On-Orbit Commissioning of High Performance Green Propulsion (HPGP) in the SkySat Constellation

Image courtesy of Terra Bella Technologies
Collected by SkySat-1 on 28 Apr 2014

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Outline

1. Introduction to HPGP® technology
   - LMP-103S propellant
   - HPGP thrusters
2. Implementation on the SkySat Constellation
   - HPGP propulsion module design
   - Launch campaign fueling operations
   - On-orbit commissioning process
   - On-orbit maneuvers

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3. Continuing Development
   - Thrusters
   - Propellant

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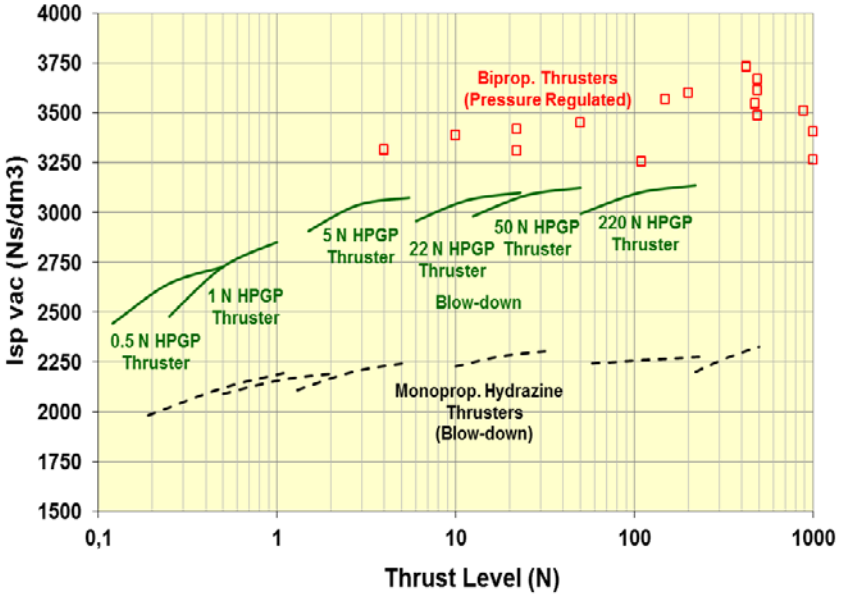
LMP-103S and HPGP Thruster Performance

LMP-103S is an ADN-based liquid propellant
(replacement for monopropellant hydrazine)

Compared to monopropellant hydrazine:

- 6% higher specific impulse
- 24% higher density

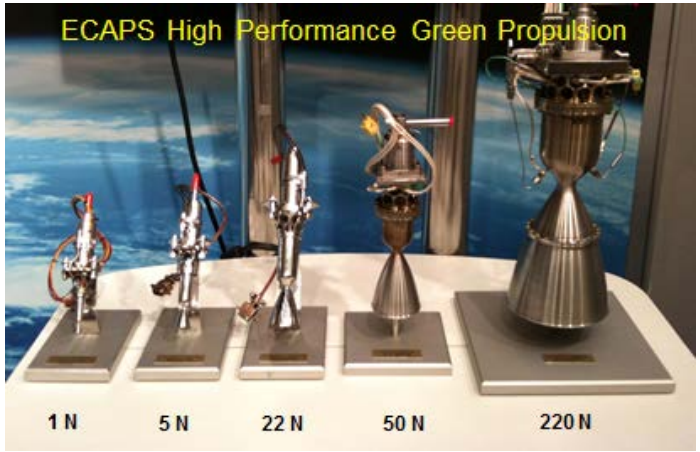
results in **30% higher density impulse**



HPGP thrusters are comparable with hydrazine thrusters for:

- Minimum impulse bit
- Combustion stability
- Pulse-to-pulse repeatability
- Response times
- ACS, RCS
- Scalability:
  - 100 mN, 1N, 5N, 22N, 50N & 200N

