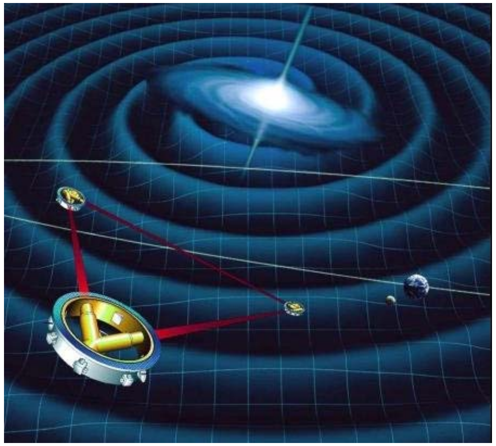
Advancing the Utility of Small Satellites with the Development of a Hybrid Electric-Laser Propulsion (HELP) System

Dr. Rachel Leach, Gerry Murphy

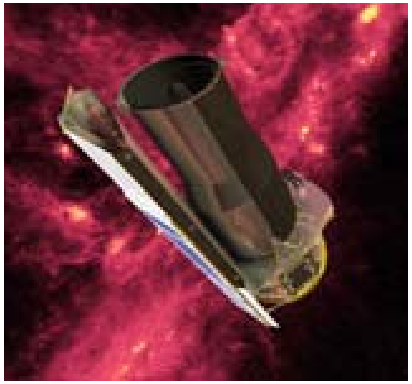
& Tom Adams

Design_Net Engineering LLC

Contents

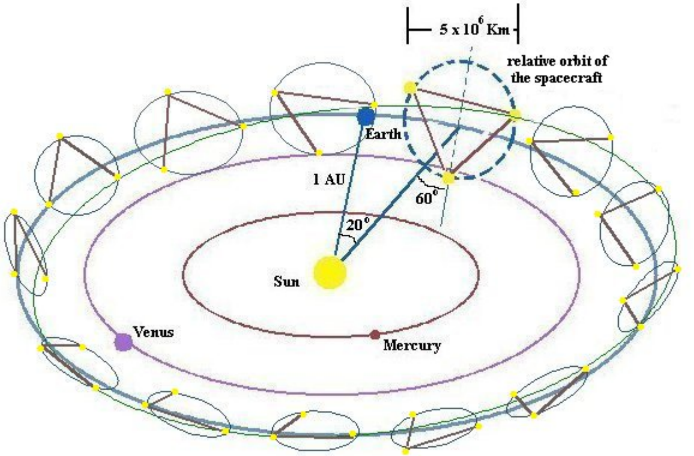


- Introduction
  - Application Performance Parameter Space
  - Imposed System Requirements
  - Anticipated Thruster Solution
- Performance Metric Spectrum of Thruster technologies
- Significance of Performance Metrics
  - Satellite Launch Cost
  - Payload Mass
  - Mission Lifetime
- “Tunable” T & I_{sp} System
- Limitations of current micro-thrusters
- Proposed HELP Design Solution
- Conclusions



Introduction

- Many upcoming ambitious missions (scientific, military)
  - ⇒ Require complex precision subsystems, formation flying satellites & new generation of highly capable micro-sats
- Area of advancement in Development of μN thrusters:
  - ⇒ Provide fine pointing control, long-term maneuvers, orbit change, & station keeping for both grand scientific missions & small satellites
- LISA, GAMMA, MAXIM, LIRE, TPF, SIM, SAR concepts….
  - ⇒ Solution: Tunable/Configurable thruster
    - → HELP system

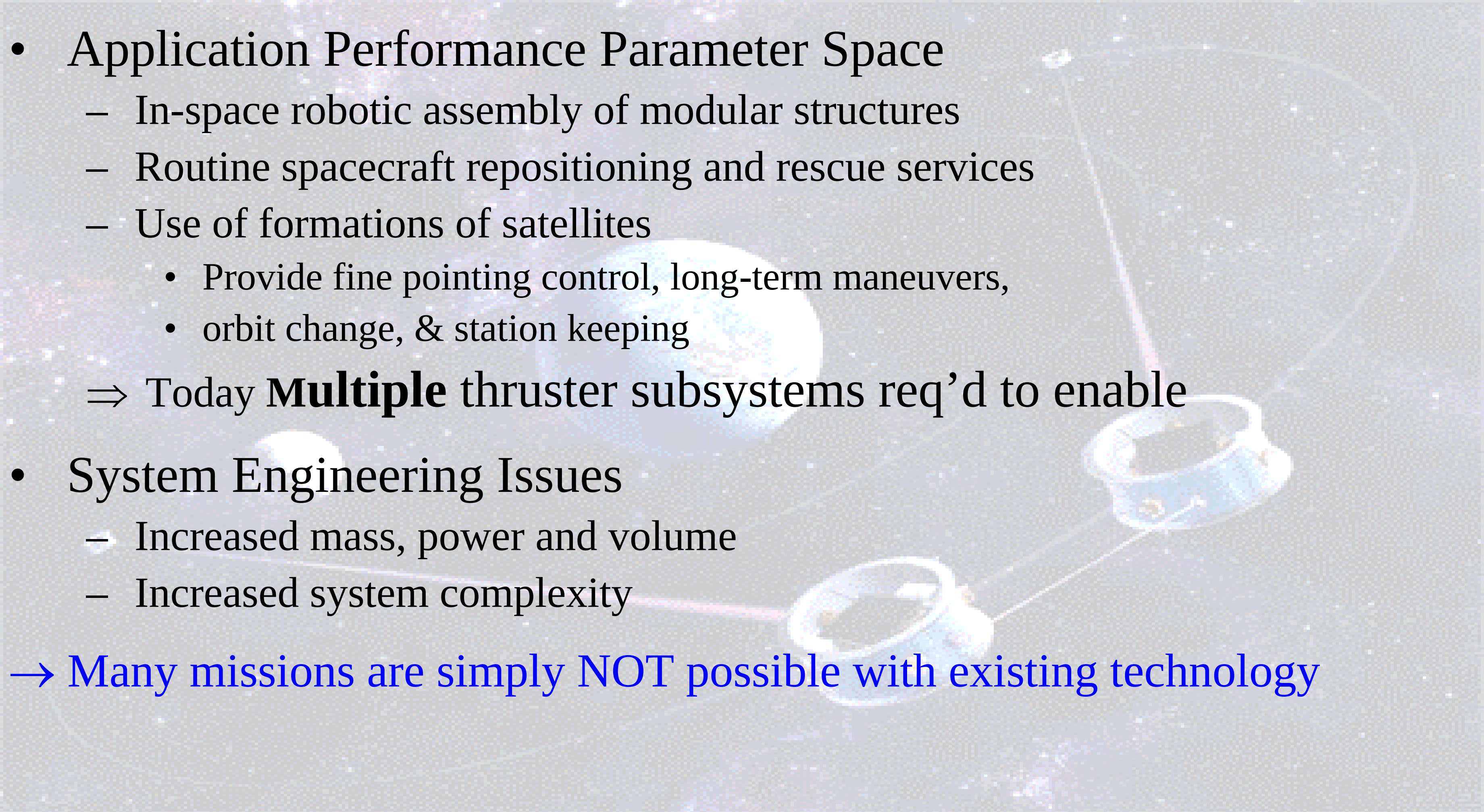


Application Performance Parameter Space

Range of challenging performance metrics associated to selection of operation tasks

