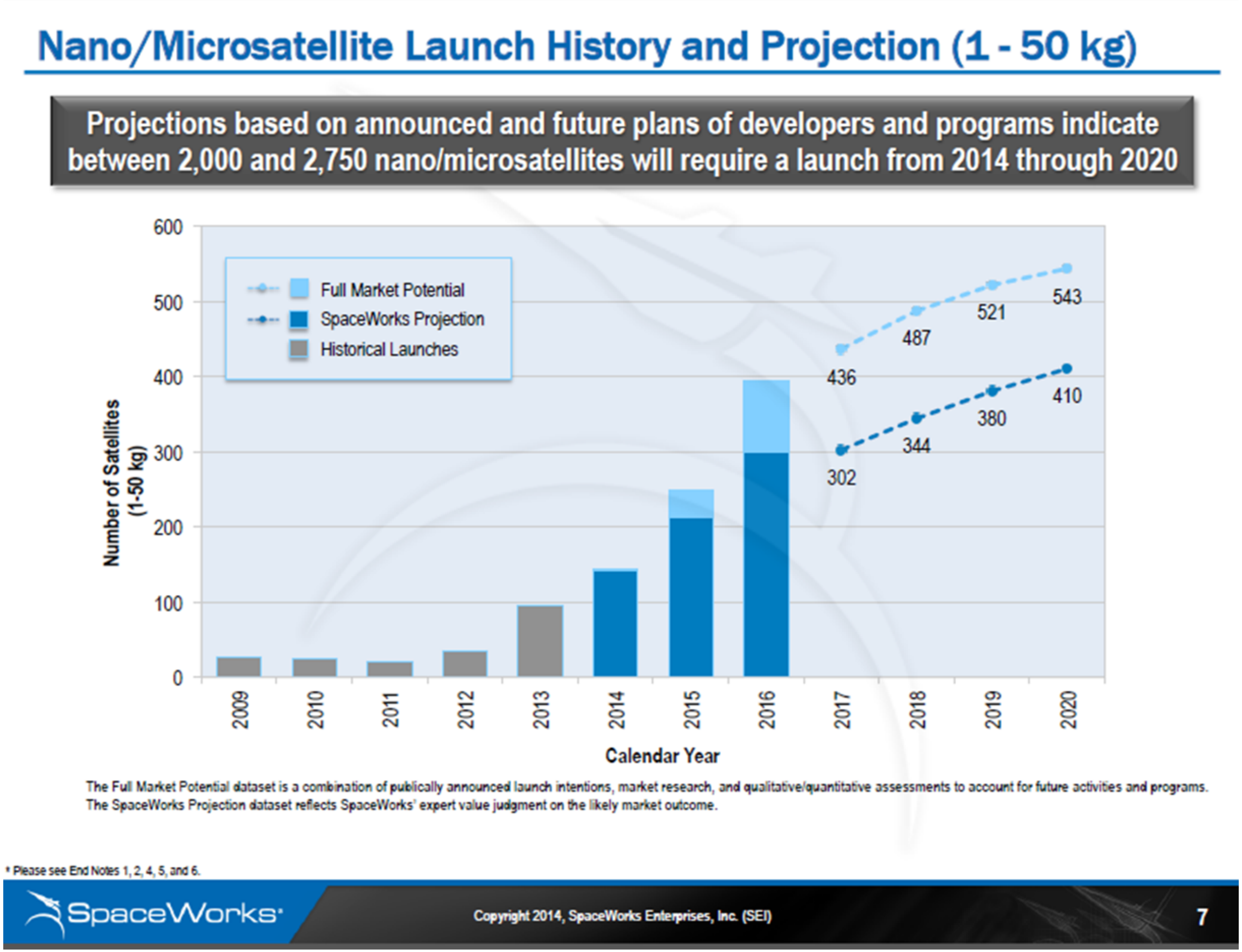


The iSAT Project launches a small spacecraft into low-Earth orbit to:

- Validate system performance in space
- Demonstrate high ΔV primary propulsion
- Reduce risk for future higher class iodine missions
- Demonstrate new power system technology for SmallSats
- Demonstrate new class of thermal control for SmallSats
- Perform secondary science phase with contributed payload
    - Increase expectation of follow-on SMD and AF missions
- Demonstrate SmallSat Deorbit
- **Validate iodine spacecraft interactions / efficacy**

High value mission for SmallSats and for future higher-class mission leveraging iodine propulsion advantages.

The SmallSat Market



Nano/Microsatellite Launch History and Projection (1 - 50 kg)

Projections based on announced and future plans of developers and programs indicate between 2,000 and 2,750 nano/microsatellites will require a launch from 2014 through 2020

The Full Market Potential dataset is a combination of publically announced launch intentions, market research, and qualitative/quantitative assessments to account for future activities and programs. The SpaceWorks Projection dataset reflects SpaceWorks' expert value judgment on the likely market outcome.

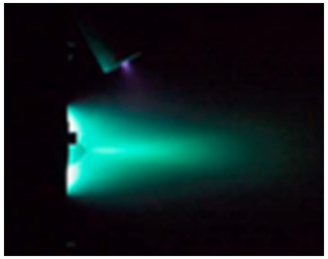
* Please see End Notes 1, 2, 4, 5, and 6.

SpaceWorks

Why Iodine?

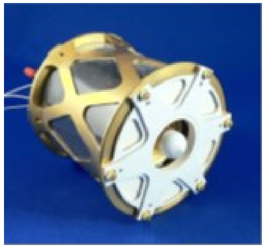
Today’s SmallSats have limited propulsion capability and most spacecraft have none

- The State of the Art is cold gas propulsion providing 10s of m/s ΔV
- No solutions exist for significant altitude or plane change, or de-orbit from high altitude
- SmallSat secondary payloads have significant constraints
  - No hazardous propellants allowed
  - Limited stored energy allowed
  - Limited volume available
  - Indefinite quiescent waiting for launch integration



Iodine is uniquely suited for SmallSat applications

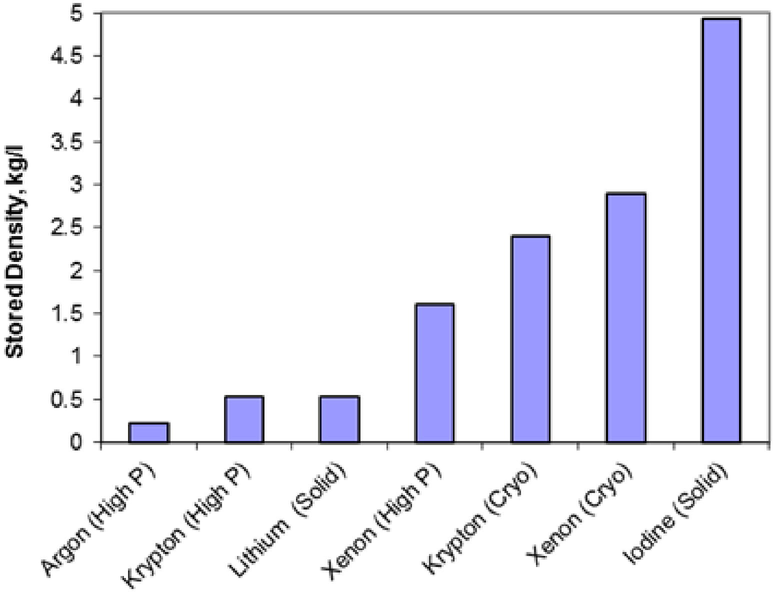
- Iodine electric propulsion provides the high ISP * Density (i.e. ΔV per unit volume)
  - 1U of iodine on a 12U vehicle can provide more than 5 km/s ΔV
    - Enables transfer to high value operations orbits
    - Enables constellation deployment from a single launch
    - Enables de-orbit from high altitude deployment (ODAR Compliance)
  - Iodine enables > 10km/s for ESPA Class Spacecraft
    - GTO deployment to GEO, Lunar Orbits, Near Earth Asteroids, Mars and Venus
      - Reduces launch access by 90%
      - Reduces mission life cycle cost by 30 – 80%
- Iodine is a solid at ambient conditions, can launch unpressurized and sit quiescent indefinitely