VACCO CubeSat propulsion module



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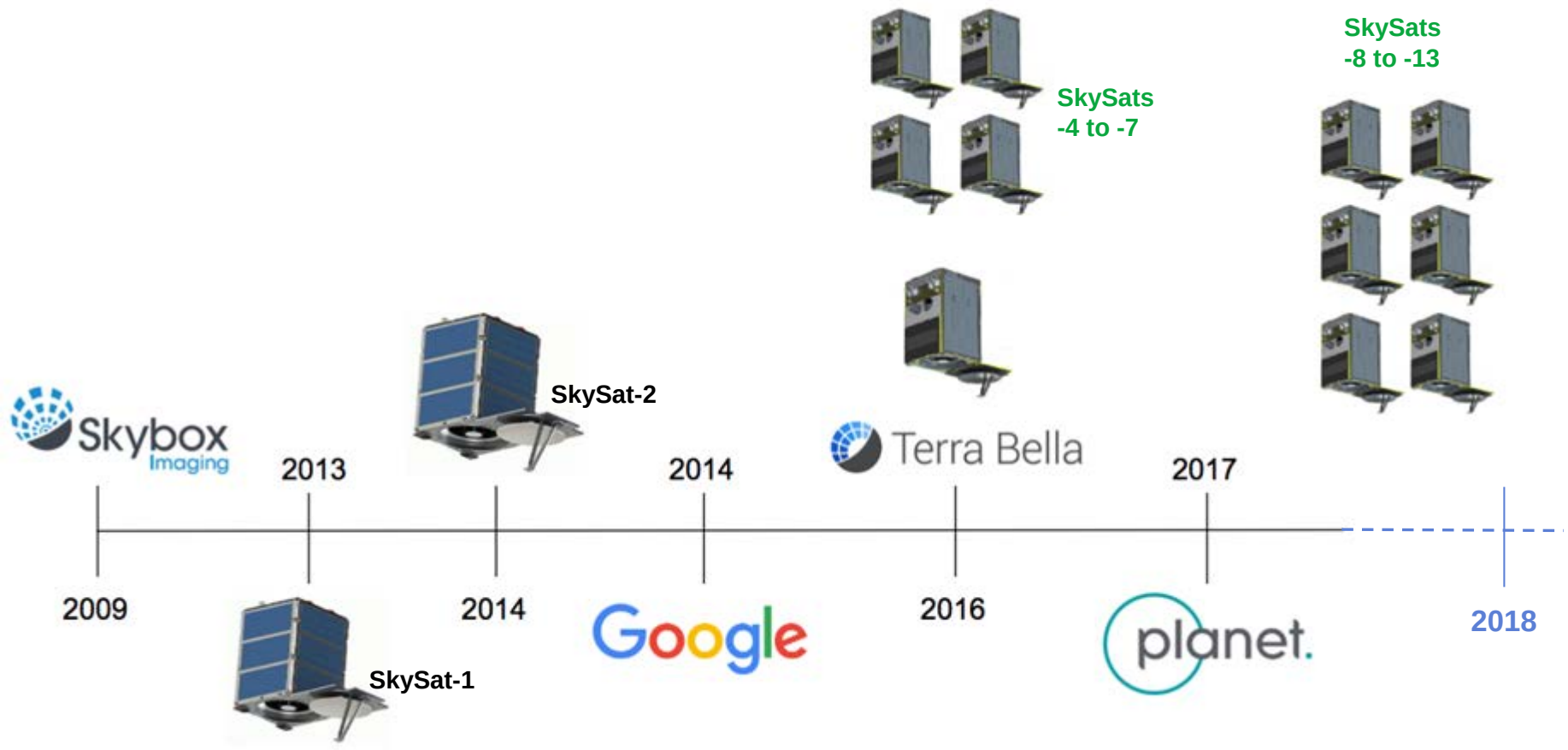
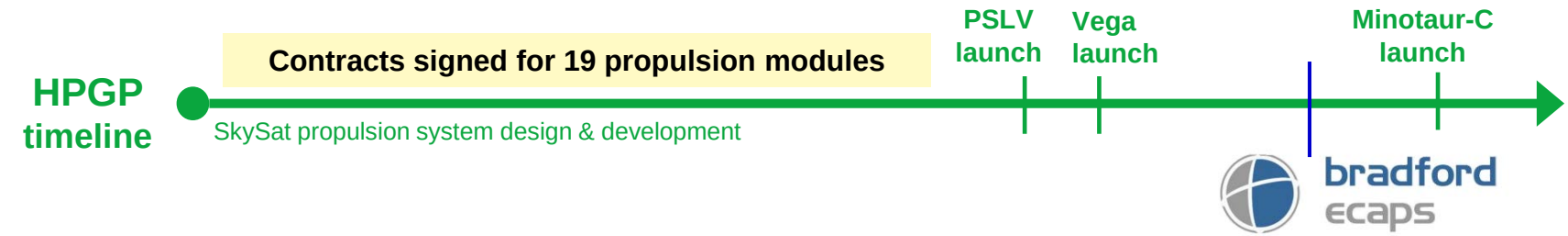
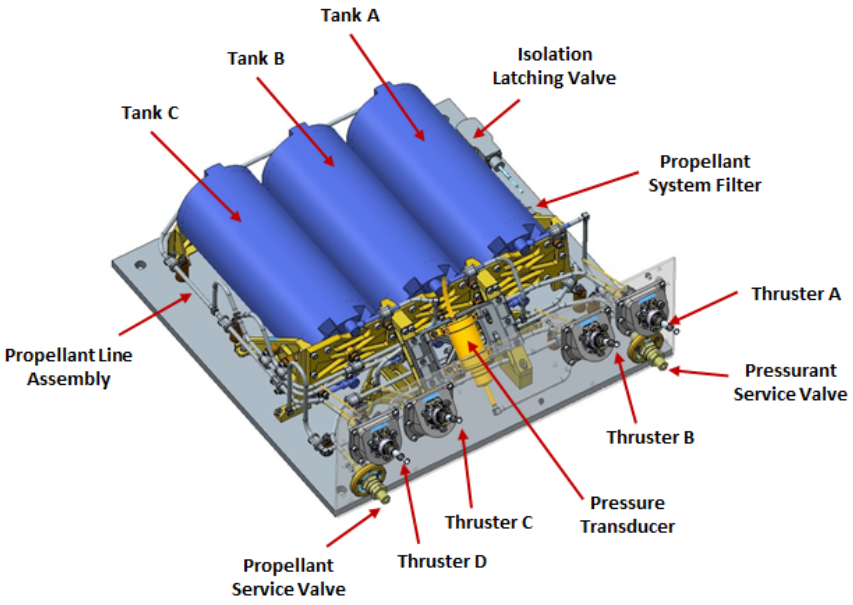
Implementation of HPGP on the SkySat Constellation