Mission Operation Task / Comment	Driving Requirement	Parameter/Range
Robotic service work done with proximity operations (<1m separation) and done over a long period of time	High ΔV, Precise Control of position	T < 1 μN with ms response time plus high I_{sp}
Provide full 3-axis control & fine position control for constellation configuration maintenance	Precision thrust	T < 10 μN
High positional accuracy - Spacecraft control to fractions of λ	Precision thrust control	MIB < 10 μN-s ± 0.1 μN-s, High BW
Oppose drag & enable orbit raising (dependent on drag assumptions & maneuvering periods) Spacecraft rearrangements in constellation	Coarse thrust and high Isp	T > 0.1 mN I_{sp} > 5000 s
Spacecraft tip-off recovery	Coarse thrust range & control	T= 25 - 100 μN $T_{control}$ ± 1 μN
Example 1 yr ΔV Straw-man mission for 100kg S/C 600Km orbit		
1 yr mission lifetime ΔV budget	Mission ΔV budget	Total= 270 m/s
Formation initialization over a 30 day maneuver period	Formation maneuver ΔV	~ 30 m/s
Over 1 yr life in ~ 600 Km orbit	Stationkeeping/drag ΔV	~ 40 m/s
Nominal 30 day maneuver period (depends on altitude change)	Orbit adjustment ΔV	~ 50 m/s
Deorbit at end of mission (dependent on orbit altitude)	Deorbit ΔV	~ 150 m/s

Imposed System Req’s



- Application Performance Parameter Space
  - In-space robotic assembly of modular structures
  - Routine spacecraft repositioning and rescue services
  - Use of formations of satellites
    - Provide fine pointing control, long-term maneuvers,
    - orbit change, & station keeping

  ⇒ Today **Multiple** thruster subsystems req’d to enable

- System Engineering Issues
  - Increased mass, power and volume
  - Increased system complexity

→ Many missions are simply NOT possible with existing technology

DESIGN_NET ENGINEERING

Significance of Performance Metrics: Isp

- Propellant mass decreases with higher I_{sp}

  ⇒ Enabling greater payload mass

  × factor 20 gain

  (cf. HELP & uPPT)

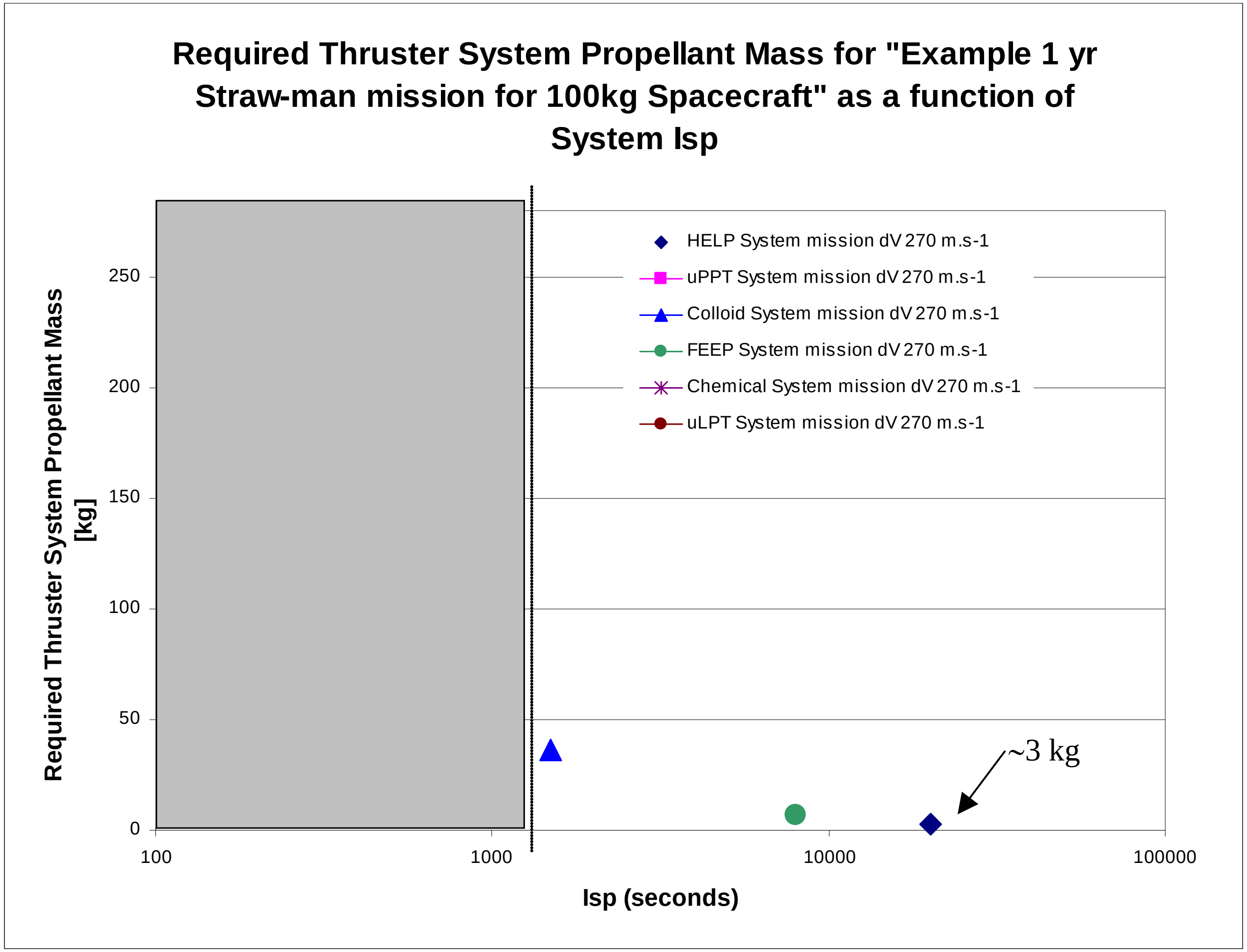
Or

  ⇒ Increased mission lifetime

Or

  ⇒ Decreased launch costs

  (1 kg ≡ $10k to $30k)



