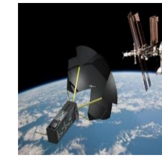


Modeling the Exo-Brake And The Development Of Strategies For De-orbit Drag Modulation

June 16, 2016

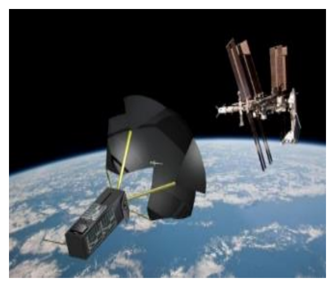
TechEdSat-1

TechEdSat-2

TechEdSat-3

TechEdSat-4

SOAREX-8, 9



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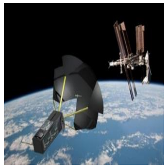
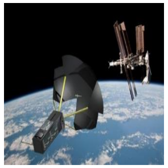
Abstract



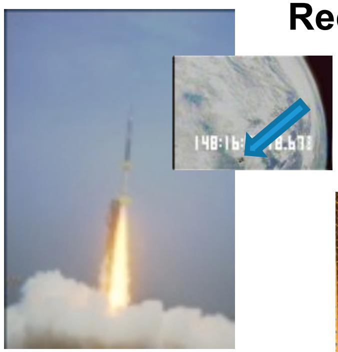
Abstract: The Exo-Brake is a simple, non-propulsive means of de-orbiting small payloads from orbital platforms such as the International Space Station (ISS). Two de-orbiting experiments with fixed surface area Exo-Brakes have been successfully conducted in the last two years on the TechEdSat-3 and -4 nano-satellite missions. The development of the free molecular flow aerodynamic data-base is presented in terms of angle of attack, projected front surface area variation, and altitude. Altitudes are considered ranging from the 400km ISS jettison altitude to 90km. Trajectory tools are then used to predict de-orbit/entry corridors with the inclusion of the key atmospheric and geomagnetic uncertainties. Control system strategies are discussed which will be applied to the next two planned TechEdSat-5 and -6 nano-satellite missions – thus increasing the targeting accuracy at the Von Karman altitude through the proposed drag modulation technique.

Relevant Flight Experiments



(Building the Flight Laboratory)

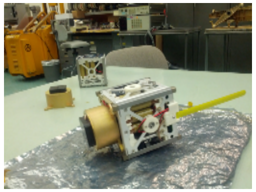
SOAREX-6
(2008)



SOAREX-7
(2009)

Recent Years of Flight Experiments
(2008-2015):
8 Flights +1 (T5P5)

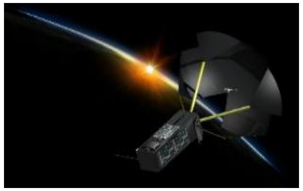
TES-1
Oct 4, 2012
FIRST off ISS



TES-2
PhoneSat
Iridium-test
Aug 21, 2013

Exo-Brake Tests:
3 Small-Scale
1 Full-Scale

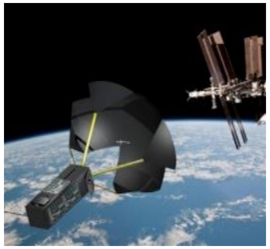
TES-3
Aug 3, 2013
(6 wk de-orbit)



…here before

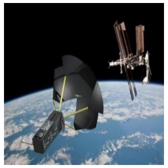
SOAREX-8,9
(2015, 2016)

TES-4
Mar 3, 2015
(4 wk de-orbit)



SOAREX/TechEdSat-X Team

Since The Last IPPW..



