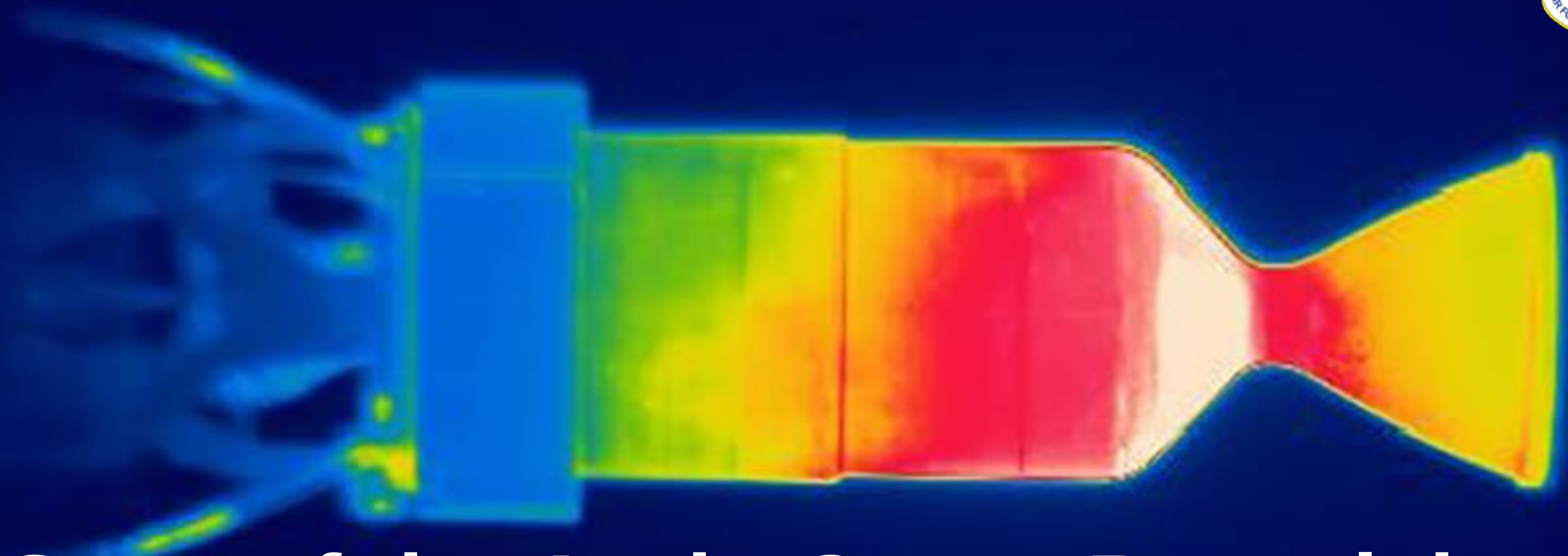

State of the Art in Green Propulsion - 2020

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In-Space Chemical Propulsion TIM – September 2020

Agenda

1. Motivation
2. DoD/USAF vs. NASA Interests
3. State of the Art (SOA) Report
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   - Progress to Mission Infusion Definitions
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4. Technologies
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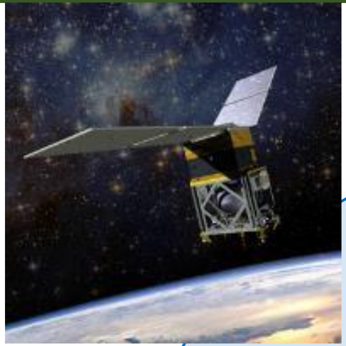
Motivation

- In 2018 NASA sought to develop its own technology roadmap following a 2015 inter-agency roadmap effort on the state of green propellant technologies
  - That document, NASA TP-NASA/TP-2018-219861, identified several areas for further technology development, and is available in the public domain
- Based on that roadmap, NASA's Green Propulsion Working Group seeks to further identify opportunities to champion infusion and maturation of green propulsion technologies
- In tandem, the USAF (via the AFRL) supports the proliferation of ASCENT thruster technology, through modeling & simulation, characterization & assessments, and thruster hardware maturation efforts
- It is of value to AFRL and NASA to identify and capture the green propulsion State of the Art (SOA)
- This presentation, a collaborative effort of NASA and AFRL, will identify the current (as of 2020) state of the art in green propulsion technologies and capabilities for public awareness