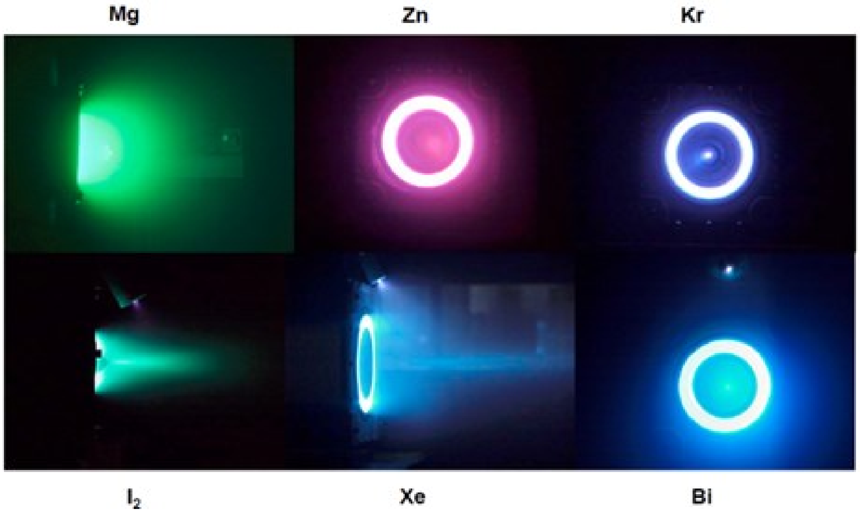


The technology leverages high heritage xenon Hall systems

- All systems currently at TRL 5 with maturation funded to achieve TRL 6 in FY16
- The iSAT System is planned for launch readiness in early 2017

Iodine vs. Alternatives



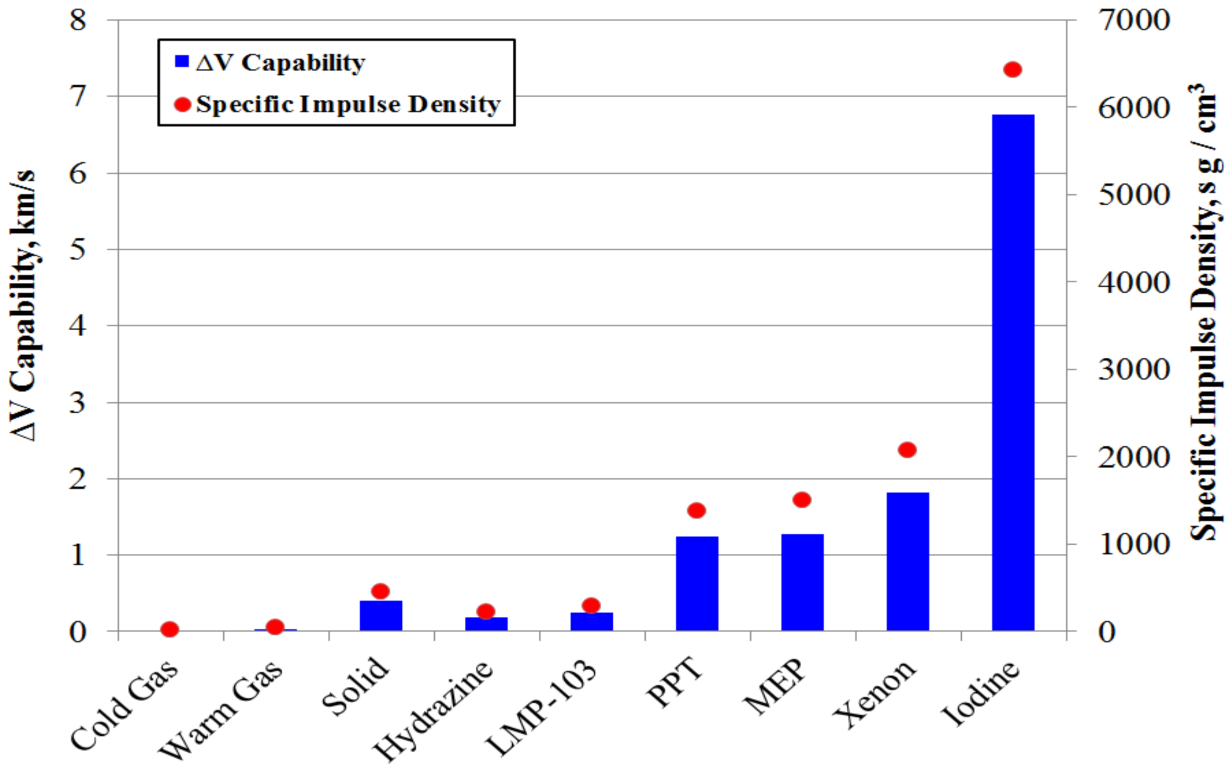


Propellant	Storage Density	Boiling Point, °C	Melting Point, °C	Vapor Pressure @ 20°C
Xe (SOA)	1.6 g/cm^3	-108.1 °C	-111.8 °C	Supercritical (>15MPa)
Iodine	4.9 g/cm^3	184.3 °C	113.7 °C	40 Pa (0.0004 atm)
Bismuth	9.8 g/cm^3	1,564 °C	271.4 °C	Solid
Magnesium	1.74 g/cm^3	1,091 °C	650 °C	Solid

Iodine has unique characteristics well suited for mission application

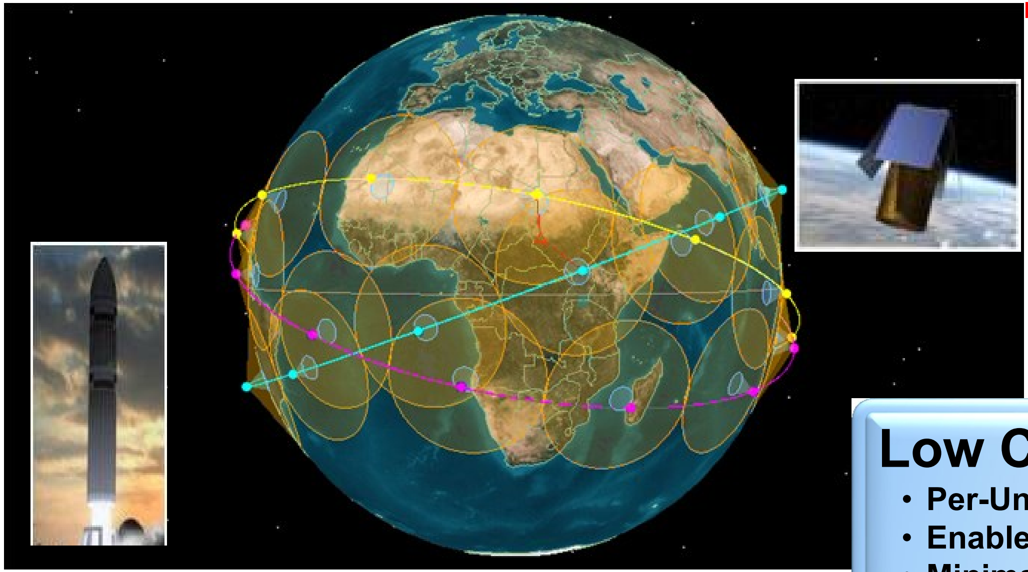
Microsatellite Advantages

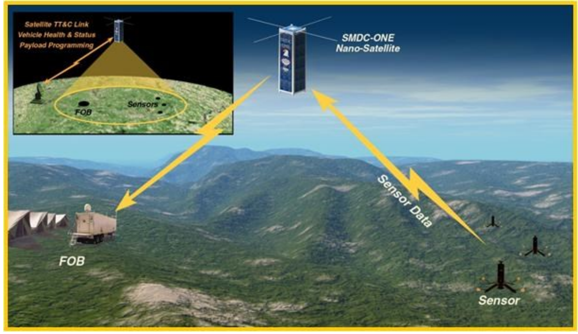
Primary mission advantages are due to 1) Increased I_{SP} * Density
2) Low storage pressure



Iodine allows very small tanks with manufacturing advantages.