1. **SOAREX-8** (July 7, 2015; Apogee 340 km)
   Test of large scale Exo-Brake

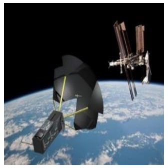
2. **SOAREX-9** (March 7, 2016; Apogee 164 km)
   Test of ancillary avionics and sensor package

3. **TES-5/P5** Design/Integration/Delivery (June 3, 2016)
   First Modulated Exo-Brake flight test

*Also -2 **VAST** Balloon flights at UofIdaho

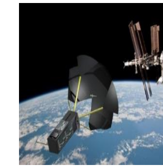
[in addition to the aero-modeling work presented here]

Flight Test Development Notes



- **Rapid-Flight Development TEAM (SOAREX/TechEdSat) is studying this problem – supported by modeling efforts.**
  - Involves Balloons (VAST series), sub-orbital (SOAREX-N), orbital (TechEdSat-N/P-SAT
  - Designing larger scale flight tests (SOAREX-8,10; SPQR-1)
  - VERY strong university intern/early-career TRAINING
- **Flight testing is crucial for timely development**
  - Corona (Discoverer) program required 13+ attempts before success
  - Current TES/SOAREX flight 'laboratory' can quickly explore different experimental protocols and topologies.
- **Parachute or drag-devices – by nature require empirical work/ development (significant experimentation!)**

Options and Objectives/Requirements



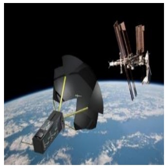
- Options – Disposal vs. Sample Return
  - Disposal - COARSE
    - Coarse targeting is adequate if object is large (hit ocean)
  - Orbit Sample Return/Recovery - FINE
    - Fine targeting required (100km target)

SOAREX-8 Camera system

- Fine Targeting Requirements
  - GPS update per orbit
  - Downlink/uplink per orbit
  - Optics/direct measurement
  - Drag modulation/control
- Small/ Full-scale Exo-Brake
  - Understanding scalability and control

Note:
-Exo-Brake is a tension structure
-Drag-sail has failure modes in the buckling of the support beams…

Modeling Efforts and Aero-Tools



List of Codes:

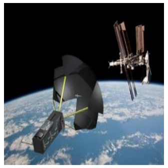
- CBAERO
- DACFREE
- DAC
- POST2
- STK
- TRAJ
- SPARTA

Modeling/ Flight Dynamics Analysis Objectives:

- -Determine/build the aero-data base
- -Understand the uncertainties
- -Run trajectory simulations to capture past data
- -Analyze control strategies for different applications
  (De-orbit vs. Targeting)

Central question: can sufficient targeting be achieved??

Sources of Error/Uncertainty

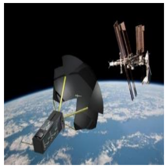


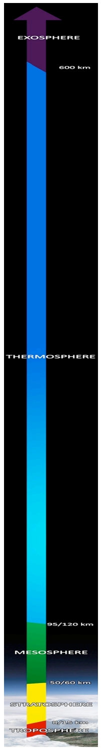
1. Entry System Uncertainty
   Ballistic Coefficient
   Vehicle dynamics
   [Reduction: Visual validation of position with camera]

