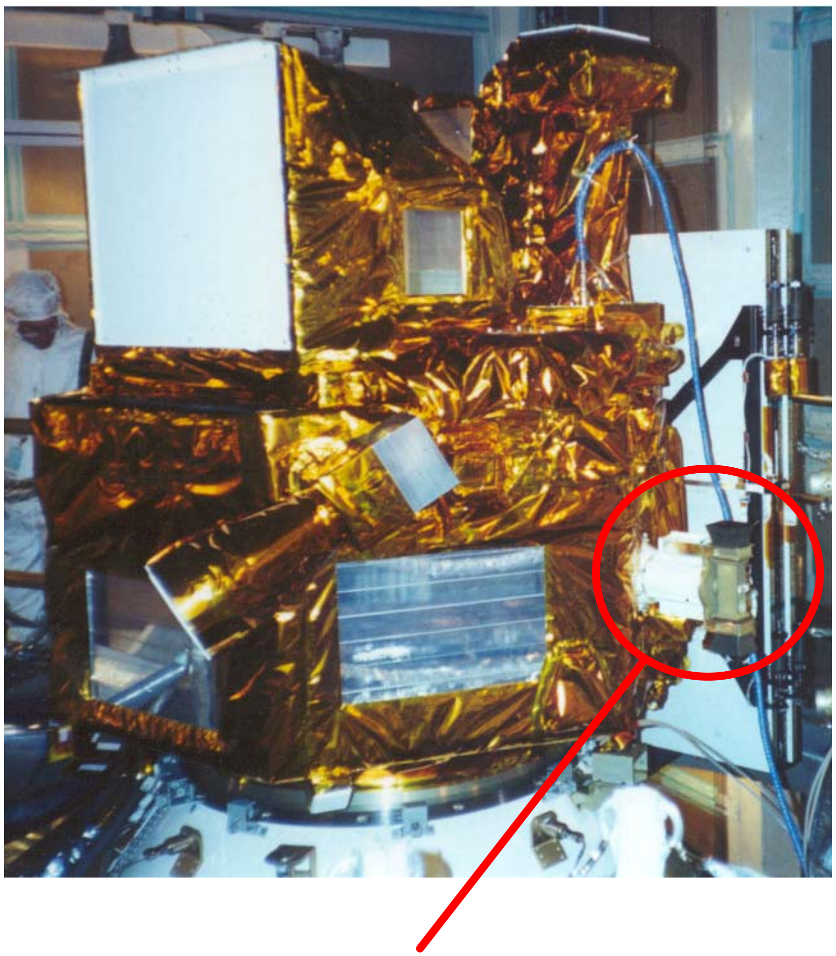
Section 25

Pulsed Plasma Thruster (PPT)

. . . Charles Zakrzwski
NASA Goddard Space Flight Center
. . . Scott Benson
NASA Glenn Research Center