DoD/USAF vs. NASA interests



DoD/USAF

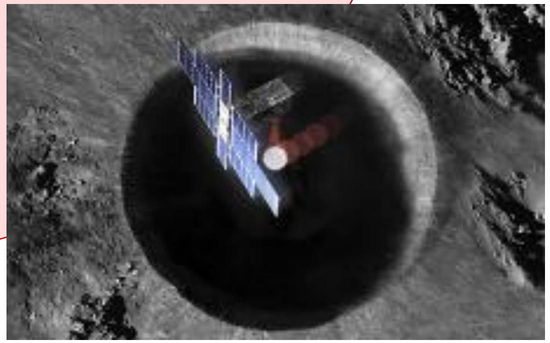
- **Resilience** of spacecraft operations over wide range of mission sets
- **Focus on ASCENT propellant**
- **Emphasis on 1-N thrust level**
  - Scale up to 22 N and 100 N
- **Fusion of measured data with theoretical models**

Shared:

- **Improved performance (Isp) and Density-Isp**
- **Lower Toxicity**
- **Robust (long-life)**
- **Mission Infusion & Maturation**

NASA

- **Low-cost systems –** willing to trade some performance for cost
- **Propellant agnostic**
- **Near-term focus SmallSat scales** 100-mN to 5-N
- **Incentivizing mission adoption through public-private partnerships**



State of the Art (SOA) Report - Foundation

- In 2013, the NASA Space Technology Mission Directorate (STMD) first published a "State-of-the-Art" report for Small Spacecraft
  - It was first commissioned by NASA's Small Spacecraft Technology Program (SSTP) in response to the rapid growth in small spacecraft
    - Covers all areas of technology – power, propulsion, comms, etc.
    - Focused as an "end-users" guide to help identify "ready" technologies
    - Revised in 2015 and 2018, with another revision to be released in 2020
- Since the SmallSat SOA report – a rapid development has occurred in green propulsion
  - However, there is still a perceived lack of flight heritage and/or development maturity
- The objective of the SOA report is to provide Mission Planners a quick reference guide to selecting green propulsion systems that are flight ready

State of the Art (SOA) Report – Progress to Mission Infusion Definitions

- TRL assessments for technologies in this report are based upon recommendations in "JANNAF Guidelines for the Application of Technology Readiness Levels (TRLs) to Micro-Propulsion Systems"
- An accurate TRL assessment, however, includes an understanding of mission-specific environments, interfaces, and verification history
- To simplify understanding of TRL assessments, we further bin TRLs into Progress to Mission Infusion (PMI) categories
  - These are described in detail in a 2020 revision of the Small Satellite SOA report's propulsion chapter
- This classification system is intended to provide end users easier to digest assessments of the SOA to understand the device and system maturities
  - This novel classification system is not intended to replace TRLs

Concept, 'C'

- At minimum, an idea has been established as scientifically feasible.
- May even include experimental verification of the underlying physics.
- May even include notional device designs.
- Approximately aligns to NASA TRL 1-3

In-Development, 'D'

- At minimum, a low-fidelity device that has been operated in an appropriate environment to demonstrate the basic functionality and predict the ultimate capabilities.
- May even be a medium- or high-fidelity device operated in a simulated final environment, but the device lacks a specific mission pull to define requirements and a qualification program.
- May even be a medium- or high-fidelity device operated in a flight demonstration, but the device lacks sufficient fidelity or demonstrated capability to reflect the anticipated final product.
- Approximately aligns to NASA TRL 4-5

Engineering-to-Flight, 'E'

- At minimum, a medium-fidelity device that has been operated in a simulated final environment and demonstrates key capabilities relative to the requirements of a specific mission.
- May even include a qualification program in-progress or completed.
- May even include a spaceflight, but the device fails to demonstrate key capabilities.
- May even include a successful spaceflight, but the device is now being applied in a new environment or platform, necessitating a delta-qualification.
- A specific mission opportunity must be identified in open literature.
- Approximately aligns to NASA TRL 5-6

Flight-Demonstrated, 'F'

- At minimum, a high-fidelity component or system (fit, form, and function) that has been operated in the intended in-space environment (e.g., LEO, GEO, deep space) on an appropriate platform, where key capabilities have been successfully demonstrated.
- May even be a final product that has completed a mission (not strictly a technology demonstration).
- May even be a product in repeat production and routine use for a number of missions.
- A successful spaceflight must be identified and the outcome described in open literature.
- Approximately aligns to NASA TRL 7-9