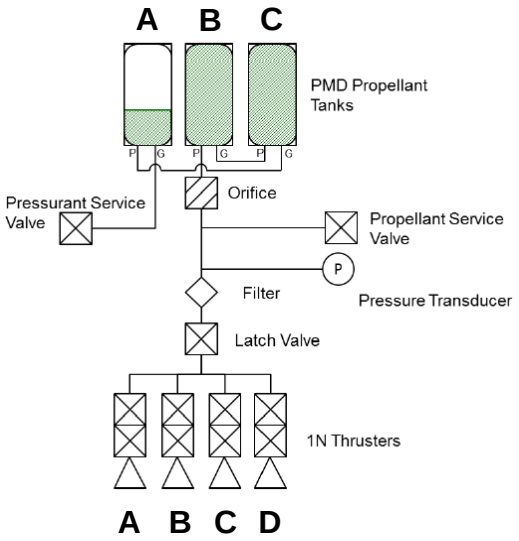




SkySat HPGP Propulsion Module

Approx. 180 m/s of delta-v for a ~120 kg satellite





- Blow-down liquid monopropellant system
- 21 kN-s total impulse
- 10.9 kg dry mass (excl. customer furnished items)
- 10.5 kg LMP-103S
- Components:
  - 3x propellant tanks (w/ PMD)
  - 2x fill & drain valves
  - 1x pressure transducer
  - 1x isolation latch valve
  - 1x system filter
  - 4x 1N HPGP thrusters
  - 8x thermistors
  - 18x spiral line heaters
  - 13x patch heaters