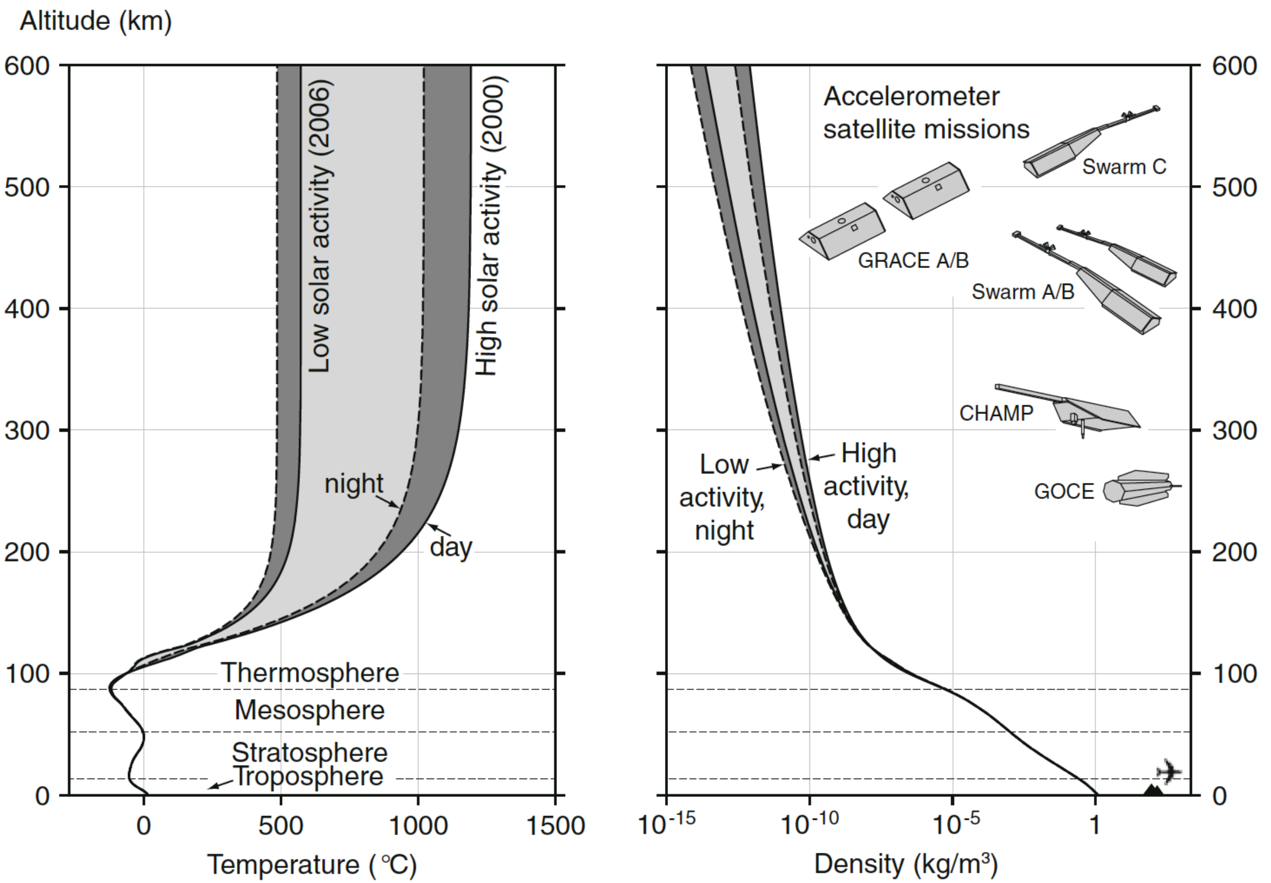
2. Position/Velocity (Command) Uncertainty
   [Reduction: GPS/COM system]