SmallSat Applications: USASMDC / ARSTRAT





Low Cost

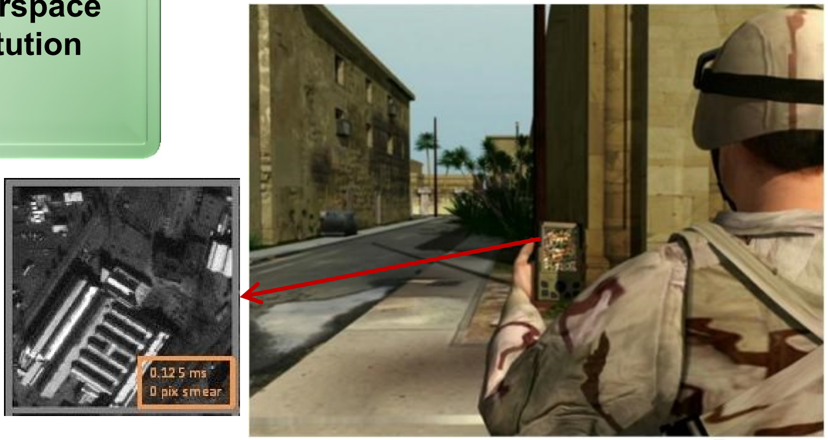
- Per-Unit Cost Very Low
- Enables Affordable Satellite Constellations
- Minimal Personnel and Logistics Tail
- Frequent Technology Refresh

Survivability

- Fly Above Threats and Crowded Airspace
- Rapid Augmentation and Reconstitution
- Very Small Target

Responsiveness

- Short-Notice Deployment
- Tasked from Theater
- Persistent and Globally Available
- Can Adapt to the Threat



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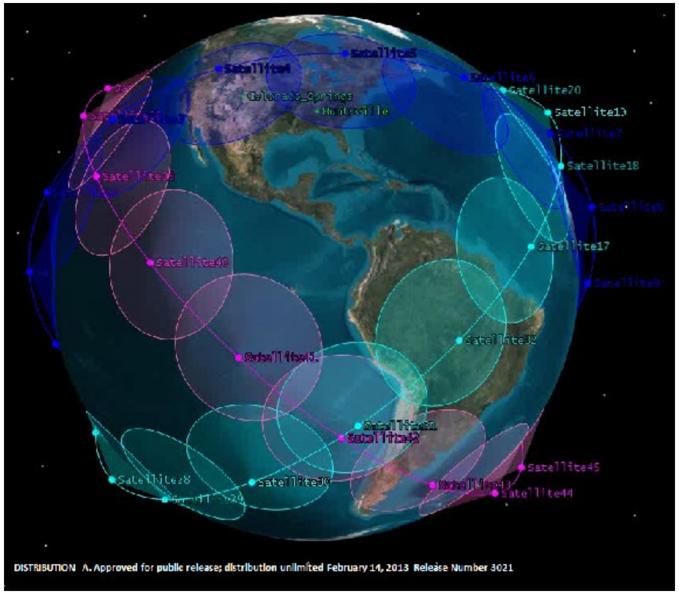
Geocentric MicroSat Application

Large increase in demand for MicroSat constellations and in-space responsive capabilities.

- The 12U with 5kg of iodine can perform 4km/s ΔV
  - 20,000km altitude change
  - 30^{o} inclination change from LEO
  - 80^{o} inclination change from GEO
- Larger spacecraft can perform even greater ΔV



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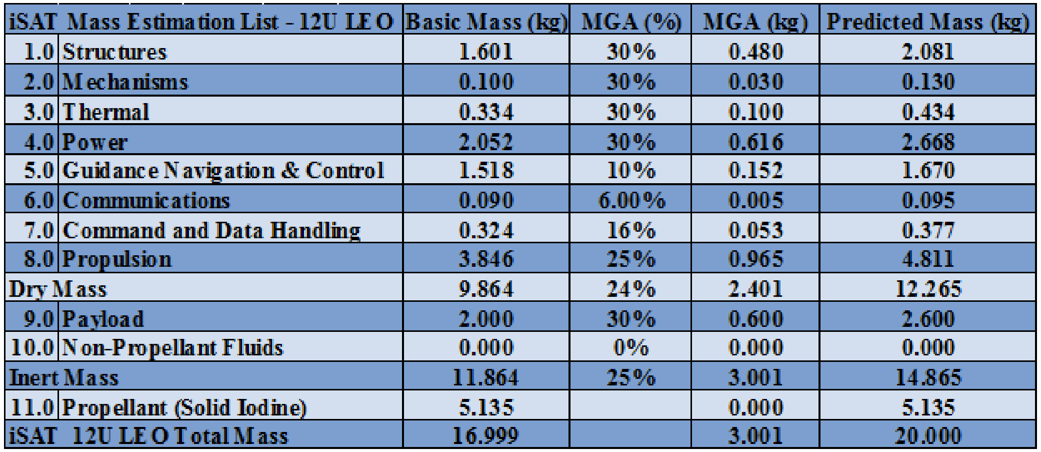


iSAT Mass Estimation List - 12U LEO		Basic Mass (kg)	MGA (%)	MGA (kg)	Predicted Mass (kg)
1.0	Structures	1.601	30%	0.480	2.081
2.0	Mechanisms	0.100	30%	0.030	0.130
3.0	Thermal	0.334	30%	0.100	0.434
4.0	Power	2.052	30%	0.616	2.668
5.0	Guidance Navigation & Control	1.518	10%	0.152	1.670
6.0	Communications	0.090	6.00%	0.005	0.095
7.0	Command and Data Handling	0.324	16%	0.053	0.377
8.0	Propulsion	3.846	25%	0.965	4.811
Dry Mass		9.864	24%	2.401	12.265
9.0	Payload	2.000	30%	0.600	2.600
10.0	Non-Propellant Fluids	0.000	0%	0.000	0.000
Inert Mass		11.864	25%	3.001	14.865
11.0	Propellant (Solid Iodine)	5.135		0.000	5.135
iSAT 12U LEO Total Mass		16.999		3.001	20.000

Iodine is enabling for propulsive missions.

iSAT Mission Requirements

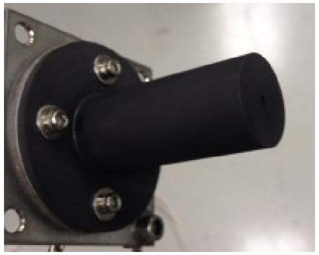
- Demonstrate no less than 100m/s of ΔV
- Determine thrust within 5% uncertainty
- Determine specific impulse within 10% uncertainty
- Perform propulsion altitude change of no less than 250km
- Perform propulsive node change
- Demonstrate no less than 80 hrs of thruster operation
  - *Nearly 2x TacSat-2
- Include instruments to assess thruster plume environment
  - *Radiometer from TacSat-2
- Include instruments to assess future payloads environment
  - *Photometer from TacSat-2
- De-orbit the spacecraft in less than 90 days following end of mission

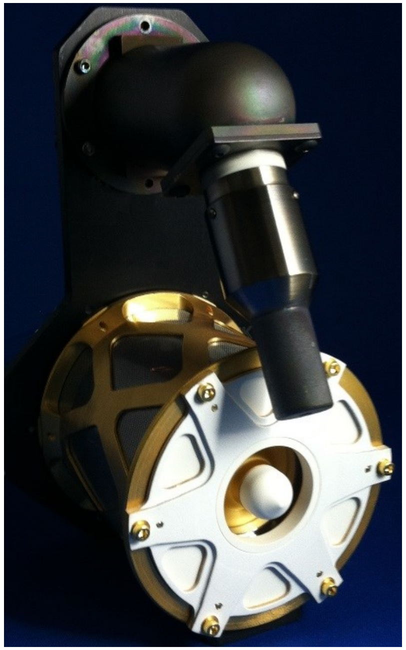
iSAT will be the first CubeSat to demonstrate significant post launch maneuverability.

iSAT Propulsion System

BHT-200-I Thruster:

- Heritage to TacSat-2
  - Most studied thruster since SPT-100
- Material changes for iodine compatibility

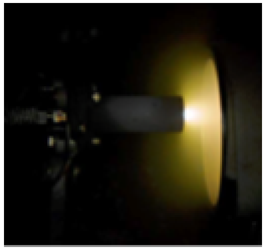




Cathode:

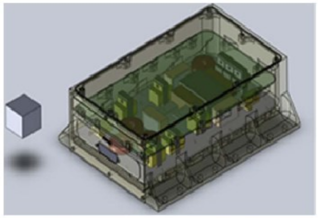
Electric Cathode

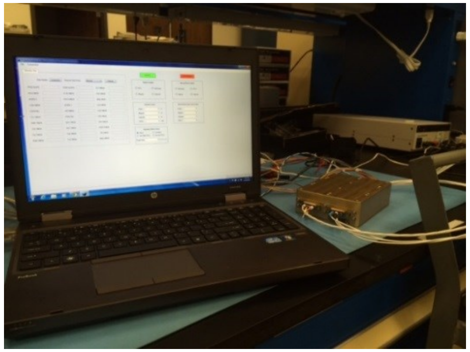
- Minimize power requirements



Compact PPU:

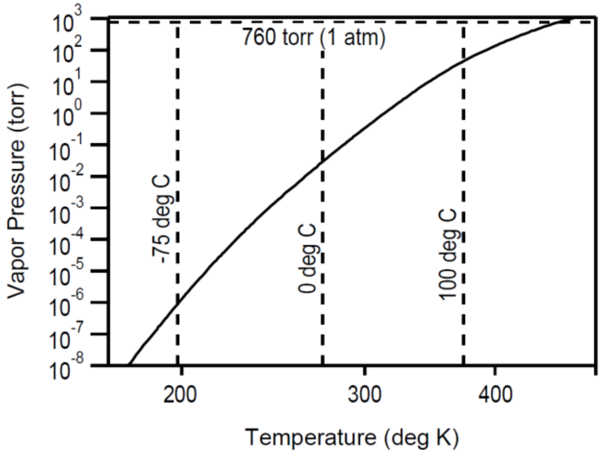
- 3rd PPU iteration ongoing
- Based on BPU-600
  - 80% Mass reduction
  - 90% Volume reduction
- Initiated under AF ORS SBIR

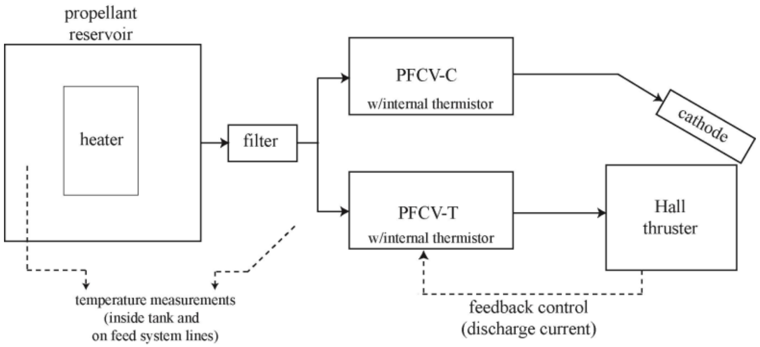




Feed System and DCIU

(Applicable to future iodine systems)

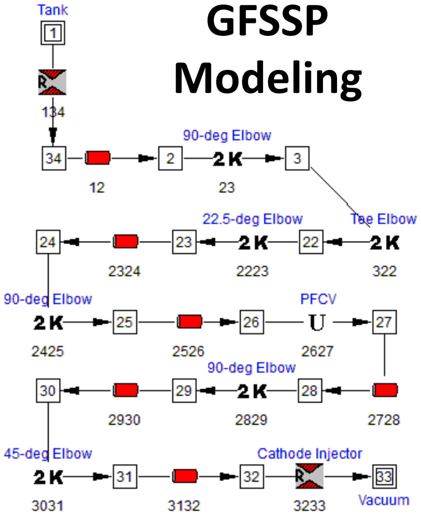




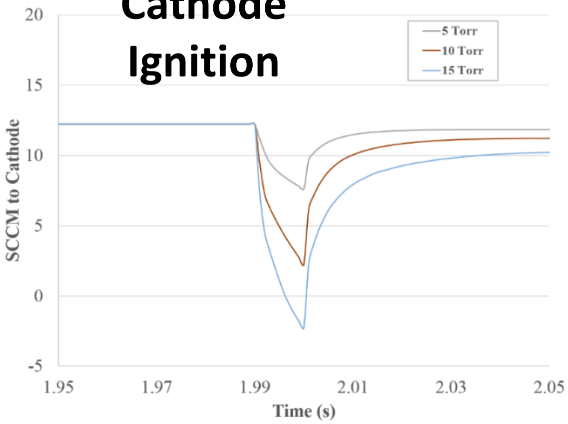
Propellant sublimes at low temperature (<100C) to become low pressure (~50 torr) gas source