ECAPS owns the design – and can provide it (or derivatives thereof) to other customers

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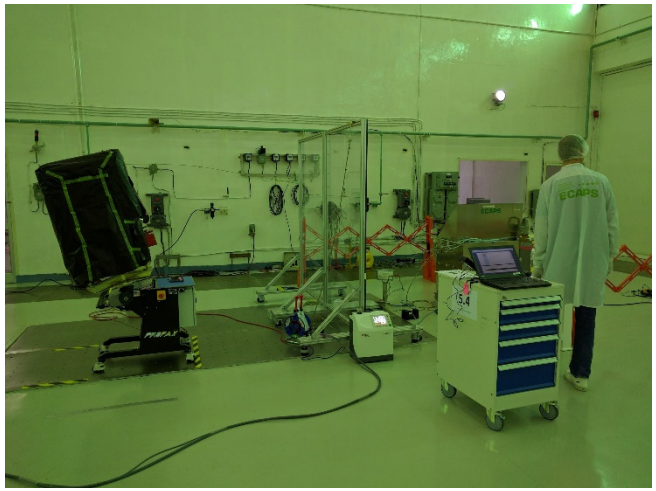
Launch Campaign Operations

SCAPE not required during LMP-103S loading

SkySat-3: Satish Dhawan Space Centre

- May 2016
- LMP-103S shipped as commercial air cargo from Stockholm to Chennai airport (via Dubai)
- SkySat-3 tested, fueled, pressurized and finalized in 2 days



SkySat-4 to -7: Guiana Space Centre

- August 2016
- LMP-103S shipped as commercial air cargo from Stockholm to Cayenne airport (via Paris)
- 2 SkySats processed in parallel
- 4 satellites tested, fueled, pressurized and finalized in 4 days

SkySat-8 to -13: Vandenberg AFB

- September 2017
- LMP-103S shipped as commercial air cargo from Stockholm to San Francisco
- 2 SkySats will be processed in parallel
- 6 satellites to be tested, fueled, pressurized and finalized in 6 days

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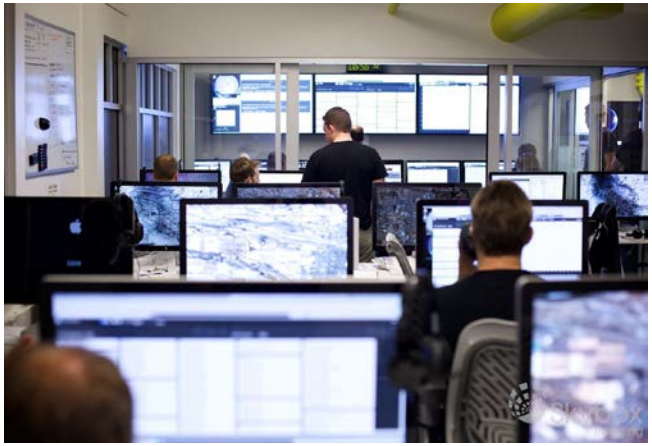
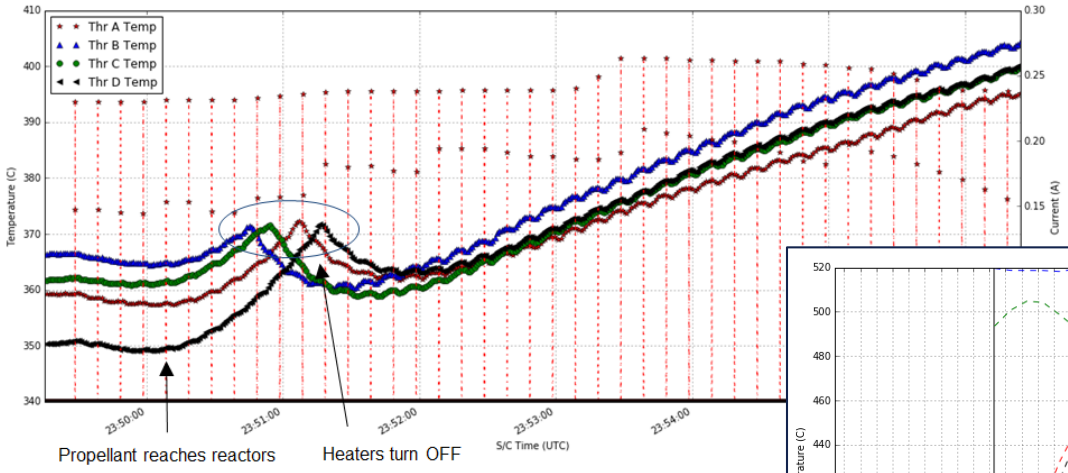
On-Orbit Commissioning