3. Atmospheric Uncertainty
   F10.7/ Geomagnetic variables
   [Reduction: daily updates; improved models]

Thermosphere Uncertainties

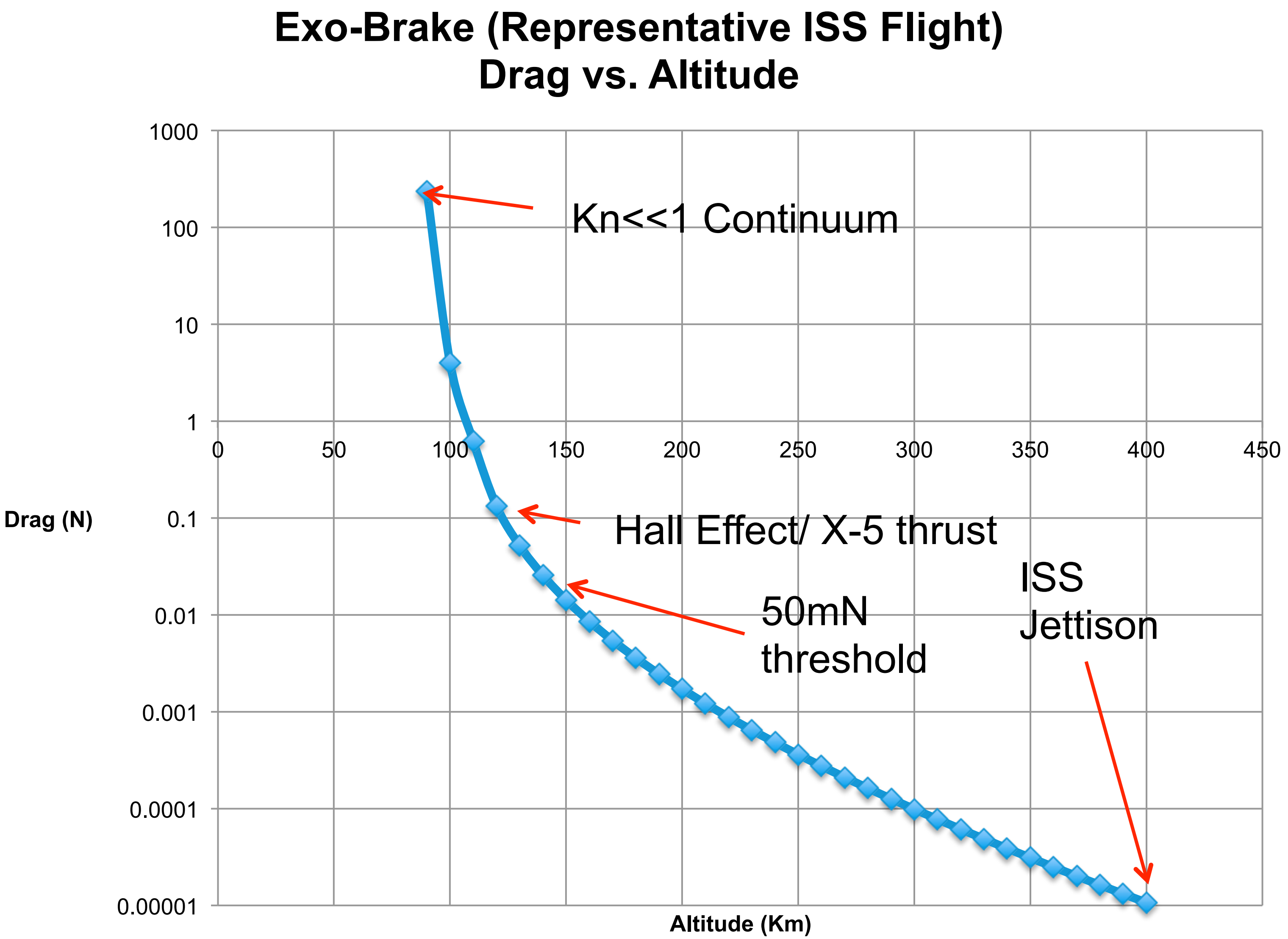