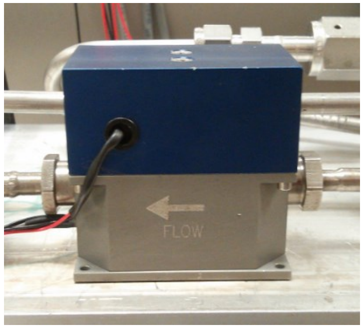
Component Characterization

GFSSP Modeling



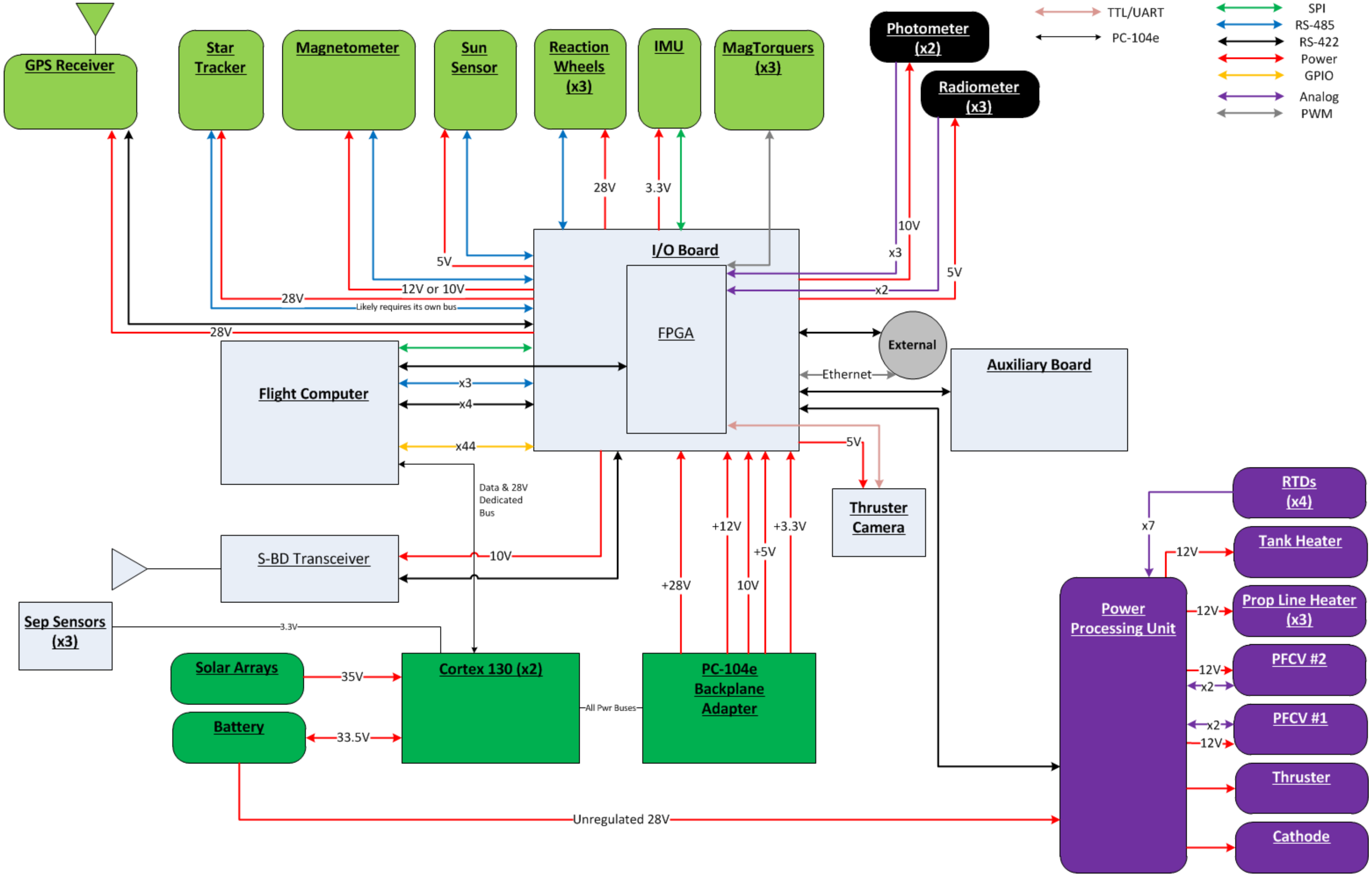
Cathode Ignition





Iodine PFCV

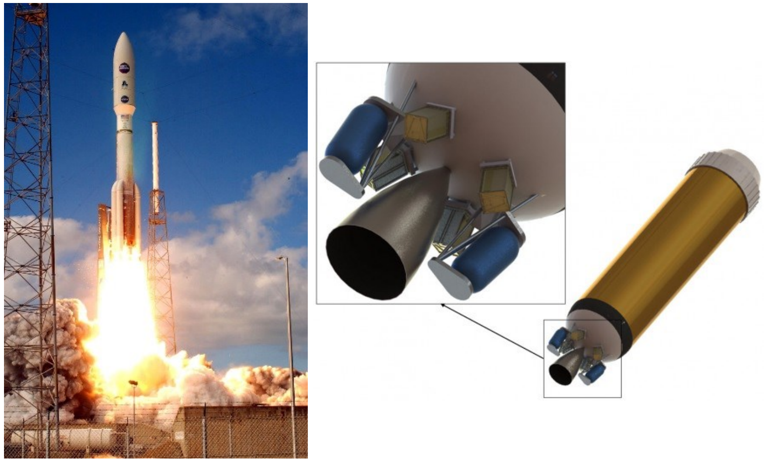
System Schematic



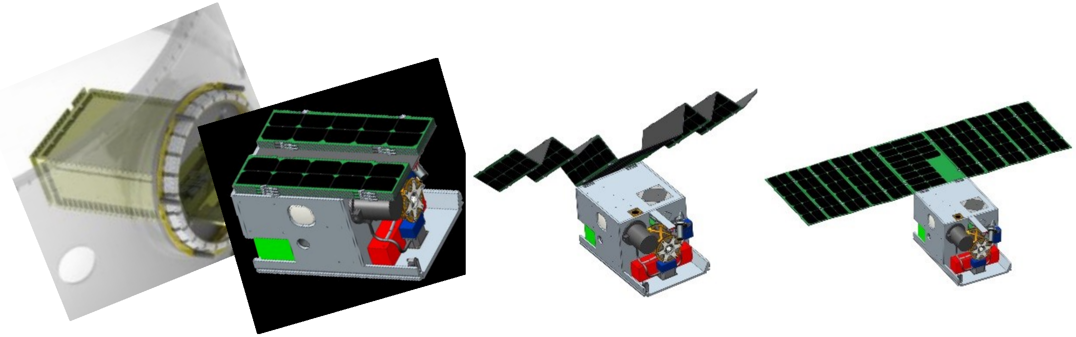
Attitude Determination and Control

Component	Quantity	Power (per unit)	Mass (per unit)	Vendor, Part #
Reaction Wheels	3	Pitch - 1.8W Steady State Roll - 0.5W Steady State Yaw - 0.5W Steady State	0.288 kg	Blue Canyon Technologies RWp100
Torque Rods	3	1W Full Power >0.2W Expected Draw	~0.1 kg	Blue Canyon Technologies $0.6Am^2$
Digital Control Electronics	1	Peak Power 1.0 W Average power 0.75W	0.2 kg	Blue Canyon Technologies DCE
Star Tracker	1	Peak Power ≤ 1.25W Average Power ~1W	0.312 kg	Blue Canyon Technologies Nano Star Tracker
Inertial Measurement Unit (IMU)	1	0.1 W	0.007 kg	Epson M-G350-PD11
GPS	1	1 W	< 0.2 kg	Spacequest SQ-GPS-12-V1
Sun Sensor	1	Peak Power 0.13W Average Power 0.04W	0.034 kg	SSBV SS-411
Magnetometer	1	Peak Power 0.525W Average Power 0.405W	0.098 kg	Honeywell HMR2300

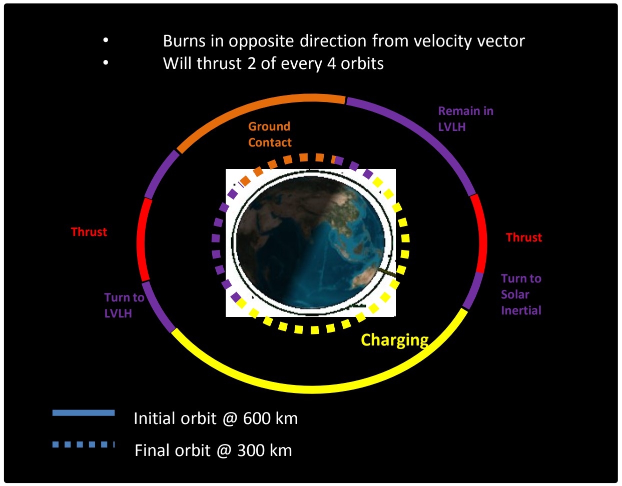
iSAT CONOPS



Launch in a PSC 12U Deployer on NRO (TBD) Launch Vehicle (Atlas V)

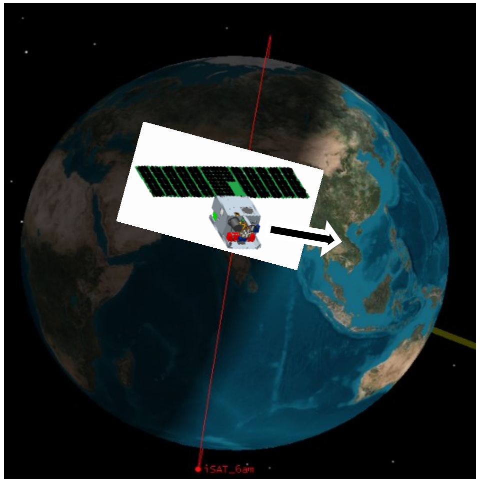


- Eject from PSC 12U Deployer
- Unfold Solar Arrays
- Checkout/Activation Process

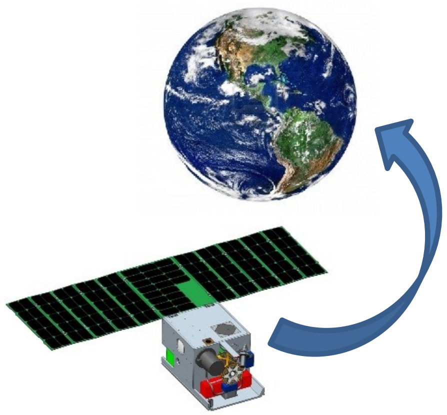


- Burns in opposite direction from velocity vector
- Will thrust 2 of every 4 orbits