Significance of Performance Metrics: Precision

- S/C drift (positional control) & associated ΔV req. improves with finer MIB

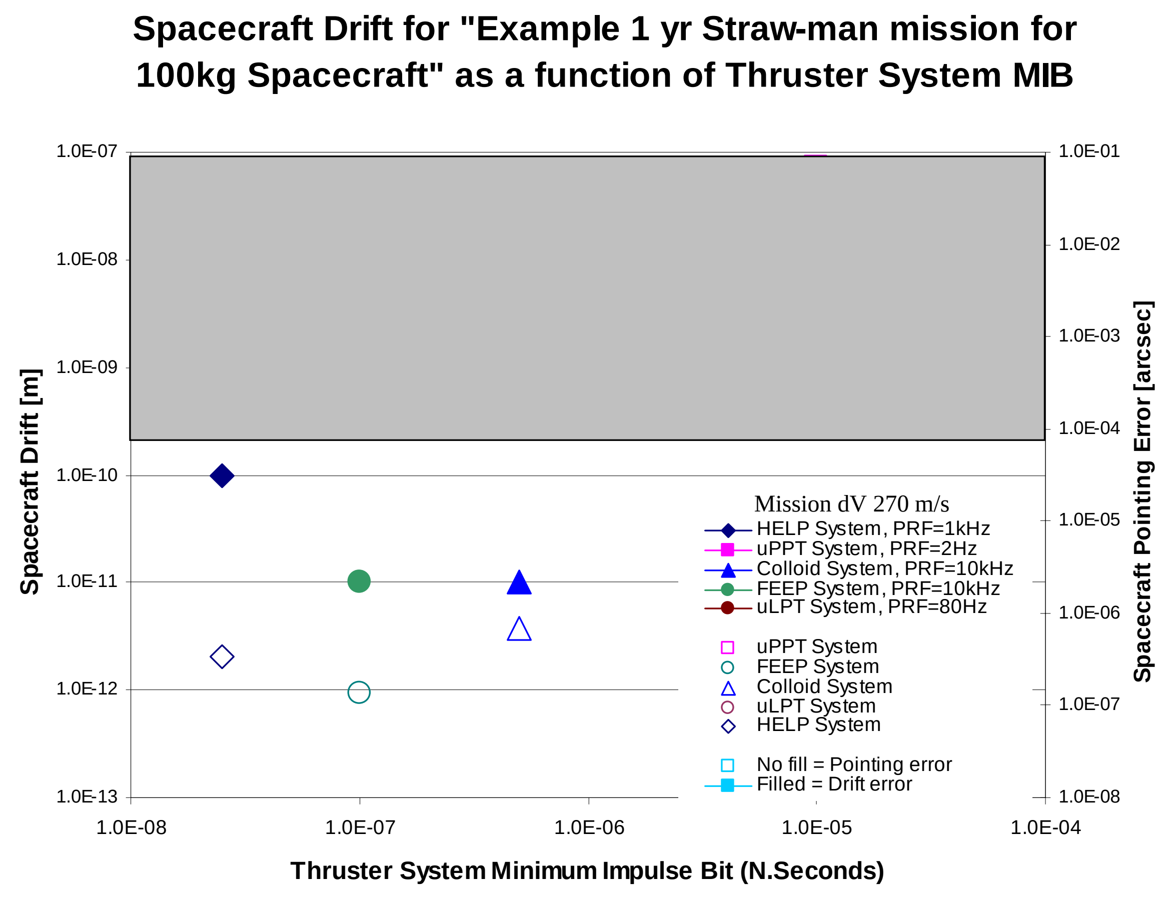
⇒ Good Positional control Important for FF Missions & SAR systems (< nm)

&

- S/C pointing control improves with finer MIB

⇒ Important for Precision pointing telescopes

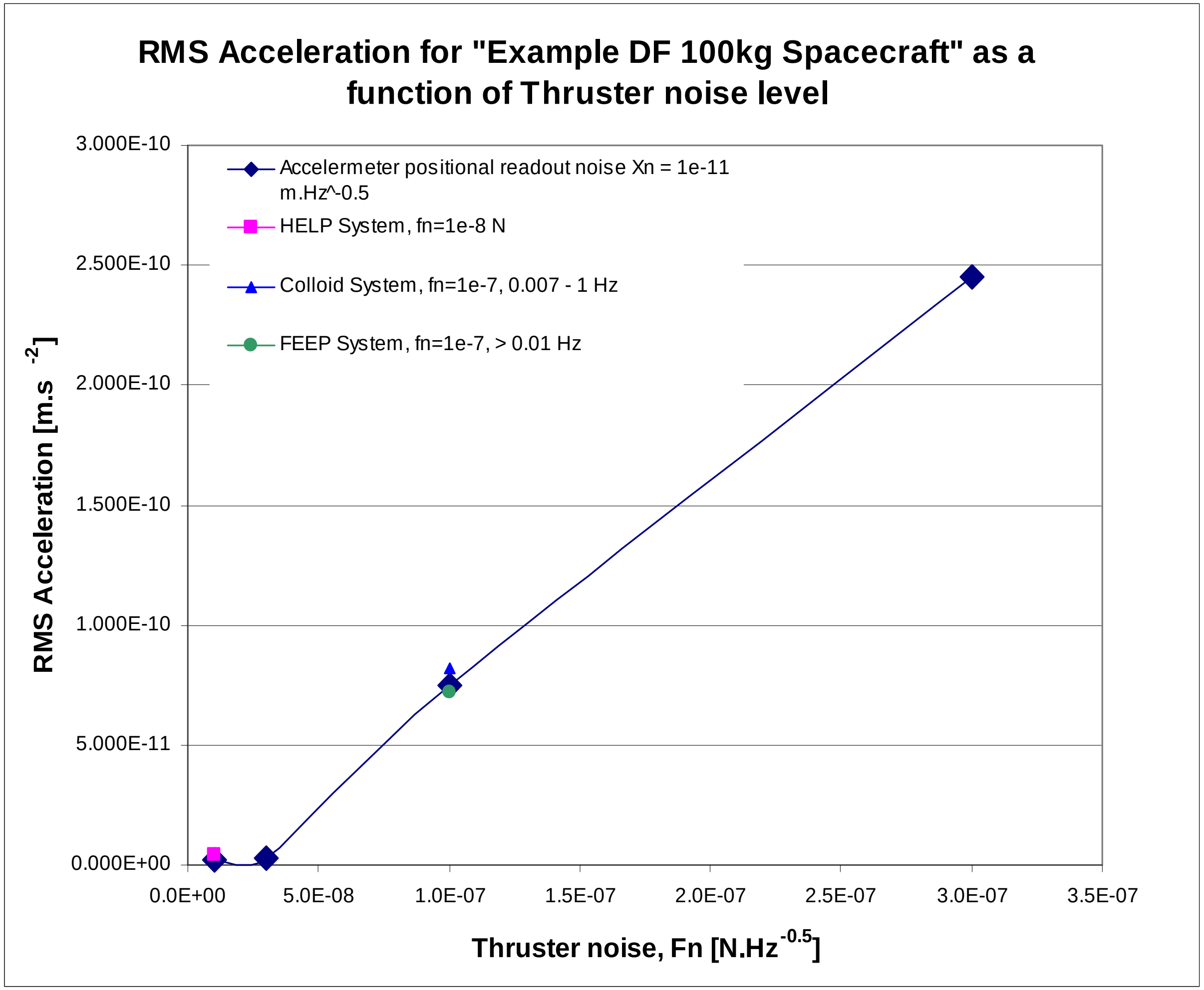
(< milli- to micro-arcsec)