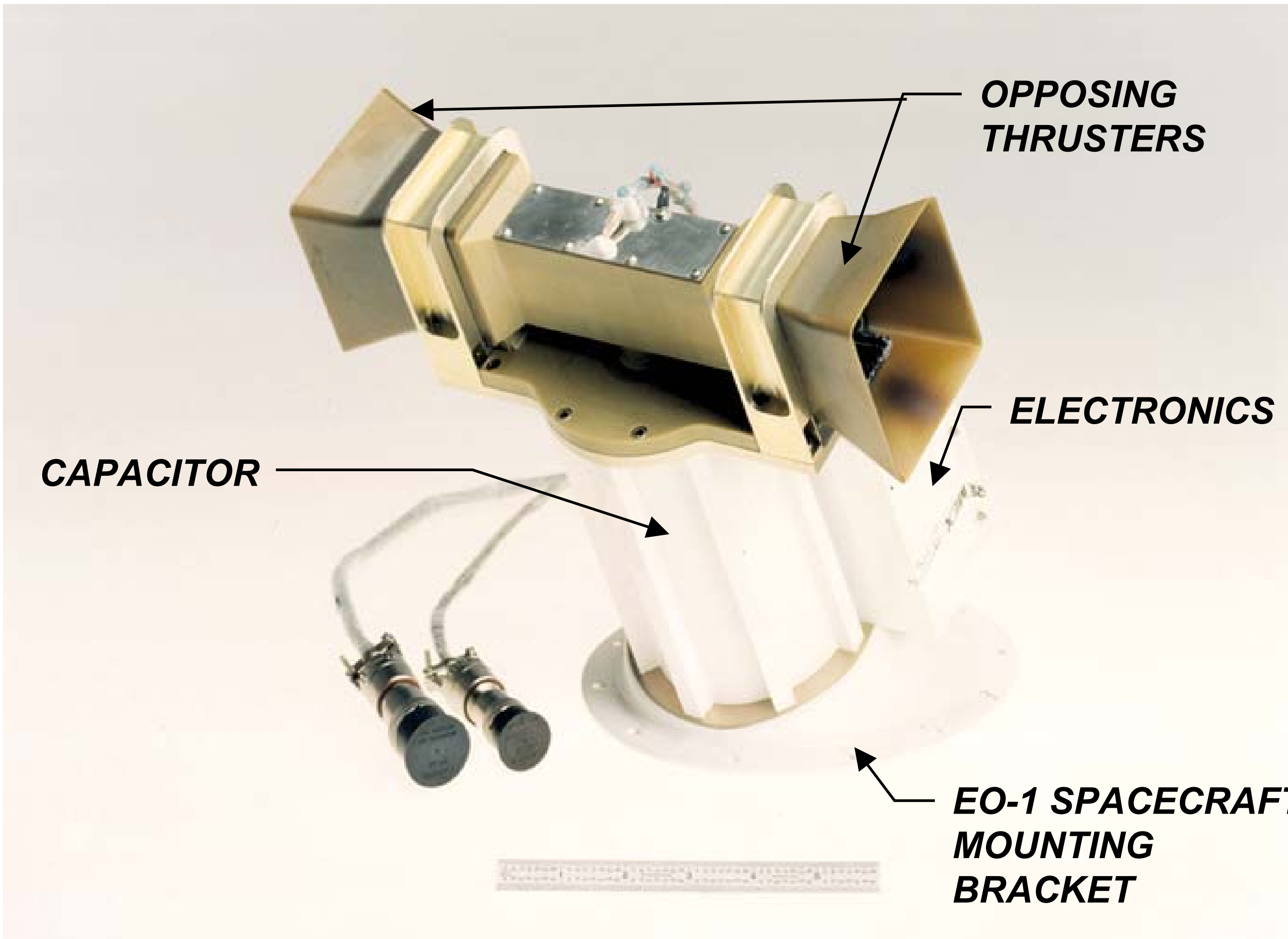
Introduction



Pulsed Plasma Thruster

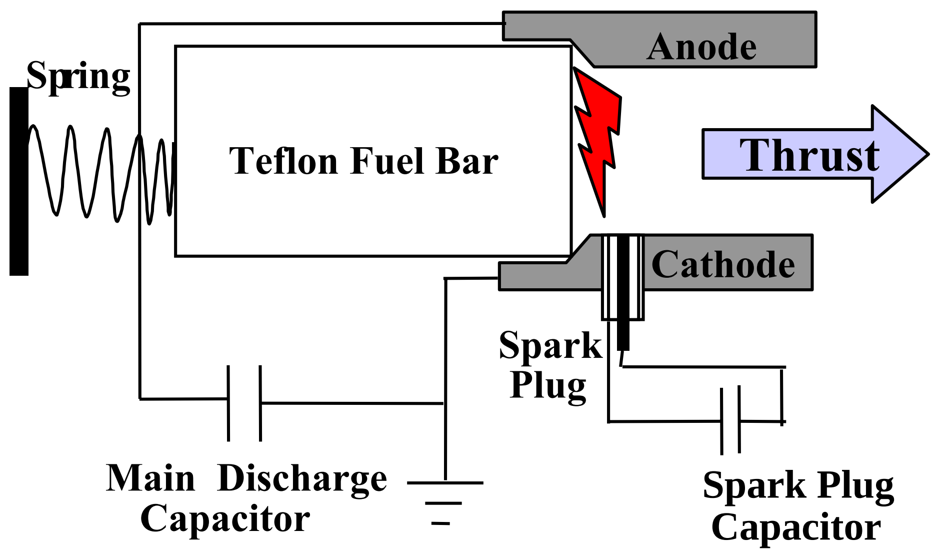
- ***Objectives***
  - ***Validate the ability of a new generation of PPT's to provide precision attitude control capability***
    - *PPT replaces pitch wheel/torquer bar*
  - ***Confirm benign interaction***
    - *Demonstrate imaging capability during PPT operation*
  - ***Confirm PPT performance parameters***
- ***PPT Team***
  - ***NASA/Glenn Research Center***
    - *Scott Benson: (216) 977-7085*
  - ***General Dynamics Space Propulsion Systems***
    - *Joe Cassady: (703) 271-7576*
  - ***NASA/Goddard Space Flight Center***
    - *Chuck Zakrzwski: (301) 286-3392*