TRL 1

TRL 9

State of the Art (SOA) Report – What's included

- Majority of document references ionic liquid blends, frequently referred to as "green monopropellants" (i.e AF-M315E (ASCENT), LMP-103S, etc)
- This document is a survey of green propulsion technologies as discussed in open literature and does not intend to be a primary, original source
  - End users should consult primary sources for specifics on performance or capabilities
- This work only considers literature in the public domain to identify and classify devices and is intended to be a open, publically available document
  - Commonly used sources for data include manufacturer datasheets, conference papers, journal papers, filings with government agencies, and news articles
  - We recognize that a greater wealth of knowledge is covered under limited distribution or restricted (e.g. export controlled) formats. Where feasible we will reference general technologies for awareness without divulging restricted specific content

State of the Art (SOA) Report – What's included

- The primary sources of data are literature produced by device manufacturer
  - To the greatest extent practical, only publically available sources are used
  - Performance and capabilities described may be speculative or otherwise based on limited data
  - Do not assume independent verification of device performance and capabilities
    - Some capabilities may be restricted from public discussion
- No discussion of technologies or specific devices herein is an endorsement by the U.S. Government
- The authors intend to regularly update this work, and current technologies that are inadvertently missed will be identified and included in future releases
  - Failure to include any specific publically identified products or technologies that might be considered relevant under a particular topic is unintentional

Technologies - Propellants

- Propellants are either blends of the ionic salts Hydroxylammonium Nitrate (HAN) or Ammonium dinitramide (ADN)
  - These salts are then dissolved into solution with other constituents & water to form a "monopropellant"
  - While not a true monopropellant (there are fuel & oxidizer components that combust), they do behave and are treated like a conventional monopropellant (e.g. hydrazine)
- A number of propellant blends exist or are in-work
    - AF-M315E/ASCENT (U.S. developed - a HAN blend)
    - LMP-103S (Swedish developed – an ADN blend)
    - SHP-163 (Japanese developed – a HAN blend)
    - RocketLab is flying a "green monopropellant", but few details exist

Technologies - Propellants

Propellant	Primary Salt	Country of Origin	Major Developer	Density (g/cm^3)	Specific Impulse (s)	PMI	Reference Mission (E/F only)	Reference
AF-M315E (ASCENT)	HAN	United States	AFRL/DSSP	1.4	235-250	F	GPIM	[1]
LMP-103S	ADN	Sweden	ECAPS	1.24	200-285	F	PRISMA/ Skybox	[2]
SHP-163	HAN	Japan	JAXA	1.4	N/A	E	RAPIS-1	[3,4]
“green monopropellant”	N/A	N/A	RocketLab	N/A	N/A	F	KickStage (“Still Testing”)	[5]
Green Electrical Monopropellant (GEM)	HAN	United States	DSSP	N/A	N/A	D	-	[6,7]

N/A = Not Available

Technologies – Catalyst Beds

- Most ionic liquid propellants require a catalyst bed to decompose and combust
- Catalyst beds
  - can be granular or monolithic
  - typically are some substrate (such as ceramic or alumina) coated with a catalytic refractory metal (such as platinum or iridium)
- Granular beds derive from historical hydrazine based system beds (S-405)
  - Typically most readily available - granules can be variety of sizes
  - Often succumb to sintering or breakdown in the high temperature environment of green propellants
  - Differences stem from granular size/distribution and/or substrate/refractory metals used
- Monolithic beds can be metal coated foams or other lattice structures
  - Have advantages with pre-heating and pressure drop, but can be limited in bed loading
  - Can also succumb to breakdown or poisoning in green propellant use
  - Differences stem from pore/lattice distribution & substrate/refractory metals used
- These are the “secret sauce” of green propulsion and often tightly held proprietary – very limited public information exists