Significance of Performance Metrics: Noise

- S/C stability improves with lower thrust noise

⇒ Important for Grand Scientific Missions - Drag-Free GW & relativity missions

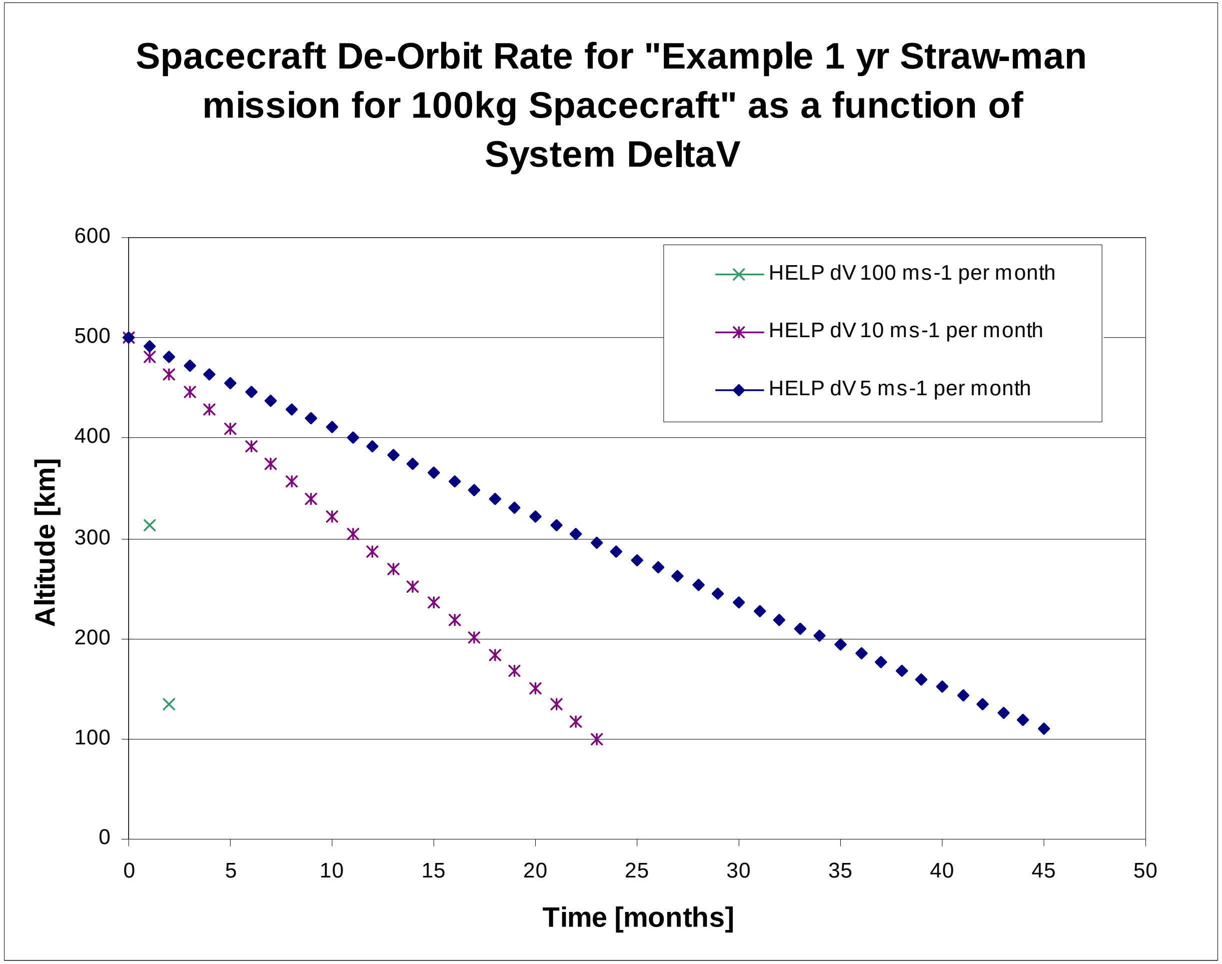


Significance of Performance Metrics: Thrust

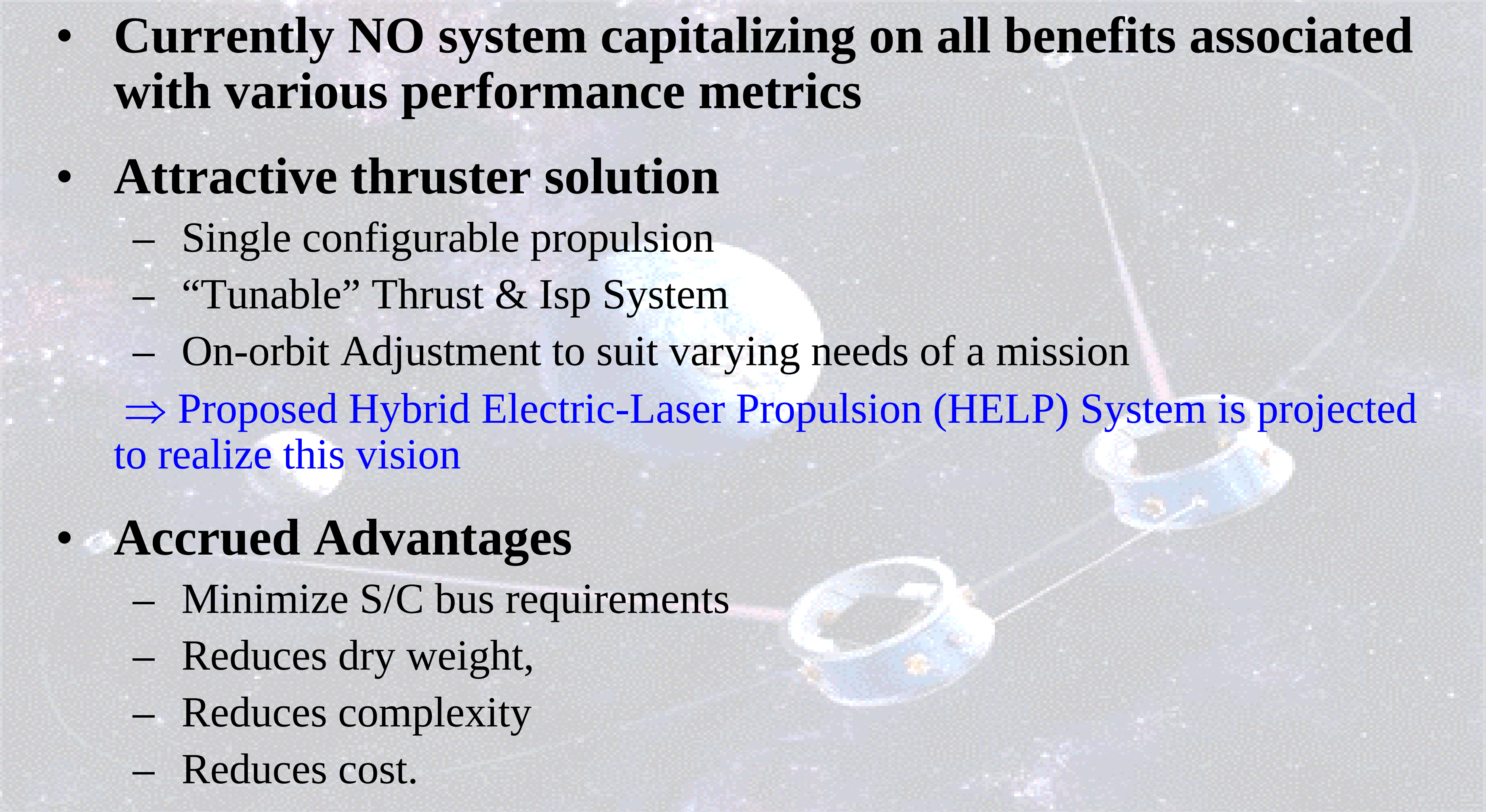
- S/C maneuver time decreases with higher Thrust