PPT Description *(1 of 4)*



PPT Description (2 of 4)

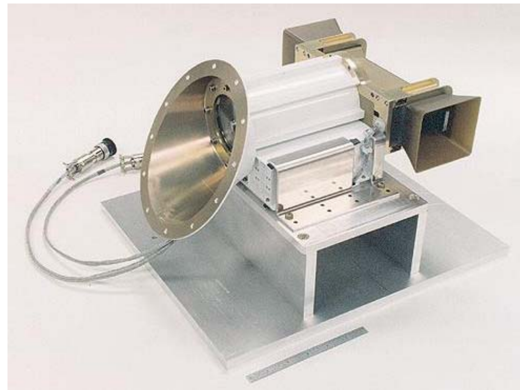
- ***Small, low power, self-contained electromagnetic propulsion system***
- ***Non-toxic solid propellant: Teflon***
- ***High Isp (650-1350 s), very low I-bit (90-860 uN-s)***
- ***Propellant ablated and ionized by capacitor discharge***
- ***Plasma is accelerated by Lorentz force***
- ***Multiple thrusters can be driven by a common capacitor***



PPT Operation

PPT Description *(3 of 4)*

EO-1 PPT (100 W)

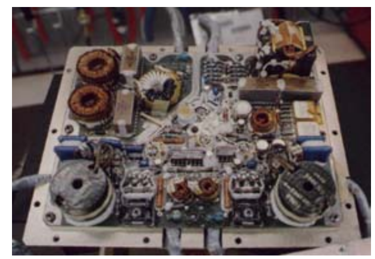


Dawgstar PPT (10 W)

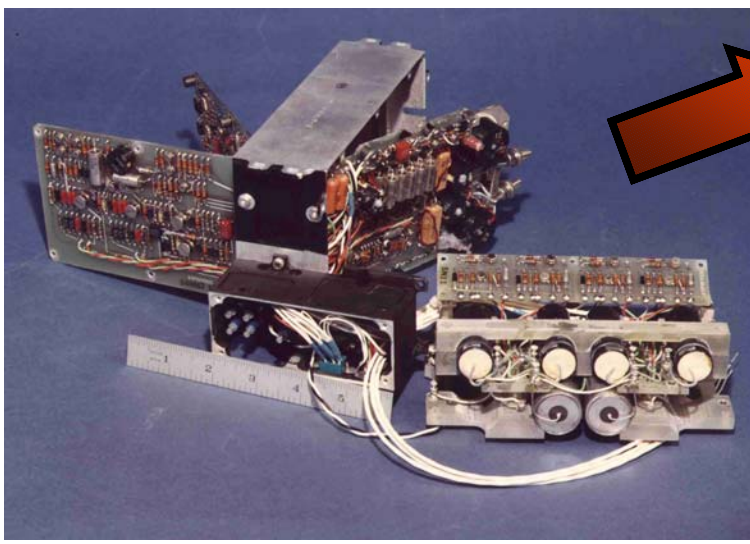
Characteristic	EO-1 (Ref. AIAA-99-2276)	Dawgstar (Ref. AIAA-00-3256)
Maximum Input Power	70 Watts (one thruster—EO-1 operations)—100 Watts design	13.1 Watts (two thrusters at once)
Thrusters/System	2	8
Total System Impulse	1850 N-sec (EO-1 propel. load) >15,000 N-sec (system life)	1125 N-sec
Impulse Bit	90-860 μN-sec, throttleable	56 μN-sec
Pulse Energy	8.5-56 Joules, throttleable	5 Joules
Maximum Thrust	860 uN (EO-1); 1.2 mN (design)	112 μN
Specific Impulse	650-1350 sec	500 sec
Thrust to Power Ratio	12.3 μN/Watt (System Input)	8.3 μN/Watt (System)
Total Mass	4.9 kg (2 PPTs, a Power Processing Unit, and fuel)	3.8 kg (8 PPTs, a Power Processing Unit, and fuel)
Propellant	Teflon	Teflon
Propel. Mass (Design)	0.07 kg/thruster (as fueled)	0.030 kg/thruster