Technologies – Thruster Units

Manufacturer	Product	Propellant	Thrust per thruster (Quantity)	Specific Impulse	Total Impulse	Mass	Power	PMI	Reference Missions (E/F only)	Reference
---	---	---	[N]	[s]	[kN-s]	[kg]	[W]	C,D,E,F	---	
Aerojet Rocketdyne	GR-1	ASCENT	0.4-1.1	231	23	N/A	12	F	GPIM	[1]
Aerojet Rocketdyne	GR-22	ASCENT	8.0-25	248	74	N/A	28	E	GPIM	[1]
Bradford-ECAPS	0.1-N HPGP (thruster)	LMP-103S	0.03 – 0.10	196-209	N/A	0.04 excl. FCV	6.3 – 8	E	ArgoMoon	[9]
Bradford-ECAPS	1-N HPGP (thruster)	LMP-103S	0.25 – 1.0	204 – 235	N/A	0.38	8-10	F	SkySat	[9]
Bradford-ECAPS	1-N GP (thruster)	LMP-103S/LT	0.25 – 1.0	194 - 227	N/A	0.38	8-10	D	-	[10]
Bradford-ECAPS	5-N HPGP (thruster)	LMP-103S	1.5 - 5.5	239 -253	N/A	0.48	15-25	D	-	[9]
Bradford-ECAPS	22-N HPGP (thruster)	LMP-103S	5.5 - 22	243 -255	N/A	1.1	25-50	D	-	[9]
Busek	BGT-X1	ASCENT	0.02 – 0.18	214	N/A	N/A	4.5	D	-	[11]
Busek	BGT-X5	ASCENT	0.05 - 0.50	220 - 225	0.56	N/A	20	D	-	[11]
Busek	BGT-5	ASCENT	1.0 – 6.0	> 230	N/A	N/A	50	D	-	[11]
NanoAvionics	EPSS-C1	ADN-blend	0.22-1.0	213	>0.4	N/A	9.6 (preheat) 1.7 (firing)	F	Lituanica-2	[12]
Plasma Processes LLC	100mN Thruster PP3490-B	ASCENT	0.1 – 0.17	195 - 208	N/A	.08	7.5 - 10	E	Lunar Flashlight	[13]
Rocket Lab	Curie Engine	unknown	120	N/A	N/A	N/A	N/A	F	Electron ‘Still Testing’	[5,14]

Note that all data is documented as provided in the references. Unless otherwise published, do not assume the data has been independently verified. N/A = Not Available

Technologies – Integrated Systems

Manufacturer	Product	Propellant	Thrust per thruster (Quantity)	Specific Impulse	Total Impulse	Mass	Envelope	Power	ACS	PMI	Reference Missions (E/F only)	Reference
---	---	---	[N]	[s]	[kN-s]	[kg]	[cm^3 or U]	[W]	Y/N	C,D,E,F	---	---
Aerojet Rocketdyne	MPS-130	ASCENT	0.25-1.0 (4)	N/A	>2.7 (2U) >1.1 (1U)	1.7 – 2.8 † 1.1 - 1.4 ‡	1U – 2U	N/A	Y	D	-	[15]
Aerojet Rocketdyne	MPS-135	ASCENT	0.25-1.0 (4)	N/A	>19 (8U) >13.7 (6U) >7.3 (4U)	7.2 - 14.7 † 3.5 – 5.1 ‡	4U – 8U	N/A	Y	D	-	[15]
Bradford-ECAPS	Skysat 1N HPGP Propulsion System	LMP-103S	1.0 (4)	200	>17	17	27U	10	Y	F	Skysat, PRISMA	[16]
Busek	AMAC	ASCENT	0.5 (1)	225	0.56	1.5 †	1U	N/A	N	D	-	[17]
Busek	BGT-X5 System	ASCENT	0.5	220-225	N/A	1.5 (BOL)	1U	20	N	D	-	[18]
Moog	Monopropellant Propulsion Module	Green or 'Traditional'	0.5 (1)	224	0.5	1.01†	1U (baseline, scalable)	2 x 22.5 W/Thruster	N	D	-	[19]
MSFC/Plasma Processes/GT	LFPS	ASCENT	0.1 (4)	N/A	N/A	N/A	N/A	N/A	Y	E	Lunar Flashlight	[13]
NanoAvionics	EPSS C1K	ADN-blend	1.0 (1) BOL 0.22 (1) EOL	213	>0.4	1.2 † 1.0 ‡	1.3U	0.19 (monitor) 9.6 (preheat) 1.7 (firing)	N	F	Lituanica-2	[12]
Rocket Lab	Kick Stage	Unknown	120	N/A	N/A	N/A	N/A	N/A	Y	F	Electron 'Still Testing'	[5,14]
VACCO	ArgoMoon Hybrid MiPS	LMP-103S/ cold-gas	0.1 (1)	190	1	14.7 † 9 ‡	~1.3U	13.6 20 (max)	Y	E	ArgoMoon	[20]
VACCO	Green Propulsion System (MiPS)	LMP-103S	0.1 (4)	190	4.5	5 † 3 ‡	~3U	15 (max)	Y	D	-	[21]
VACCO	Integrated Propulsion System	LMP-103S	1.0 (4)	200	12.5	14.7 † 9 ‡	~1U – 19,000 cm^3	15-50 (max)	Y	D	-	[21]