⇒ Fast maneuver times Important for Reconnaissance Missions

⇒ Longer maneuver times may be permissible for de-orbiting



Significance of Performance Metrics

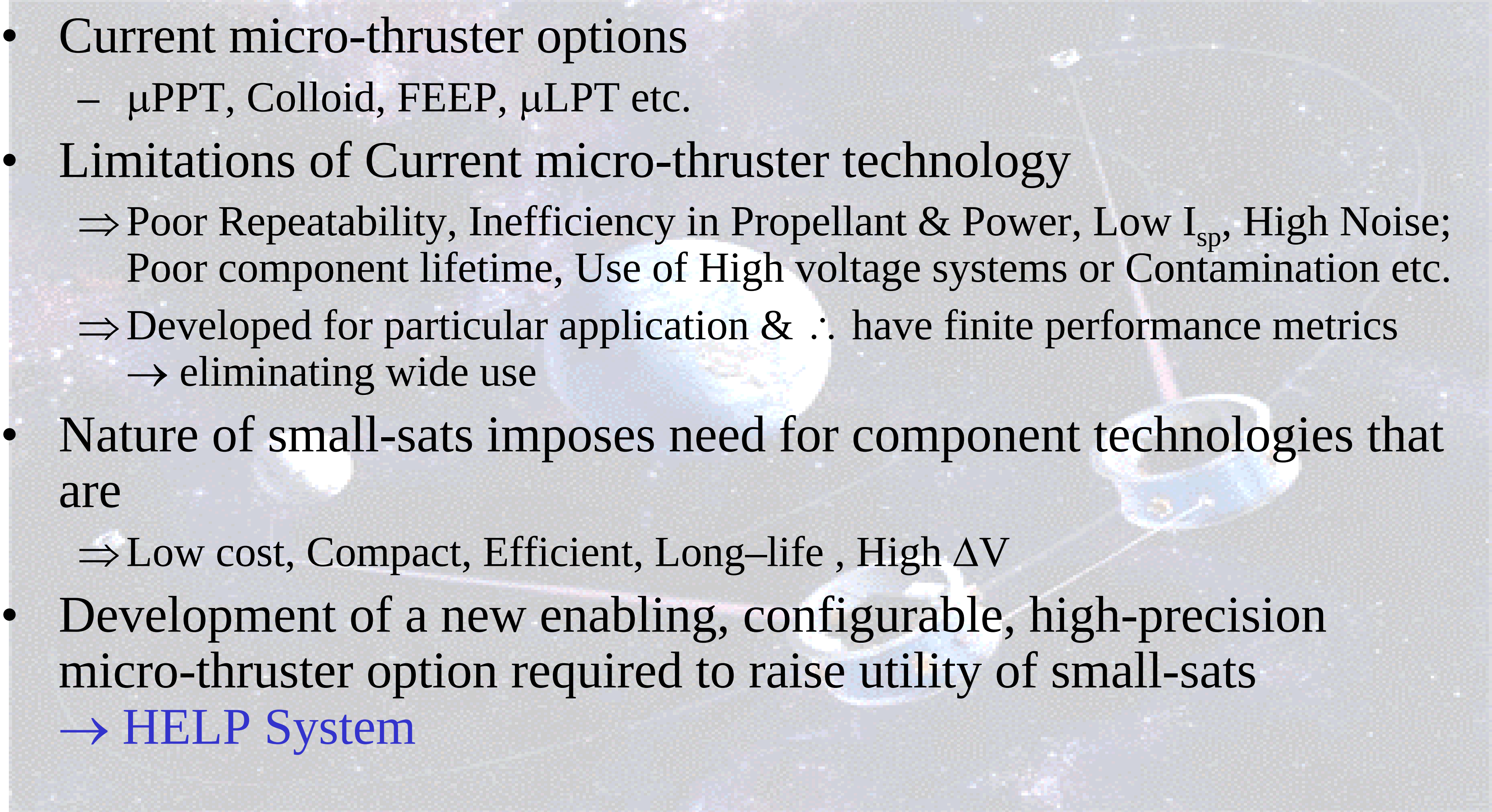


- **Currently NO system capitalizing on all benefits associated with various performance metrics**
- **Attractive thruster solution**
  - Single configurable propulsion
  - “Tunable” Thrust & Isp System
  - On-orbit Adjustment to suit varying needs of a mission

⇒ Proposed Hybrid Electric-Laser Propulsion (HELP) System is projected to realize this vision

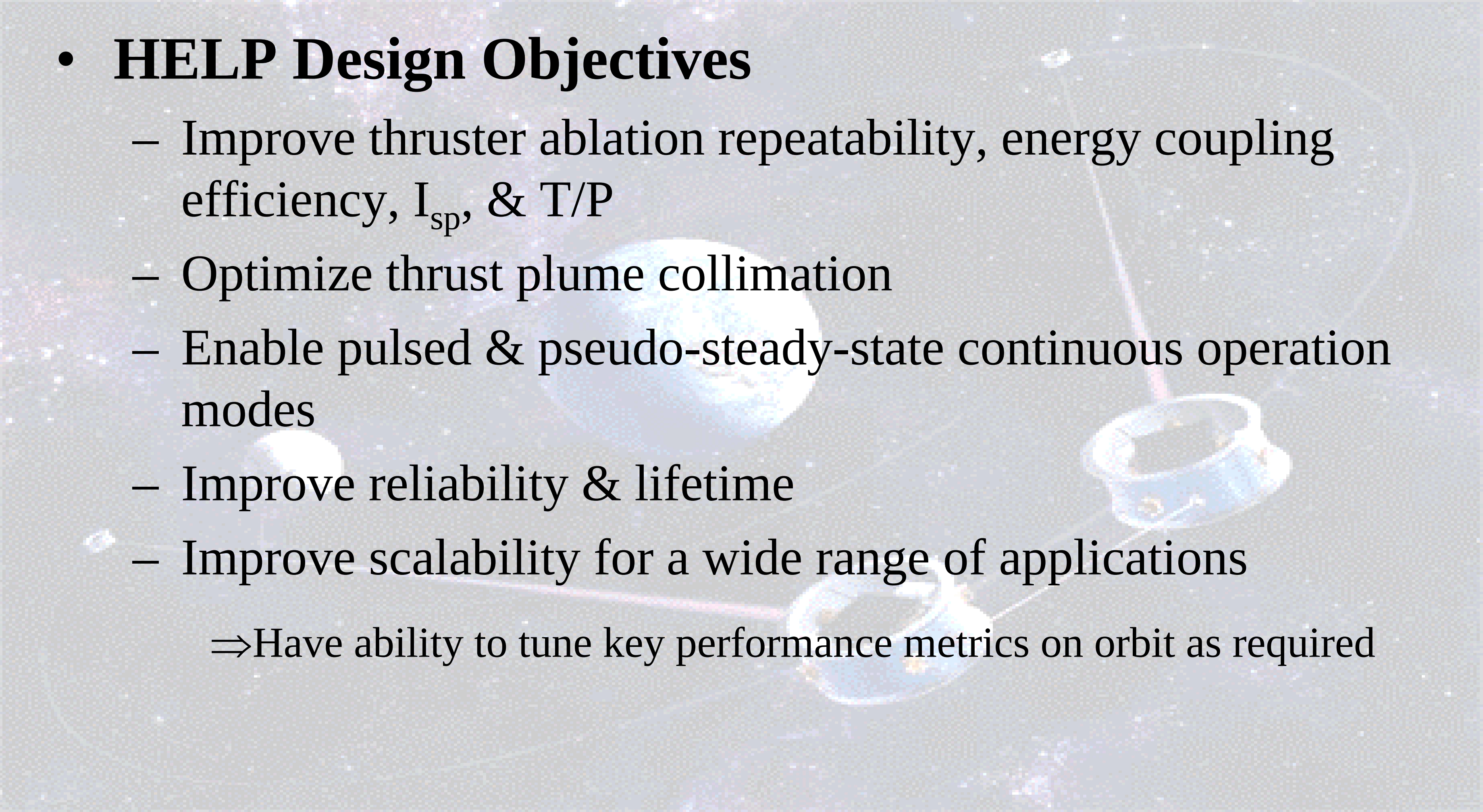
- **Accrued Advantages**
  - Minimize S/C bus requirements
  - Reduces dry weight,
  - Reduces complexity
  - Reduces cost.