PPT Description *(4 of 4)*

- ***EO-1 PPT Technology Advancements***
  - *Reduced dry mass from 6.5 to 4.8 kg through cap and electronics reductions [EO-1 PPT mass includes external mounting structure (AIAA 99-2276)]*
  - *EO-1 PPT made significant strides in reducing electronics mass.*



EO-1 Electronics, 750 g (incl cables and connectors, but not base plate)



Photos to same scale

LES 8/9 Electronics, 1130 g (not incl housing shown)

PPT Validation *(1 of 5)*

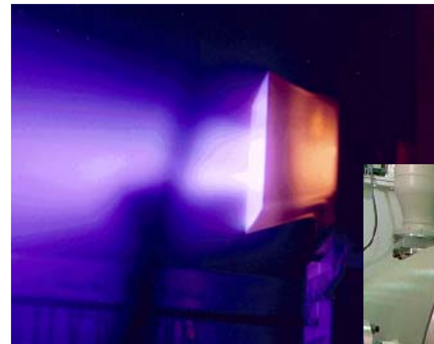
- ***Flight Validation scheduled for October 2001***
- ***PPT Flight unit underwent extensive proto-flight hardware validation/development path***
  - ***(NASA TM-2000-210340 "Development of a PPT for the EO-1 Spacecraft")***
    - *Functionality: Demonstrate range of orbital operations and functionality of test support equipment*
    - *Performance: Demonstrate performance characteristics*
    - *Vibration: Acceptance level vibration testing to Delta II levels*
    - *Thermal Vacuum/Cycle: Demonstrate survival and operations across required temperature range*
    - *EMI/EMC: Measure characteristic conducted and radiated emissions and evaluate PPT susceptibility to EMI*
    - *Life/Contamination: Demonstrate thruster life capability through duration of minimum flight experiment. Evaluate plume contamination effects on spacecraft surfaces.*
- ***Attitude control capability of PPT confirmed in high fidelity spacecraft simulations***