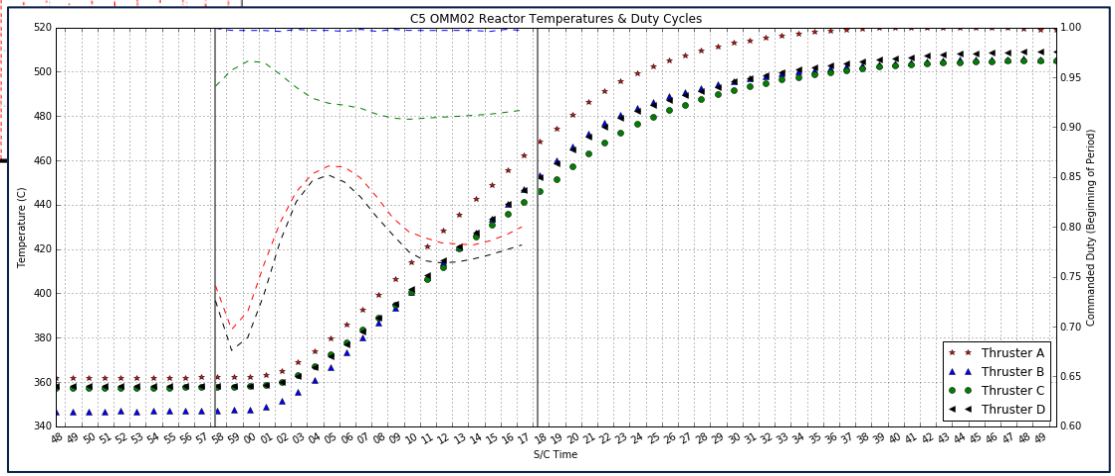
- Thruster catalyst heaters enabled with setpoints of 330C – 370C for 60 minutes
- All thruster Flow Control Valves (FCVs) opened to vent 2 bar(a) Helium
- FCVs closed
- Isolation latch valve opened
- **Priming maneuver**
- **20 second closed-loop burn**



Priming Maneuver



20 Second Closed-Loop Burn



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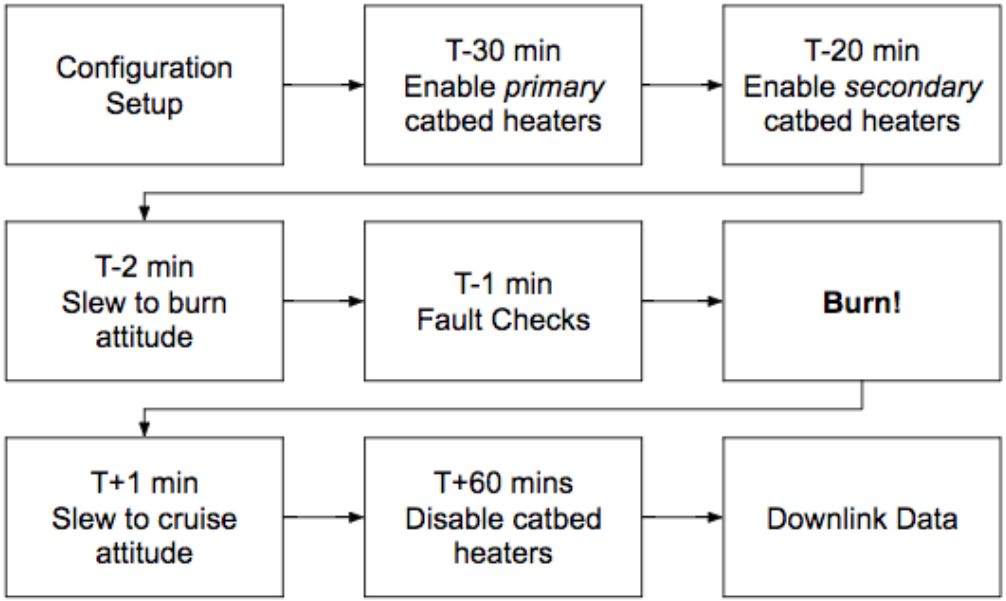
On-Orbit Maneuvers