Perform Propulsive Altitude Change

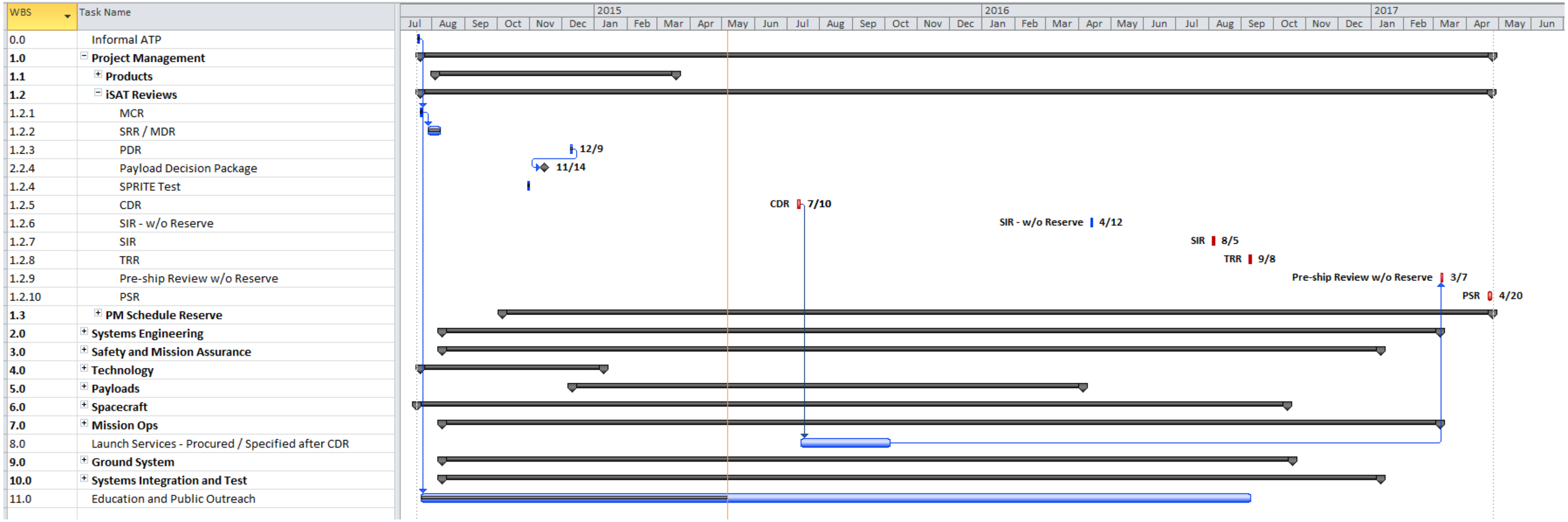


Perform Propulsive Inclination Change



Place iSAT in disposal orbit (<90 day decay)

Project Schedule / Milestones



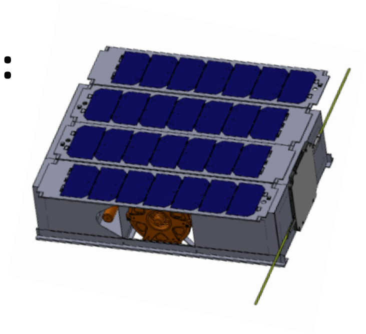
WBS	Task Name
0.0	Informal ATP
1.0	**Project Management**
1.1	**Products**
1.2	**iSAT Reviews**
1.2.1	MCR
1.2.2	SRR / MDR
1.2.3	PDR
2.2.4	Payload Decision Package
1.2.4	SPRITE Test
1.2.5	CDR
1.2.6	SIR - w/o Reserve
1.2.7	SIR
1.2.8	TRR
1.2.9	Pre-ship Review w/o Reserve
1.2.10	PSR
1.3	**PM Schedule Reserve**
2.0	**Systems Engineering**
3.0	**Safety and Mission Assurance**
4.0	**Technology**
5.0	**Payloads**
6.0	**Spacecraft**
7.0	**Mission Ops**
8.0	Launch Services - Procured / Specified after CDR
9.0	**Ground System**
10.0	**Systems Integration and Test**
11.0	Education and Public Outreach

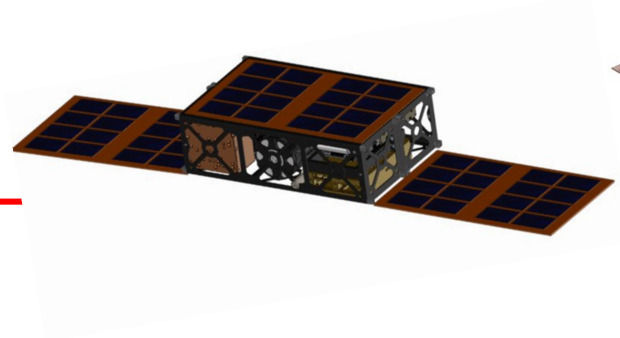
- CDR: Summer, 2015
- SIR: Spring, 2016
- TRR: Summer, 2016
- PSR: Spring, 2017
- Launch: Fall, 2017 (TBD)

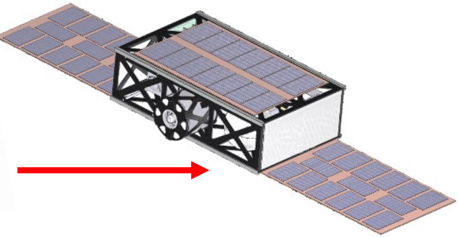
iSAT project has ~25% schedule reserves remaining for April PSR.

Design Evolution

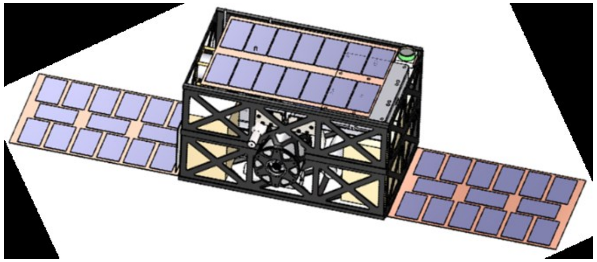
Pre-Phase A:



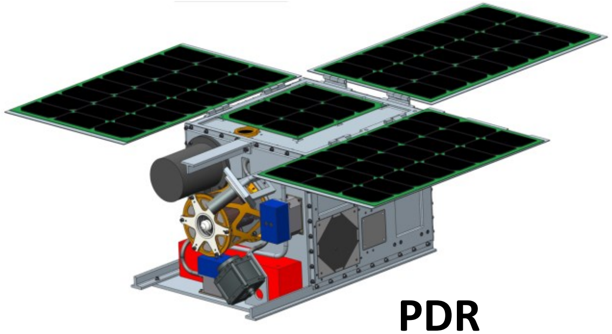




Phase A:

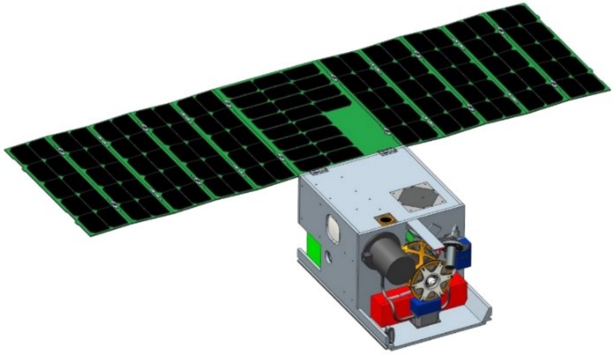


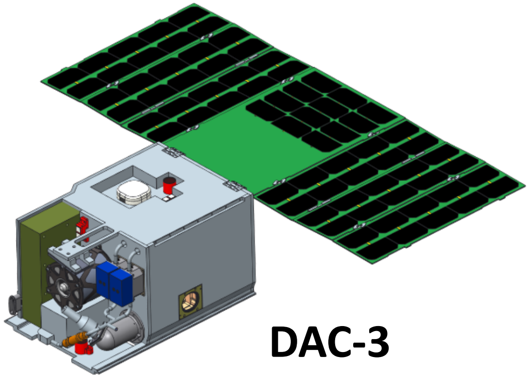
Phase B:



PDR

Phase C:

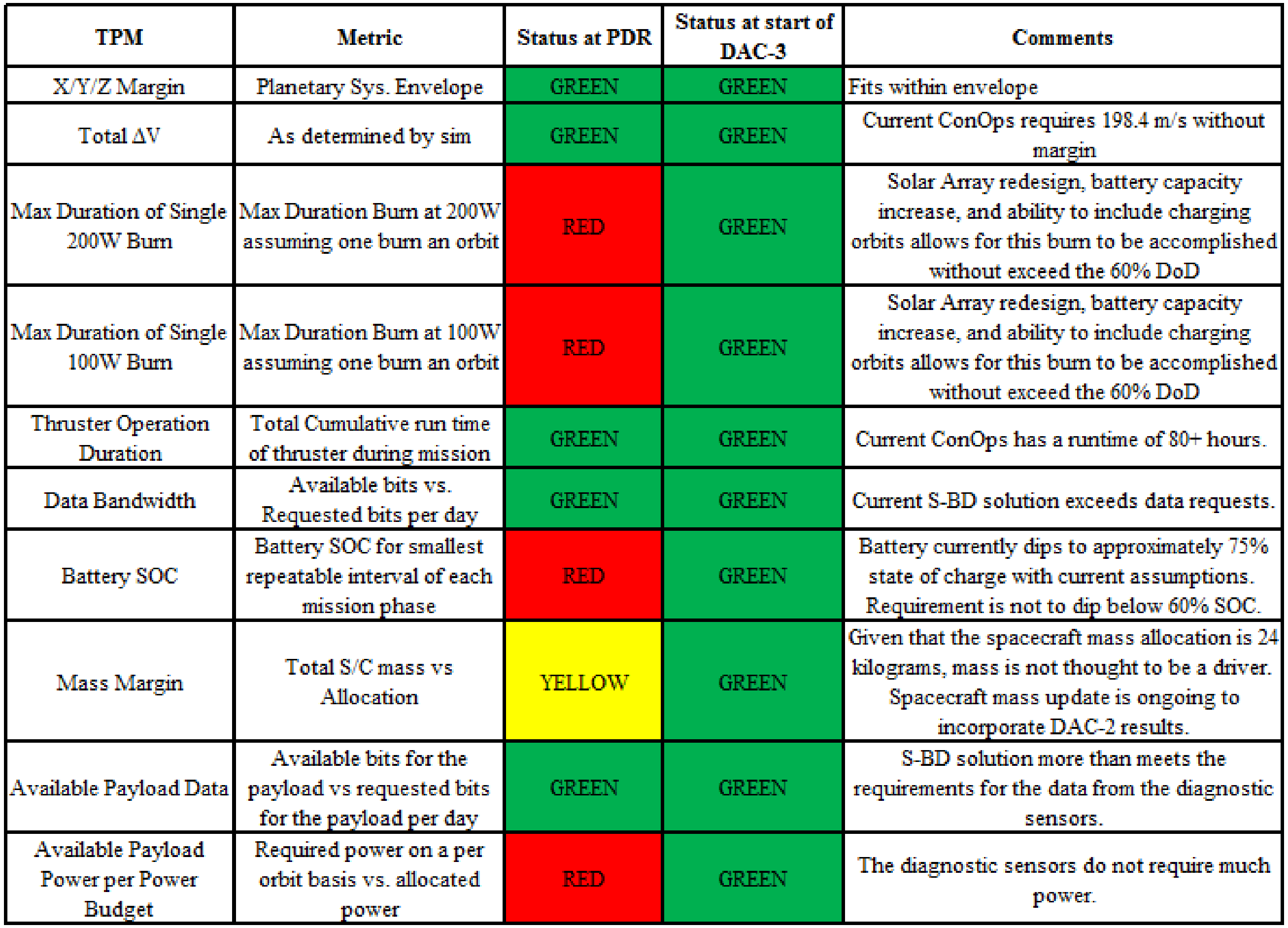




DAC-3

iSAT Design has Evolved Significantly as the Design Matured

Technical Performance Metrics Progress

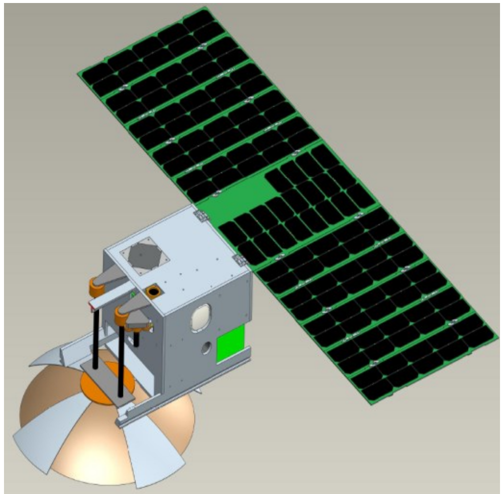


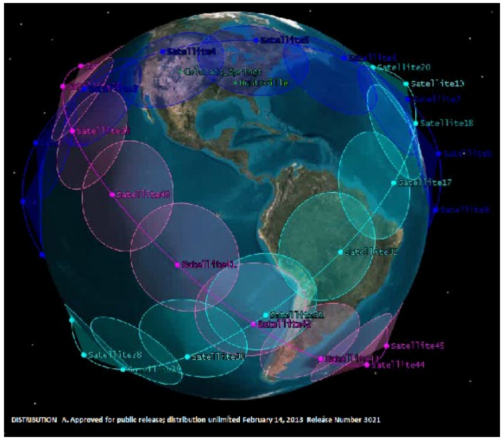
TPM	Metric	Status at PDR	Status at start of DAC-3	Comments
X/Y/Z Margin	Planetary Sys. Envelope	GREEN	GREEN	Fits within envelope
Total ΔV	As determined by sim	GREEN	GREEN	Current ConOps requires 198.4 m/s without margin
Max Duration of Single 200W Burn	Max Duration Burn at 200W assuming one burn an orbit	RED	GREEN	Solar Array redesign, battery capacity increase, and ability to include charging orbits allows for this burn to be accomplished without exceed the 60% DoD
Max Duration of Single 100W Burn	Max Duration Burn at 100W assuming one burn an orbit	RED	GREEN	Solar Array redesign, battery capacity increase, and ability to include charging orbits allows for this burn to be accomplished without exceed the 60% DoD
Thruster Operation Duration	Total Cumulative run time of thruster during mission	GREEN	GREEN	Current ConOps has a runtime of 80+ hours.
Data Bandwidth	Available bits vs. Requested bits per day	GREEN	GREEN	Current S-BD solution exceeds data requests.
Battery SOC	Battery SOC for smallest repeatable interval of each mission phase	RED	GREEN	Battery currently dips to approximately 75% state of charge with current assumptions. Requirement is not to dip below 60% SOC.
Mass Margin	Total S/C mass vs Allocation	YELLOW	GREEN	Given that the spacecraft mass allocation is 24 kilograms, mass is not thought to be a driver. Spacecraft mass update is ongoing to incorporate DAC-2 results.
Available Payload Data	Available bits for the payload vs requested bits for the payload per day	GREEN	GREEN	S-BD solution more than meets the requirements for the data from the diagnostic sensors.
Available Payload Power per Power Budget	Required power on a per orbit basis vs. allocated power	RED	GREEN	The diagnostic sensors do not require much power.

Significant progress since PDR to meet all mission requirements.

Bus Future Use

- The iSAT spacecraft leverages a high performance integrated bus solution in a 12U Package
  - 100W Solar Array
  - Thermal solution for high power density small spacecraft
  - Large suite of avionics I/O capability
  - Full ACS System with Star Trackers, Reaction Wheels, Mag Torquers, IMU, etc.
  - Power system for >200W >10min power bursts at 28V





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In addition to the propulsion, the bus has future mission applicability.