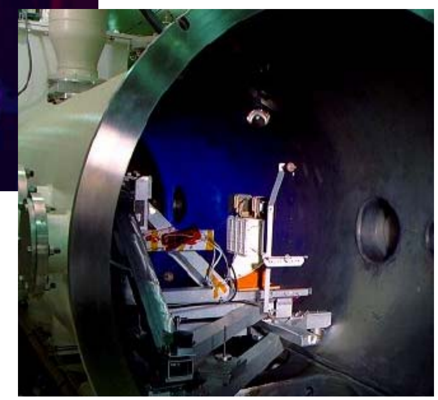
PPT Validation *(2 of 5)*

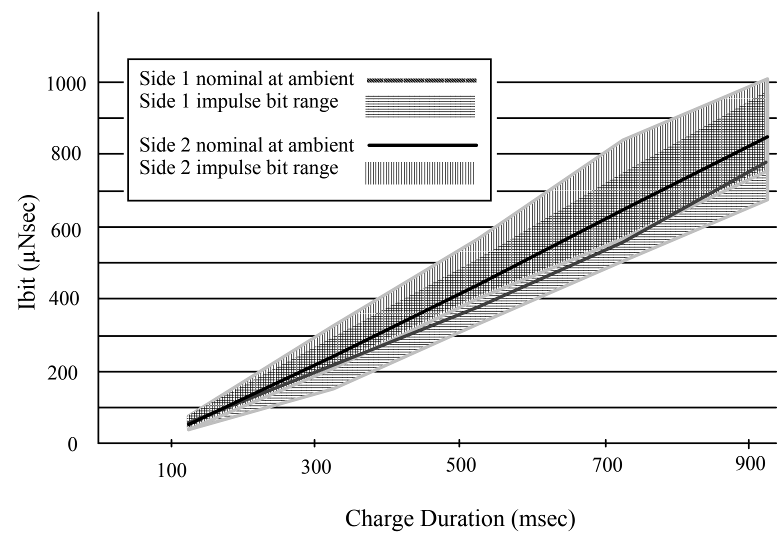
- ***Functionality***
  - ***Benchtop and vacuum testing***
  - ***Demonstrate range of planned orbital operations***
    - *Throttling through charge duration control (120 - 920 msec)*
- ***Performance***

AIAA-99-2290 "Multi-Axis Thrust Measurements of the EO-1 Pulsed Plasma Thruster"

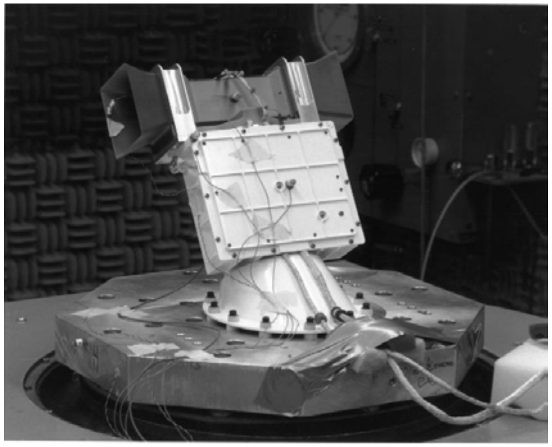
  - ***Determine thrust and impulse bit across throttle range***
    - *Before and after life testing - no change*
  - ***Evaluate off-axis impulse bit component***
  - ***Characterize shot-to-shot repeatability***





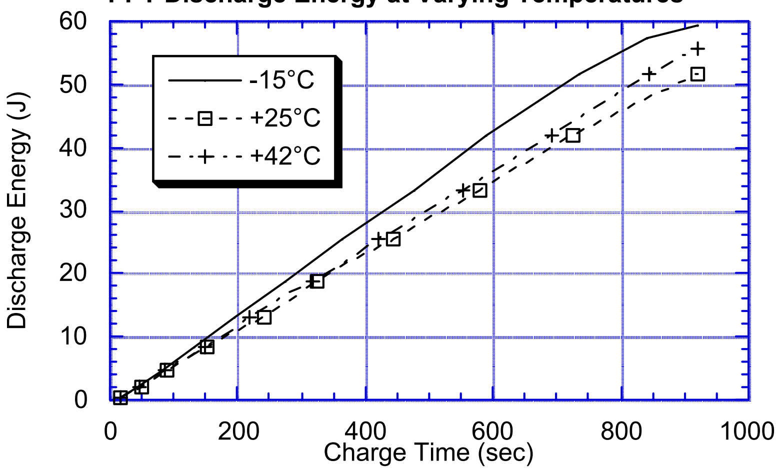


PPT Validation *(3 of 5)*



- ***Vibration***
  - ***Acceptance level vibration testing to Delta II levels***
    - *Random vibration to 14.1 grms on 3 axes*
- ***Thermal Vacuum***
  - ***Demonstrate survival and operations across required temperature range***
    - *-32 to +42°C survival range*
    - *-15 to +42°C operating range*
    - *Characterized sensitivity in main capacitor charge rate to temperature*
      - *Factored into performance results*
      - *Function of charge duration throttling approach*