43 burns to-date

- 5 minute burn on SkySat-3!
- Collision avoidance burn on SkySat-4

Spacecraft	Maneuvers	Impulse To-Date
SkySat-3	14	2370 N-s
SkySat-4	4	70 N-s *
SkySat-5	5	150 N-s
SkySat-6	6	334 N-s
SkySat-7	14	317 N-s

* Note: SkySat-4 is being used as the 'reference' for maintaining constellation phasing (and has thus required fewer maneuvers than all of the other satellites)

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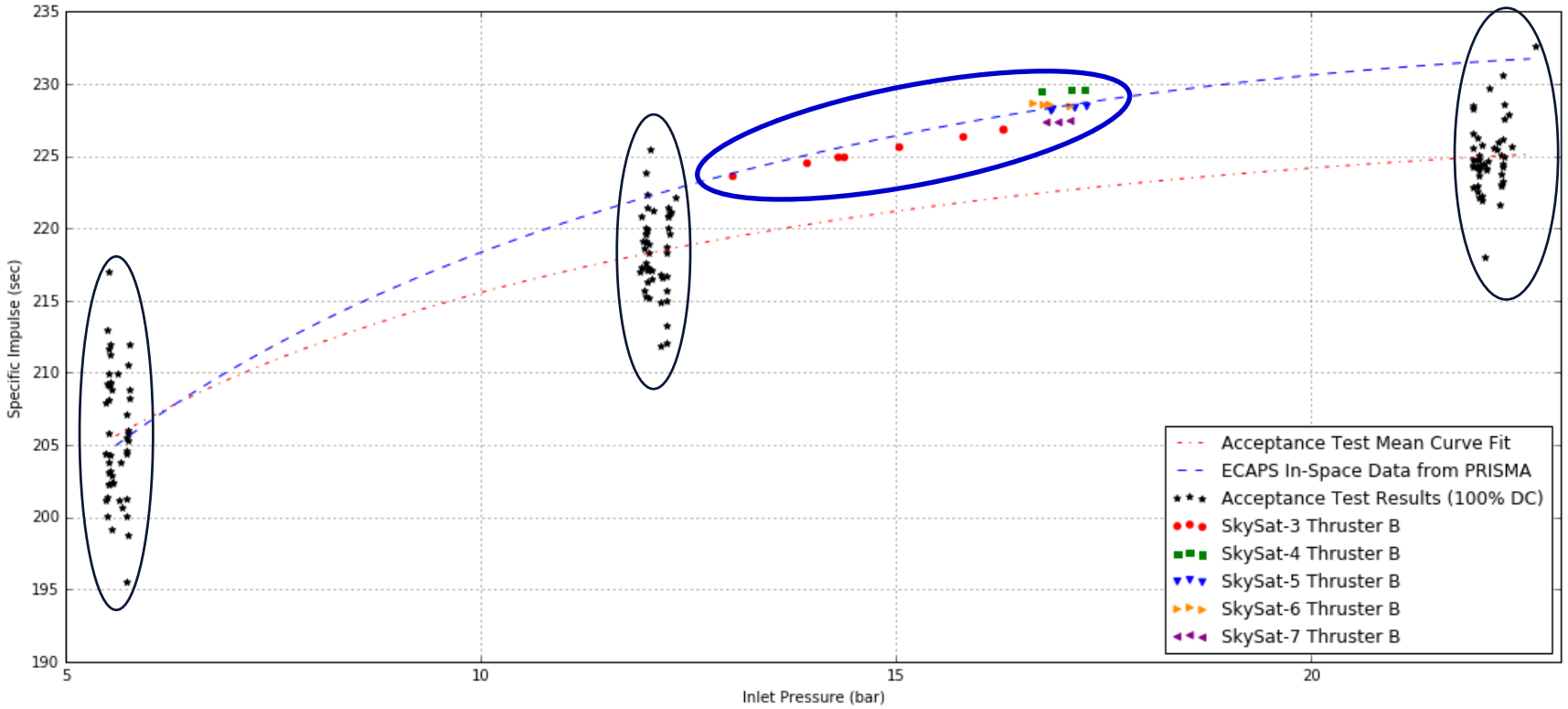
On-Orbit Maneuvers (cont'd)