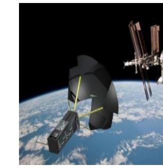


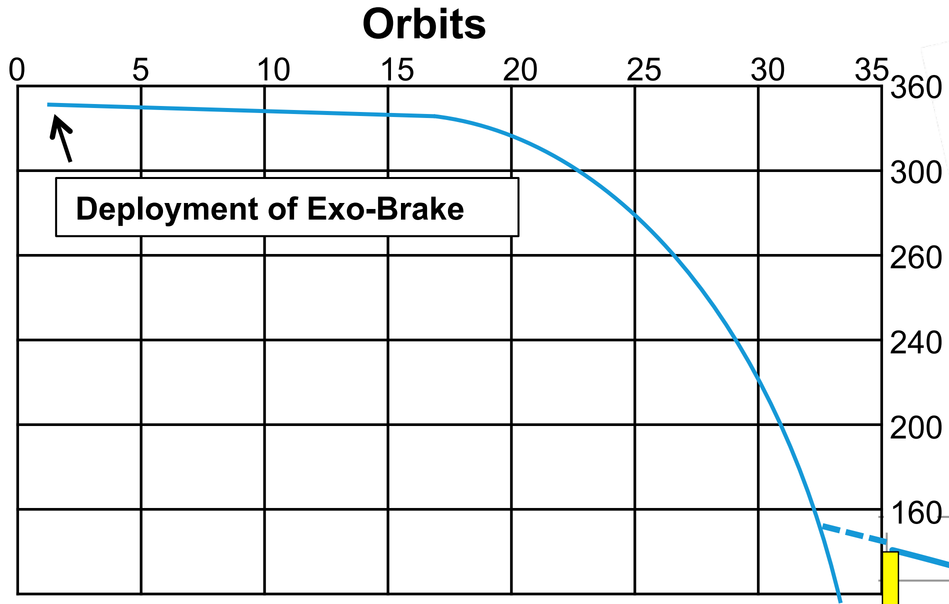
[Add Reerence]

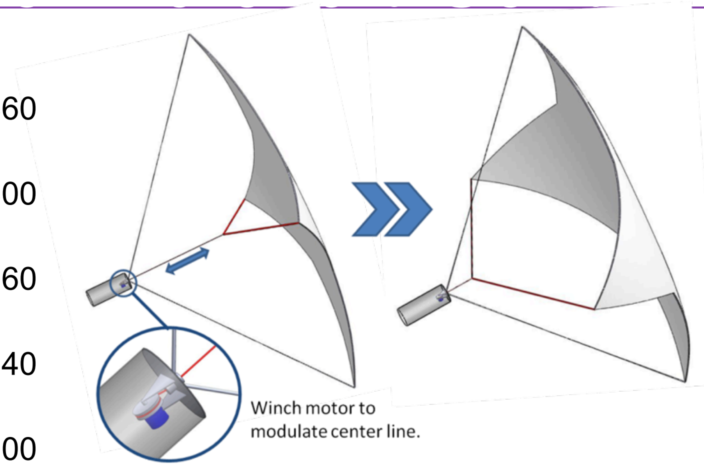
How Much Drag is Produced?