PPT Discharge Energy at Varying Temperatures

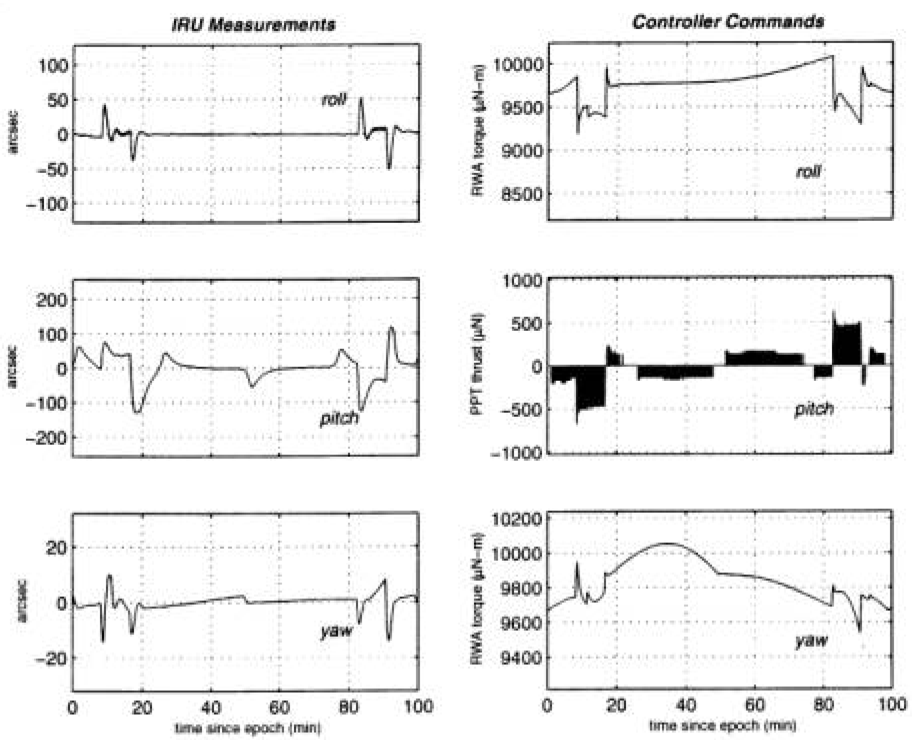


PPT Validation *(4 of 5)*

- ***Life/Contamination***
  - ***Demonstrate thruster life***
    - *Minimum experiment life (100,000 pulses/side)*
  - ***Evaluate plume contamination effects on spacecraft surfaces.***
    - *Spacecraft surface samples (X-band antenna surface ,radiator, MLI)*
- ***EMI/EMC:***
  - ***Characterised conducted and radiated emissions***
    - *Consistent with previous electric propulsion devices*
    - *RE01, CE01 and CE07 results within spec*
    - *CE03 limits (conducted emissions) exceed by up to 12 dB below 4 MHz – waiver accepted*
  - ***RE02 broadband radiated emissions exceed levels below 100 MHz***

    AIAA 2001-3641 "Addressing EO-1 Spacecraft PPT EMI Concerns"
  - ***Continuing PPT EMI evaluation at GRC***

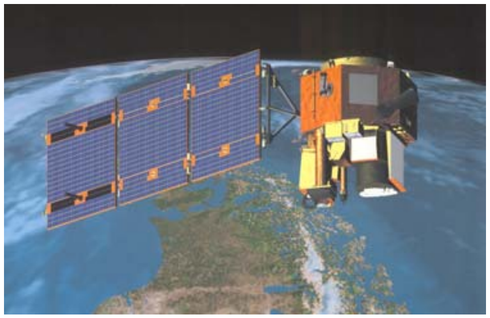
PPT Validation *(5 of 5)*

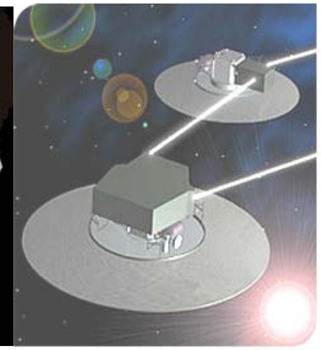


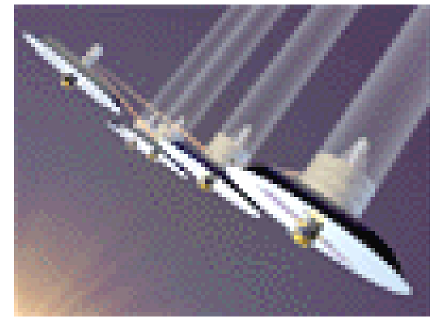
High Fidelity Simulation Results for nominal imaging orbit