System Performance



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On-Orbit Maneuvers (cont'd)

Maneuver Calibration

Maneuver	SkySat-3	SkySat-4	SkySat-5	SkySat-6	SkySat-7
OMM 01 (Priming)	-	-	-	-	-
OMM 02	N/A	-1.1%	-3.5%	-2.4%	+1.6%
OMM 03	+4.6%	+3.4%	+3.1%	+2.8%	Abort
OMM 04	-4.4%	-3.3%	+3.9%	+5.4%	Test
OMM 05	Abort		-0.7%	+3.2%	Test
OMM 06	Test			+1.9%	Test
OMM 07	Test				Test
OMM 08	-2.7%				Test
OMM 09	-3.3%				Test
OMM 10	Abort				Test
OMM 11	Test				Test
OMM 12	-0.1%				Test
OMM 13	-0.2%				+7.6%
OMM 14	-1.8%				+6.9%

Anomaly Resolution

SkySat-7 Thruster B

- Dec 2016: Automatic abort ~ 4.5s into burn
  - Insufficient torque to maintain attitude
  - Probable thruster non-fire
- Collaborative investigation by Planet and ECAPS
  - 9 on-orbit test maneuvers
  - Numerous ground tests
- Determination of most likely cause
  - Leaking down-stream FCV seat
  - ADN precipitate resulted in clogged valve or feed tube

Resolved!

- **Successfully recovered in Feb 2017**
  - New flight software command to increase FCV pull-in voltage application and duration
- Help mitigate recurrence with 1 hour post-heat
- 4 burns completed since recovery
- Thruster performance is unaffected after the non-fire
- **S/C released to normal operations**

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Continuing Development

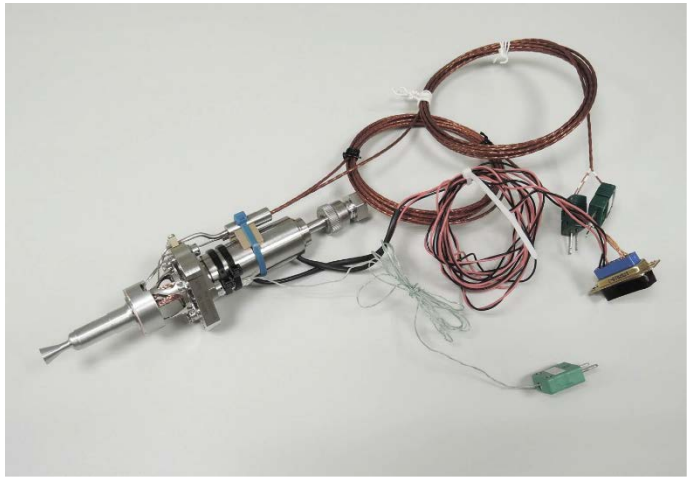
Next Generation 1N Thruster

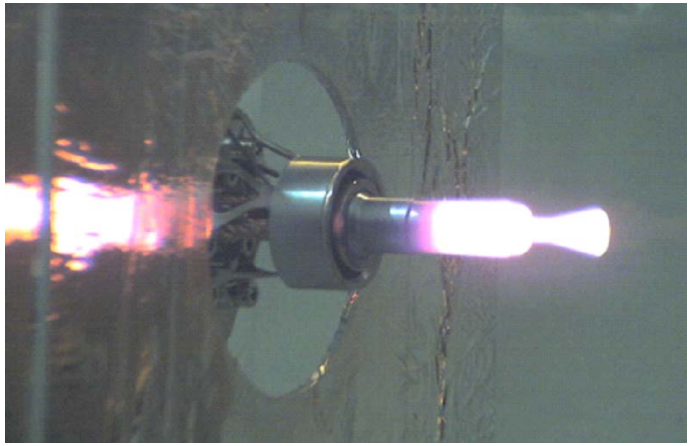
Planet's goals for future SkySat platform:

- Reduced manufacturing time
- Lower system cost
- Increased system operational flexibility

In support of Planet's future platform goals, ECAPS is developing & testing a new 'GP' (Green Propulsion) thruster design

- Drop-in replacement for the existing 1N HPGP thruster
  - No system-level modifications needed
- Operates using a derivative of LMP-103S with a lower combustion temperature
  - Comparable steady-state Isp performance as hydrazine, but 20% higher density impulse
- Allows thrust chamber components to be fabricated from lower-cost materials
  - Able to be conventionally machined
- Initial hot-fire successfully demonstrated in Dec 2016





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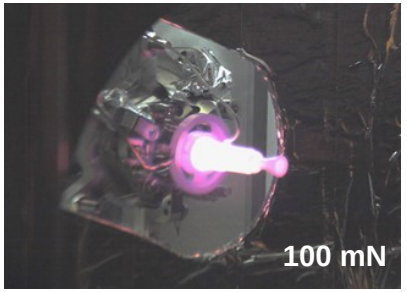
Continuing Development (cont'd)

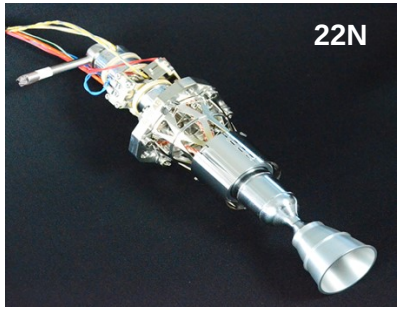
Thruster up- & down- scaling

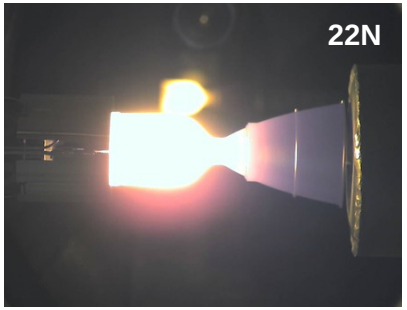
Progress continues on maturing additional sizes of HPGP thrusters:

- **100 mN HPGP thruster**
  - Hot-fire demonstrations of a Development Model successfully performed
  - Testing of a Qualification Model has begun



- **5N & 22N HPGP thrusters**
  - Flight representative (TRL-6) designs of both are finalized
  - 22N Engineering Qualification Model (EQM) assembly has been completed
    - Environmental and hot-fire life testing is currently underway
  - 5N EQM to be assembled during 4Q2017
    - Environmental and hot-fire life testing scheduled for 2018





- **50N HPGP thruster**
  - Updated design has been completed for a planned in-space flight demonstration

- **200N HPGP thruster**
  - Development of an apogee engine, for use on a small launch vehicle 'orbit raiser', is ongoing

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Conclusion

- SkySat-3 was the first commercial S/C to fly a HPGP system
- SkySat fleet has performed 43 propulsive maneuvers for a combined total of 3241 N-s impulse
  - Non-fire anomalies have been overcome
  - HPGP systems are performing well and as expected
- 6 more SkySats with HPGP systems to be launched in Q4 2017, bringing the on-orbit total to 11
  - 8 additional SkySats with HPGP systems to be launched starting in 2018, bringing the on-orbit total to 19
- ECAPS' next generation 1N 'GP' thruster will be incorporated into future SkySat platforms
  - The GP thruster will provide approximately 20% more delta-v than a comparable hydrazine thruster (based on an equivalent volume of propellant)
- Progress on bringing both smaller and larger HPGP thrusters to market continues

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Questions?