Note that all data is documented as provided in the references. Unless otherwise published, do not assume the data has been independently verified.
† denotes a wet mass, ‡ denotes a dry mass, N/A = Not Available

Modeling Capabilities

Model Type	Model/Simulation Capability	Maturity Assessment
Basic Physics Model	Molecular Dynamics for catalytic and non-catalytic reactions	Moderate
	Zonal decomposition model	Moderate-High
Multi-Physics Analysis	1-D steady state reactor model for single step chemistry	High
	1-D steady state model for multi-step reactions	Moderate
	Coupled steady state/pressure drop model	Low
Systems Level Analysis	System component model	Moderate-High
	System model with multi-physics	Low

Goal is validated design tools for thruster performance / evaluation

Diagnostic Capabilities

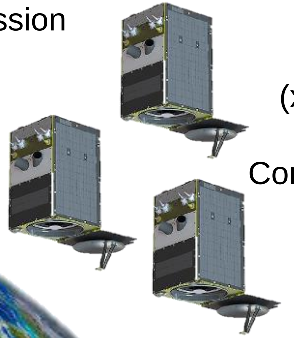
Characterization Tool	Capability	Maturity Assessment
High Speed Diagnostics	Thrust measurement	High
	Pressure measurement	High
	Flow Rate measurement	Moderate
Plume Diagnostics	FTIR Spectroscopy	High
	High Speed IR	Low
	Diode Laser Absorption Spectroscopy	Moderate
	Laser Induced Breakdown Spectroscopy	Moderate
	Raman Spectroscopy	High
Catalyst Health/Degradation	3D Microscope	High
	X-Ray Micro Tomography	High
	Focused Ion Beam	High
	Energy Dispersive Spectroscopy	High
	Brunauer-Emmet-Teller (BET)	High

Government Test Capabilities

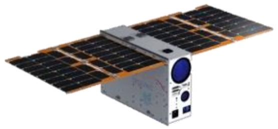
Test Cell	Location	Thrust Range	Test Type	Propellants	Status
CDA Facility	MSFC	0-440 N	Component Test, Hot-Fire Altitude Propulsion	ASCENT/ LMP-103S	Active
4205	MSFC	0-1 N	Hot-Fire Altitude Propulsion	ASCENT/ LMP-103S	Active
ACS	GRC	1-N to 440-N	Hot-Fire Altitude Propulsion	ASCENT (LMP-103S possible)	Inactive (standby)
Bldg 407	GSFC	0-440 N (TBR)	Flow testing	ASCENT/ LMP-103S	Active
Area 1-42, E-cell	AFRL	10mN-22N (current thrust stand) > 100N for short duration	Hot-Fire Altitude Propulsion	ASCENT	Active
Building 8595, chamber 4	AFRL	< or = 1N	Hot-Fire Altitude Propulsion	ASCENT	Active

Flight Demonstrations of Green Propellants (as of 2020)

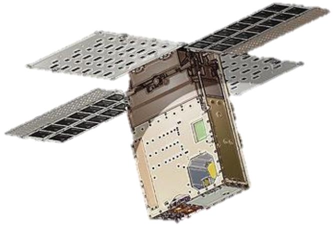
"PRISMA"
Swedish National Space Board
(SNSB)
ECAPS 1-N HPGP
(x 2 thrusters)
(**LMP-103S**)
Prototype/Demonstration Mission
2009 - 2011



"SkyBox"
Planet
ECAPS 1-N HPGP
(x4 thrusters per S/C)
(**LMP-103S**)
Commercial Development
(11+ units)
2018 +



"ArgoMoon"
ESA/ASI
100 mN VACCO MiPS
(x1 thruster per S/C
w/ cold-gas RCS)
(**LMP-103S**)
Artemis-1
2021 (?)



"Lunar Flashlight"
NASA / JPL
100 mN LFPS
(x4 thrusters per S/C)
(**AF-M315E/ASCENT**)
SMD Mission/Artemis-1
2021 (?)