- ***Attitude Control Experiment***
  - ***PPT Replaces pitch momentum wheel***
  - ***Minimum impact to existing ACS architecture***
  - ***Same PID controller used***
    - *Computed pitch torque commands processed for PPT control*
    - *PID control gains adjusted*
  - ***Pitch wheel speed brought to zero***
    - *Pitch magnetic torquer turned off*
- ***Simulation Results***
  - ***During imaging mode pointing errors within 5 arcsec requirement***
  - ***Worst case roll, pitch, and yaw errors: 52.1, 129.3, 14.2 arcsec***
    - *Caused by solar array wind/rewind*
  - ***Orbital average power 12.6 W***

PPT Technology Transfer & Infusion







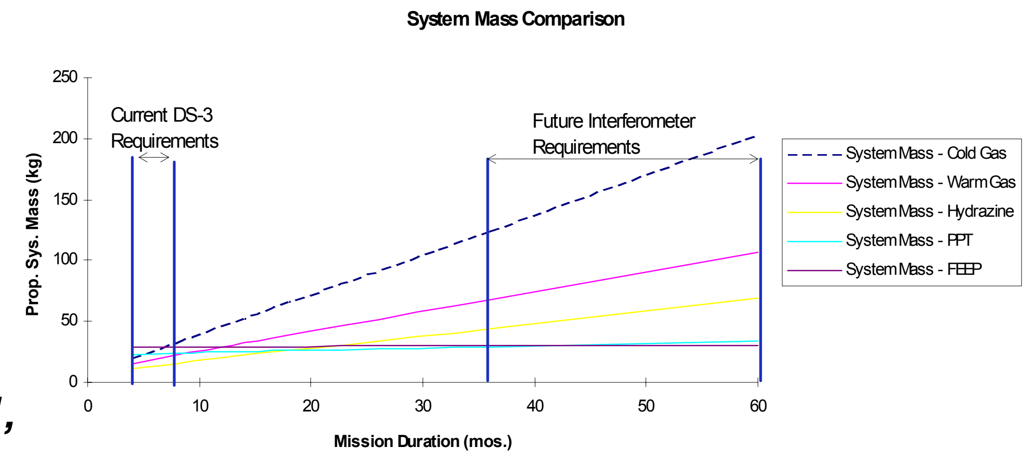
Current (EO-1) → **Near Term (DawgStar, StarLight)** → **Far Term (TPF, MAXIM)**

Multi-Thruster System Architecture, Long Life, Low Mass/Volume, Integration Ease, Specific Impulse, Efficiency, Thrust-to-Power, Impulse Bit Accuracy

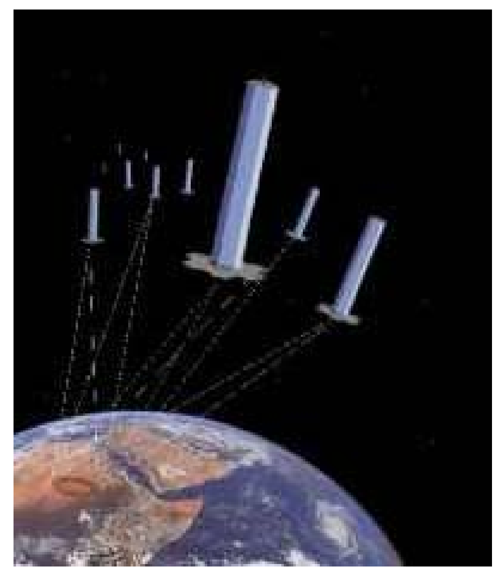
Continued PPT Technology Development and Improvement

Formation Flying

- ***Interferometry Missions (Starlight, TPF, Planet Imager)***
  - *Require 1 cm separation control between spacecraft*
  - *PPTs have been leading candidates for these missions due to high precision thrust pulses, high Isp*