Summary

- Propulsion remains a key limiting capability for SmallSats that iodine can address
  - High I_{SP} * Density (ΔV per volume)
  - Indefinite quiescence, unpressurized and non-hazardous as a secondary payload

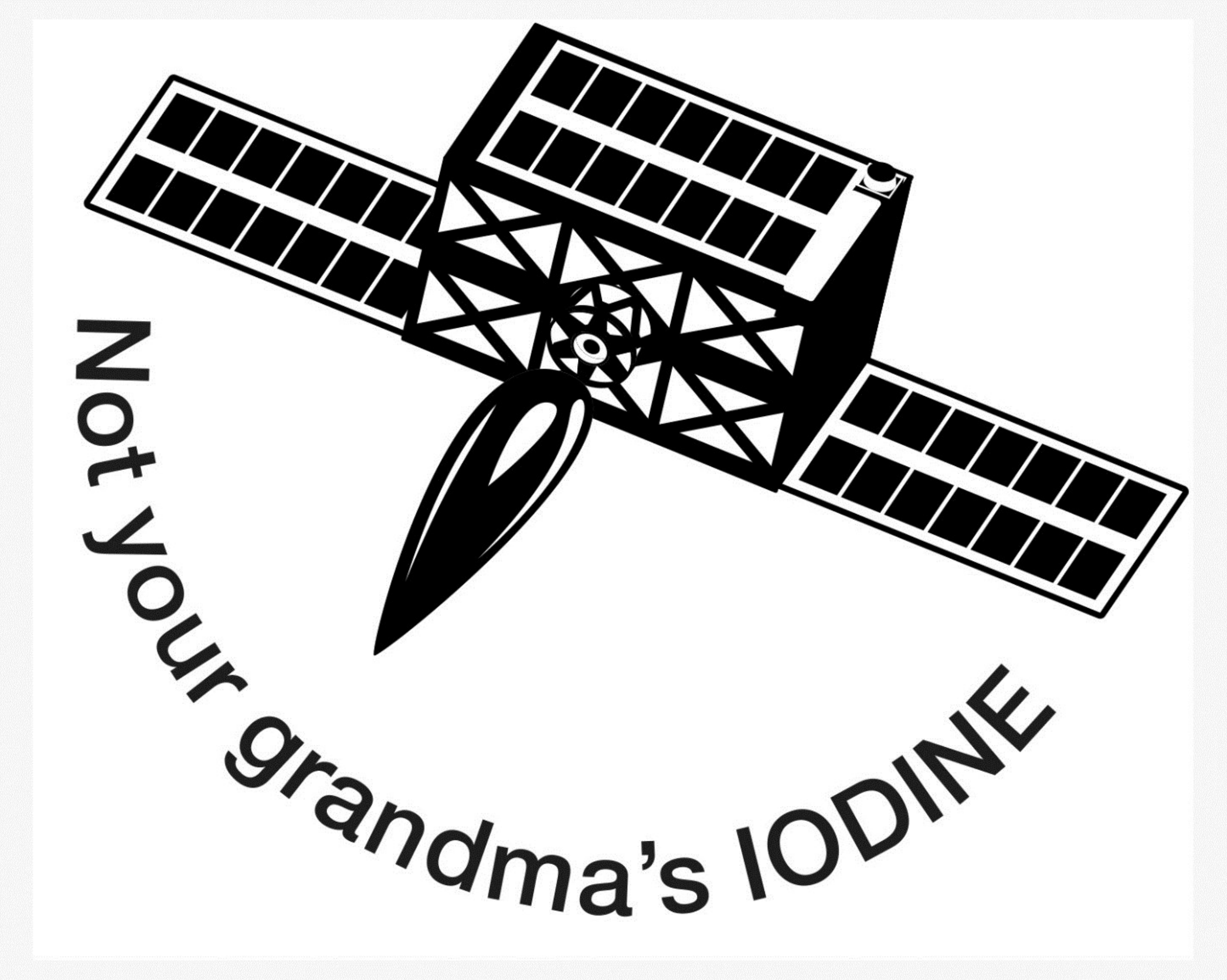
- The iSAT project is a fast pace high value iodine Hall technology demonstration mission
  - Partnership with NASA GRC and NASA MSFC with industry partner – Busek
    - Air Force SMC Sponsored Contract to Busek
    - Aerospace Corporation contributed cameras
    - AFRL contributed instrumentation
  - Delivery for launch spring of 2017

- Preliminary system-level testing complete with SPRITE and additional testing throughout life-cycle development
  - Long duration thruster testing at NASA GRC in May 2015

- The project has successfully passed mission PDR and is heading towards CDR summer 2015

- Both the propulsion system and the spacecraft bus have significant future mission potential

Questions?



Backup

iSAT Project Overview

Mission Justification

There is an emerging and rapidly growing market for SmallSats

- SmallSats are significantly limited by primary propulsion
  - Desire to transfer to higher value science / operations orbit and responsive space
  - Desire to extend mission life / perform drag make-up
  - Requirement to deorbit within 25 years of end-of-mission

Limitations on SmallSats limit primary propulsion options

- Requirements imposed by nature of secondary payloads
  - Limitations for volume, mass and power
  - Limitations on hazardous and stored energy from propellants
  - Limitations for high pressure systems
  - Systems must sit quiescent for unknown periods before integration with primary

Why perform flight validation?

- Reduce risk of implementation of iodine for future higher class missions
- Gain experience with condensable propellant spacecraft interactions
- Reduce risk of custom support systems
  - Power generation, storage and distribution
  - Thermal control
- Cost effective risk reduction before maturing higher power systems

Material Testing - Literature

Iodine Vapor Literature Search

A literature search for iodine vapor interaction found two sources that qualitatively and in some cases quantitatively documented the resistance of various materials to iodine.

Systems	Metal or Alloy	Base Elements	Dry Iodine Vapor @ 25 °C	Dry Iodine Vapor @ 100 ° C	Dry Iodine Vapor @ 300 °C, 0.53 atm (Corrosion Rate mm/year)	Dry Iodine Vapor @ 450 °C, 0.53 atm (Corrosion Rate mm/year)
Nickel Alloys	Pure Nickel	Ni	Resistant	Resistant	0.27	1.2
	Inconel 600	Ni-Cr-Fe	Resistant	Resistant	0.107	0.54
	Inconel 625	Ni-Cr-Mo	Resistant	Resistant	0.057	No Data
Noble Metals	Pure Platinum	Pt	Resistant	Resistant	0	0.006
	Pure Gold	Au	Resistant	Resistant	0	0.024
Refractory Metals	Pure Tungsten	W	Resistant	Resistant	0	0.008
	Pure Molybdenum	Mo	Resistant	Resistant	0.003	0.033
	Pure Tantalum	Ta	Resistant	Resistant	0.005	0.88
Aluminum	Pure Aluminum	Al	Unusable	Unusable	Unusable	Unusable
Copper Alloys	Pure Copper	Cu	Resistant	Unusable	Unusable	Unusable
	Brass	Cu-Zn	Resistant	Unusable	Unusable	Unusable
Iron Allloys	Iron, Cast Iron, Steel	Fe	Resistant	Unusable	Unusable	Unusable
	Enamelled Cast Iron	Fe + Duran or Pyrex	Resistant	Resistant to 200 °C	Unusable	Unusable
	316 Stainless Steel	Fe-Cr-Ni	Resistant	Resistant	0.4 Est.*	2.1
	304 Stainless Steel	Fe-Cr-Ni	Resistant	Resistant	0.6 Est.*	3.2

* Estimated corrosion rate at 300 °C based on extrapolation from 450 °C data

Limited relevant data in the literature.

Material Testing – MSFC Matrix

Sample Matrix for Iodine Exposure Testing

Material Category	Material Identification	Test Specimen ID
Steel Alloys	304 Stainless Steel	S3
	316 Stainless Steel	S6
	4130 Alloy Steel	S4
Aluminum Alloys	6061 Aluminum	A6
	7075 Aluminum	A7
	7075 Aluminum, Anodized	AA
Copper Alloys	110 Copper	CU
	Brass	C2
Titanium Alloys	Titanium 6-Al-4V	T6
	Commercially Pure Ti	TI
Polymers	Buna-N	BN
	Viton	VT
	Teflon	TF
	Kapton Tape	KP
Composites	Carbon Fiber Composite	CC
Glass	Plate Glass	GL
Circuit Boards & Electronic Materials	Populated Circuit Board	EC
	Potting Compound	PC
	Arathane 5750LV Conformal Coating	AC

Significant material testing ongoing at NASA MSFC.

Communications

(PDR Design – Currently S-Band Only)

Baseline to use Near-Earth-Network; only 3/15 stations for the baseline