State of Practice



- Current micro-thruster options
  - μPPT, Colloid, FEEP, μLPT etc.
- Limitations of Current micro-thruster technology
  - ⇒ Poor Repeatability, Inefficiency in Propellant & Power, Low I_{sp}, High Noise; Poor component lifetime, Use of High voltage systems or Contamination etc.
  - ⇒ Developed for particular application & ∴ have finite performance metrics → eliminating wide use
- Nature of small-sats imposes need for component technologies that are
  - ⇒ Low cost, Compact, Efficient, Long–life , High ΔV
- Development of a new enabling, configurable, high-precision micro-thruster option required to raise utility of small-sats → HELP System

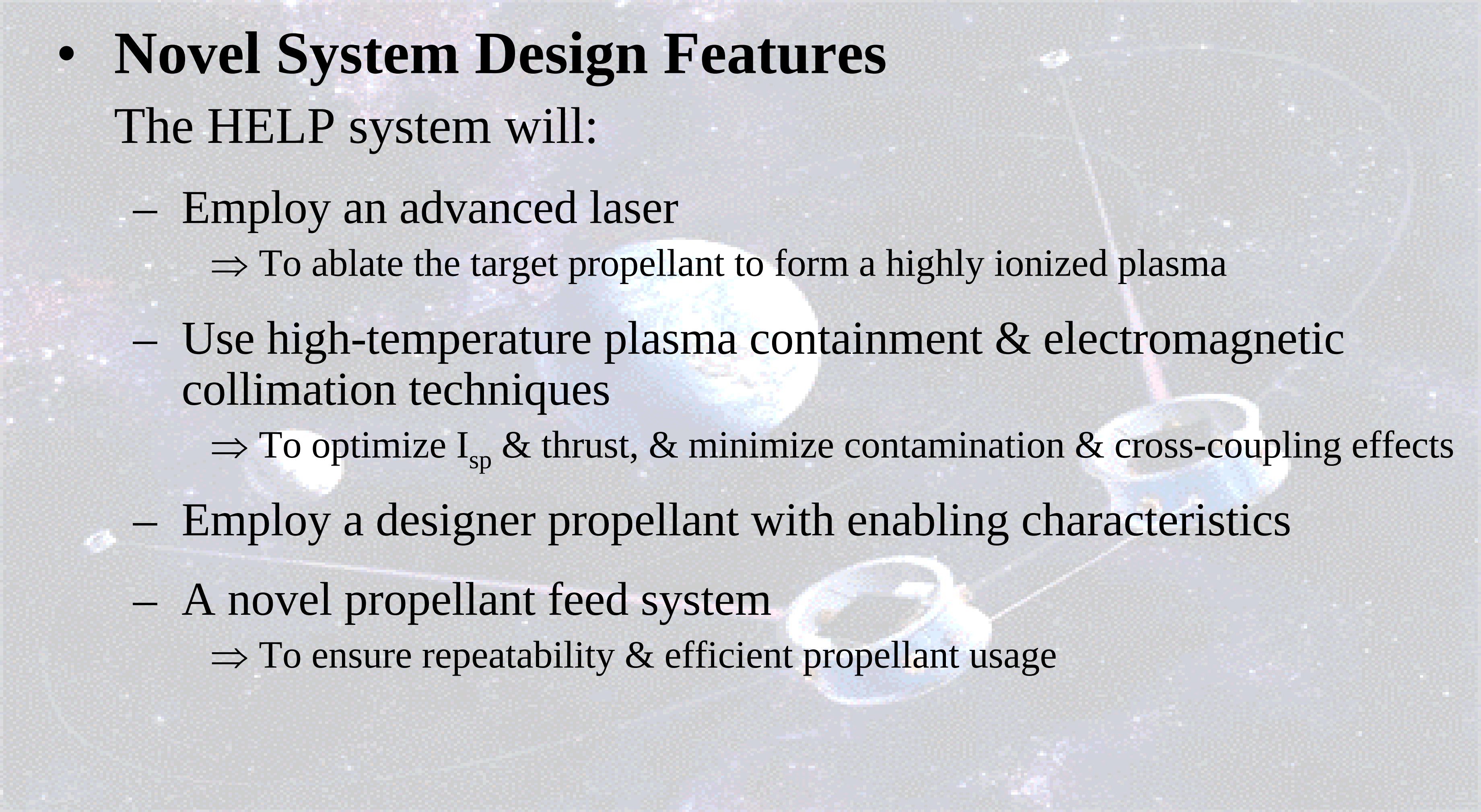
HELP Thruster Design



- **HELP Design Objectives**
  - Improve thruster ablation repeatability, energy coupling efficiency, I_{sp}, & T/P
  - Optimize thrust plume collimation
  - Enable pulsed & pseudo-steady-state continuous operation modes
  - Improve reliability & lifetime
  - Improve scalability for a wide range of applications

⇒Have ability to tune key performance metrics on orbit as required

HELP Thruster Design cont.



- **Novel System Design Features**

  The HELP system will:

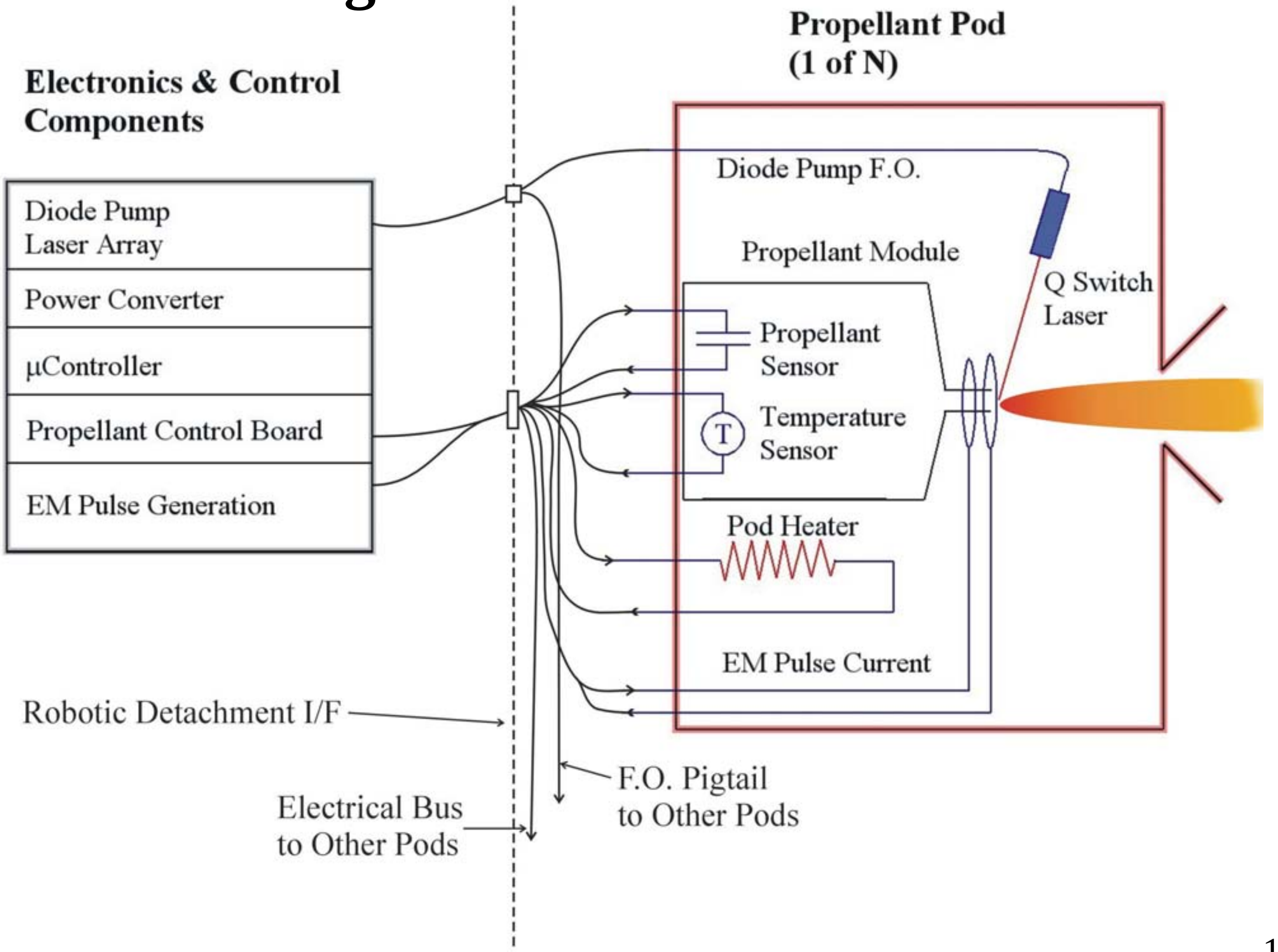
  - Employ an advanced laser
    - ⇒ To ablate the target propellant to form a highly ionized plasma
  - Use high-temperature plasma containment & electromagnetic collimation techniques
    - ⇒ To optimize I_{sp} & thrust, & minimize contamination & cross-coupling effects
  - Employ a designer propellant with enabling characteristics
  - A novel propellant feed system
    - ⇒ To ensure repeatability & efficient propellant usage

HELP Thruster Design cont.

- **HELP system comprises of 4 functional subsystems**
  - 1) Laser Ablation subsystem, 2) Plasma Collimation subsystem, 3) Propellant Feed subsystem, 4) Control & Power Conversion subsystem
  - 4 Subsystems are housed in 2 discrete & easily connected units
    - ⇒ "Electronics & Control Components" Unit & Modular "Propellant Pod" Unit
      - ⇒ This physical layout enables robotic servicing
- **HELP system operation entails 3 sub-processes**
  - Propellant feed → maintains viscosity of fuel to allow feed to target ablation area
  - Laser Ablation → operates & controls lasers
  - Plasma collimation → operates & controls collimating EM field

HELP Thruster Design cont.

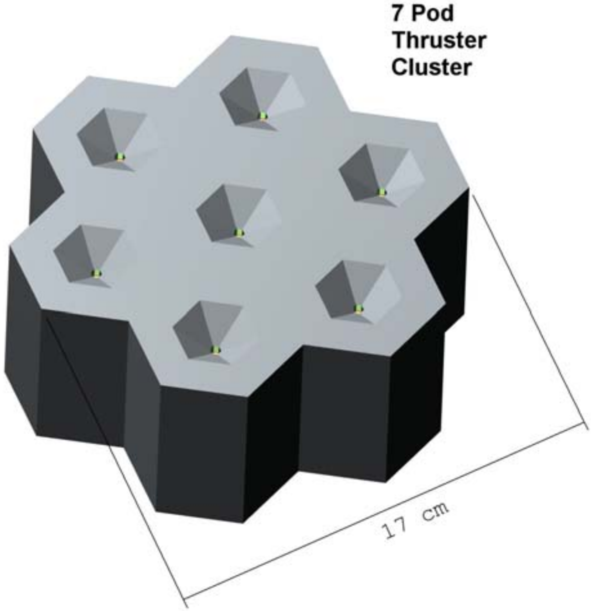
- **HELP System Block Diagram**



HELP Thruster Design cont.

- **Conceptual HELP Thruster Unit Design**
  - Modular “honeycomb” fashion of propellant pods facilitates ganging
    - ⇒ ∴Size of multi-pod system is configurable & scaleable to application
      - →Through ganging of singular HELP systems one can provide higher thrust levels to support additional tasks
    - ⇒ This physical layout enables greater operational flexibility & applicability

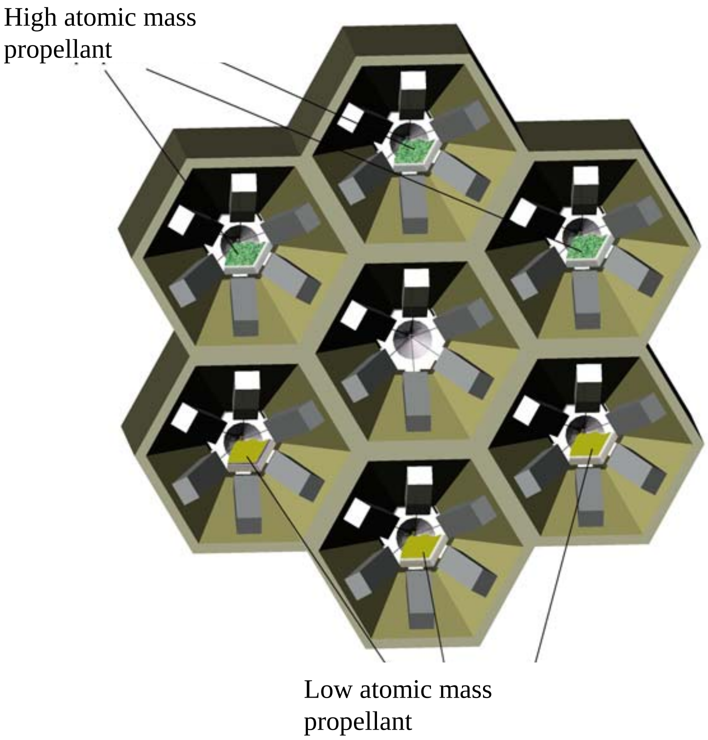
“Multiple Configuration System”



HELP Thruster Design cont.

- **Conceptual HELP Thruster Unit Design**
  - Hexagonal design of propellant pods facilitates ganging & multi-component use
    - ⇒ Use selection of propellants with varying atomic masses
    - ⇒ Use selection of lasers with different operation characteristics – P, I, τ, λ, d
    - ⇒ Use multiple lasers per pod
      - → ∴ Enabling greater performance metric ranges
    - ⇒ This physical layout enables greater operational flexibility & applicability

“Multiple Configuration System”



HELP Thruster Design cont.