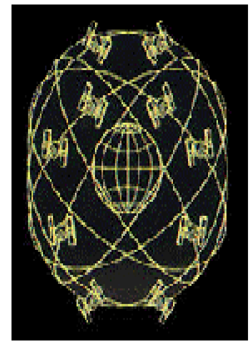
- ***Earth Observing Mission (Techsat 21, Leonardo)***
  - *Air Force and NASA are studying ways to deploy constellations of small satellites in co-orbiting formations*
  - *Typically requires 1 mN - 100 mN of thrust, with capability to generate 0.5 mN - 2 mN-s impulse bit*
  - *PPTs trade well because of small impulse bit, high Isp, and small volume*



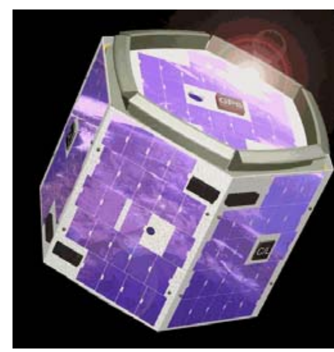
Precision Pointing (Maxium)

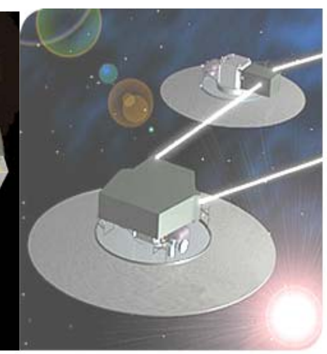
– *Fine attitude control for pointing optical instruments*

- ***Continuous disturbance reduction***
  - ***Drag free control (GRACE and GPS follow-ons)***
    - *Repeatable low thrust range of PPT use to cancel atmospheric drag forces*
    - *Maintains orbit, improves prediction accuracy*
  - ***Other (TDRSS type GEO missions)***
    - *PPTs can cancel disturbance forces to reduce size of attitude control system*



- ***Micro/Nanosats (Dawgstar, MMS)***
  - ***Low mass/volume/power ideally suited for microsats***
  - ***Simple to integrate, No chemical/pressure hazard***
    - *Well suited multiple S/C on a deplorer ship and university project*





- ***Large Space Structures***
  - ***Used as active control actuators***

Lessons Learned

- ***PPTs can be implemented as attitude control actuators with minimal impact to existing attitude control subsystem architectures***
- ***Increasing range of PPT thrust would expand the use of PPT as ACS actuators***
  - ***On going PPT development efforts are addressing concern by looking at changes to components and changes in operation methods***
- ***Radiated emission concerns must be addressed earlier in project timeline***
  - ***Special test with PPT in bell jar while electrically mated to S/C to confirmed benign effect on S/C bus (without instruments).***
  - ***Successful ambient testing with GSE performed with ALI integrated***
  - ***Effort to conclusively quantify risk to instruments unit beyond program constraints at time issue was identified***
    - *Most desirable solution for EO-1 would be to test with high fidelity ALI engineering unit*
- ***Continuing research into PPT EMI reduction leveraging EO-1 experience***
  - ***Addressing: lower discharge energies, improved component characteristics, geometry effects, sparkplug characteristics***

Summary / Conclusion

- ***Benefits of PPT Technology***
  - *Micro impulse capability for precision pointing/positioning*
  - *Unique high Isp, low power attributes well suited to small spacecraft*
  - *Eliminates distributed, toxic propellant systems*
  - *Low mass / power / volume alternative for mission in which both conventional ACS and delta-V systems can be replaced.*
- ***Applications***
  - *Formation flying/precision pointing (Starlight,SAR, TPF, Maxium)*
  - *Propulsive attitude and drag free control (Future GRACE/GPS missons, GEO solar disturbances)*
  - *Micro/small satellite propulsion (Dawgstar, Techsat 21)*
- ***EO-1 Flight Validation***
  - *EO-1 PPT experiment will validate the capability of a new generation of PPTs to perform spacecraft attitude control*
  - *Ground validation tests indicate adequate PPT performance*