"GPIM"
NASA / Ball Aerospace
1-N Aerojet GR-1
(x5 thrusters per S/C)
(**AF-M315E**)
STMD TDM Mission
2019 - 2020

"Kick Stage"
Rocket Lab
120-N Curie Engine
(x1 thruster per S/C
w/ cold-gas RCS)
(**"green" monopropellant**)
Commercial Development
"Still Testing" Mission & others
2018 +

Summary

- **Green Propulsion systems are flying!!**
  - GPIM Success!
  - Commercialization of Bradford-ECAPS HPGP 1-N Systems!
- USAF continues to develop ASCENT based systems & capabilities for 1-N to 100-N scales
  - Objective of AFRL portfolio approach is to combine theoretical tools and empirical sources
    - Primary work addresses the fusion of measured data with theoretical models
- NASA's approach is to overcome infusion and transition challenges by incentivizing mission adoption through public-private partnerships to mature a wide-range of thrust classes, with SmallSats scales in the near-term

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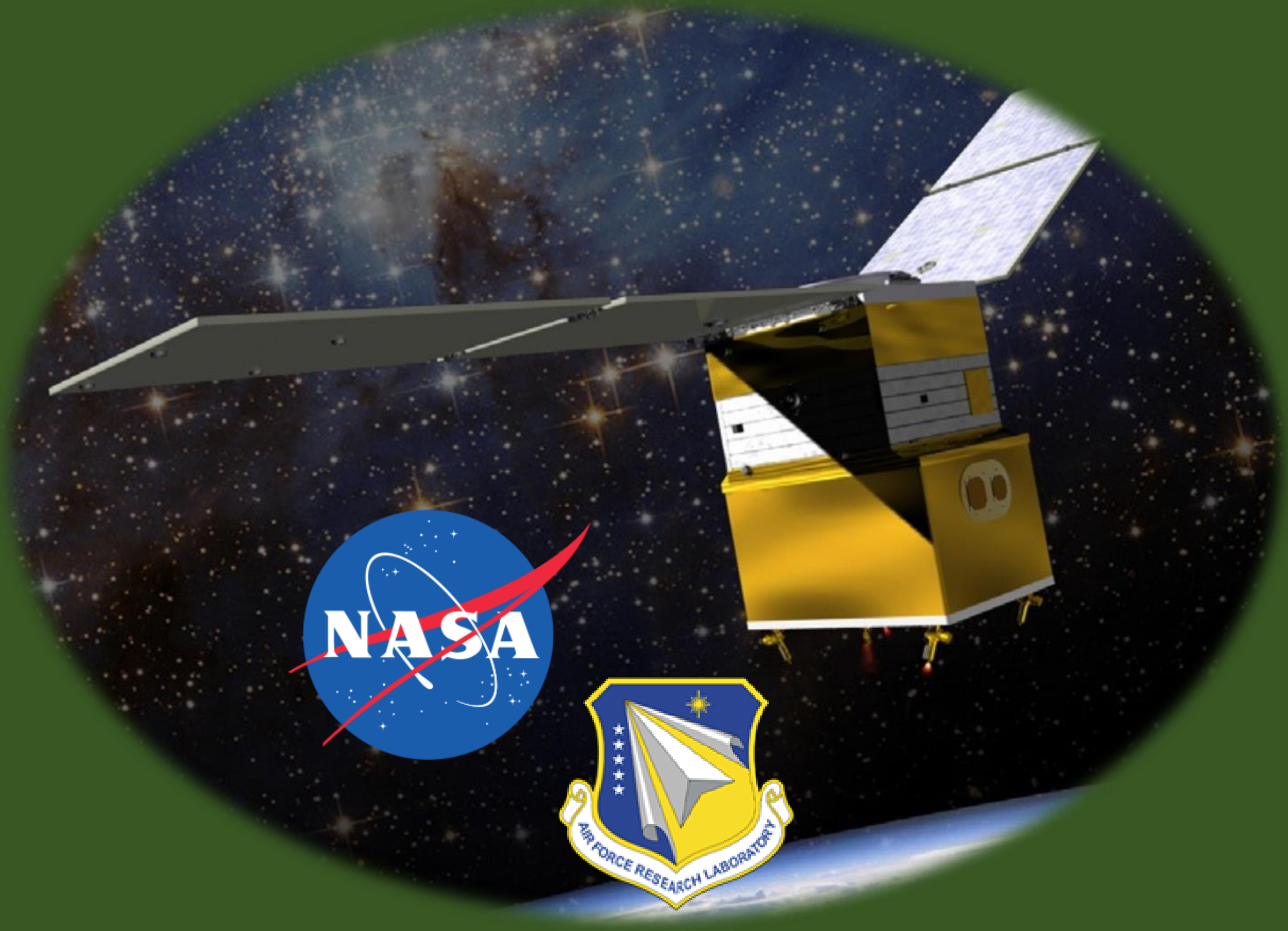
NASA
AIR FORCE RESEARCH LABORATORY