- **Estimated Performance Characteristics**

Propulsion System Type	**HELP:** Multi-pod config **(single)**
Thruster Operation Modes	Pseudo-Continuous or Pulsed
Thrust Range (tunable & scaleable with pod design) **[μN]**	175 – > 10,000 **(25 - >1,000)**
Specific Impulse [s]	**500 – >20,000**
T/P ratio [μN/W]	**5 – > 200**
Minimum Impulse Bit [N·s]	**< 2.5e^{-8}**
System Mass (excl. supporting electronics & propellant) **[kg]**	0.315 (**0.045**) scalable
System Efficiency %	≥ 30
Req. mission propellant mass (ΔV~270 m/s, 100kg S/C) **[kg]**	**0.135 – <5.4**

Estimated values, Not measured

$$F = C_m \cdot P = \frac{m \cdot \Delta v \cdot P}{W} \equiv \frac{\Delta m \cdot v \cdot P}{W}$$

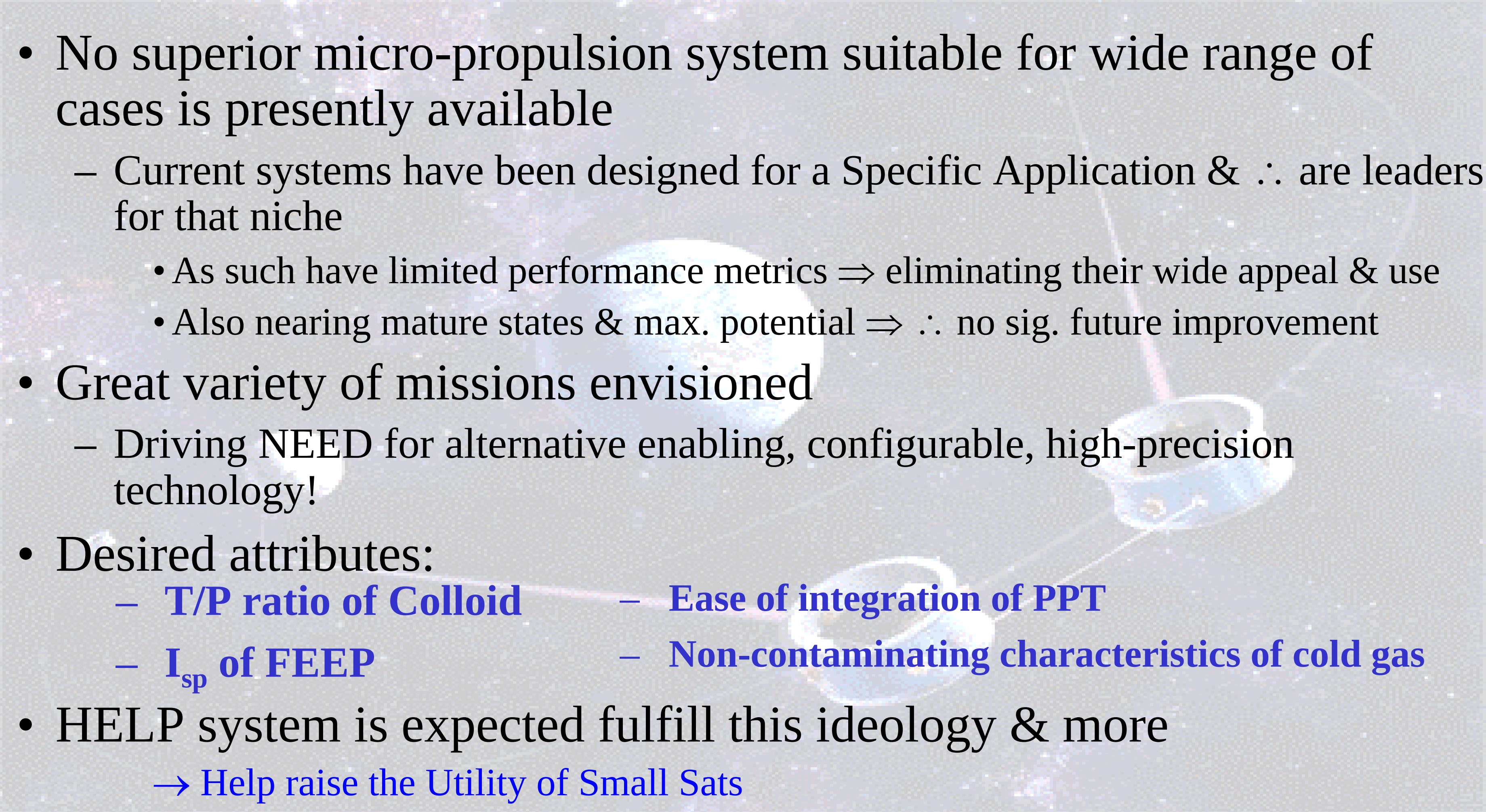
C_m= momentum coupling coefficient,
P= incident power,
W= incident laser energy

Comparison of Thruster Performance Characteristics

Propulsion System Type	**µPPT**	**FEEP**	**Hall**	**µLPT**	**Colloid**	**HELP**
Thruster Operation Modes	Pulsed	Continuous or Pulsed	Continuous or Pulsed	Pulsed	Continuous or Pulsed	Pseudo-Continuous or Pulsed
Thrust Range [µN]	40	800	10,000	150	20	**25 – >1000**
Specific Impulse [s]	1000	8000	1500	650	500 – 1500	**500 – > 20,000**
Minimum Impulse Bit [N·s]	1e^{-5} – 1e^{-3}	<10e^{-8}		1e^{-6}	0.5e^{-6}	**< 2.5e^{-8}**
T/P ratio [µN/W]	10	6.7	50	45	50	**5 – > 200**
System Mass (excl. supporting electronics & propellant) **[kg]**	0.12	3.5	1	0.55	0.08	**0.045 – 0.315**
System Efficiency %	5	25	~35	≥50	~50	**≥30**
Design	Simplistic	Complex	Complex	Simplistic	Simplistic	Simplistic
Life Limiting Element	Spark Plug	Cathode	Cathode	Propellant	Cathode	**Propellant**

Estimated values

Conclusions



- No superior micro-propulsion system suitable for wide range of cases is presently available
  - Current systems have been designed for a Specific Application & ∴ are leaders for that niche
    - As such have limited performance metrics ⇒ eliminating their wide appeal & use
    - Also nearing mature states & max. potential ⇒ ∴ no sig. future improvement
- Great variety of missions envisioned
  - Driving NEED for alternative enabling, configurable, high-precision technology!
- Desired attributes:
  - **T/P ratio of Colloid**
  - **I_{sp} of FEEP**
  - **Ease of integration of PPT**
  - **Non-contaminating characteristics of cold gas**
- HELP system is expected fulfill this ideology & more

  → Help raise the Utility of Small Sats

Acknowledgements

DARPA

CENTROSPAZIO

JPL

ONERA

NASA

BUSEK

Photonic Associates

AUSTRIAN RESEARCH CENTERS

THE UNIVERSITY
OF BIRMINGHAM

esa SCIENCE