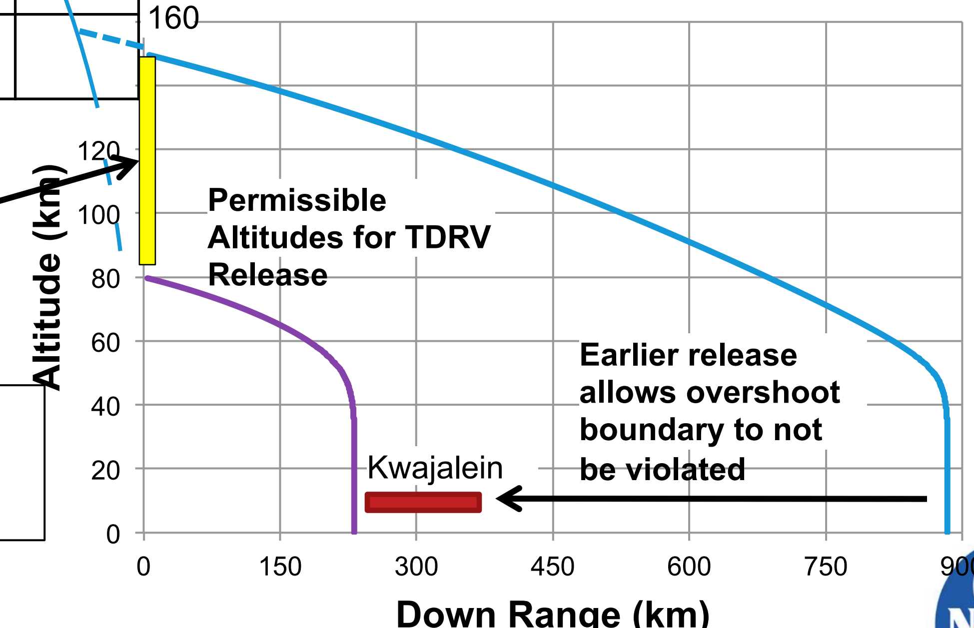
Overview of Targeting/Methodology





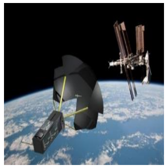


Initial Target Location Control:
- **GPS/Tracking permits selection of TDRV entry state vector**
- **TDRV release occurs between 80-150 km to compensate for atmospheric uncertainties**



Follow-On Targeting Refinement/Control:
•Addition of *drag-modulation* technique controlled by single tow line control variable

*Note: Times / Altitudes between graphs are not to scale



Improved Levels of Control

(Course to Fine Control)

1. System disposal through de-orbit
   (Fixed Exo-Brake throughout de-orbit phase)

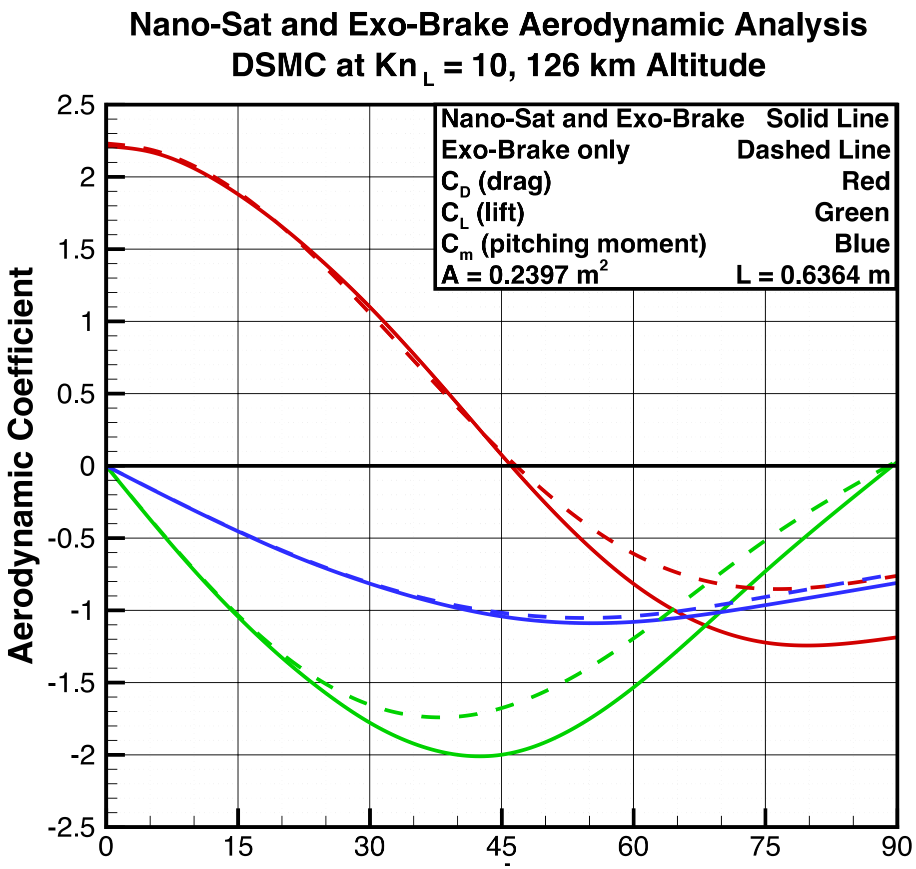
2. Two-point control
   (Cutting the Exo-Brake on final/approach pass)

3. Two-state Drag Modulation: TES-5
   (Two ballistic coefficient settings)

4. Variable Drag Modulation: TES-6,7
   (Variable Exo-Brake settings)

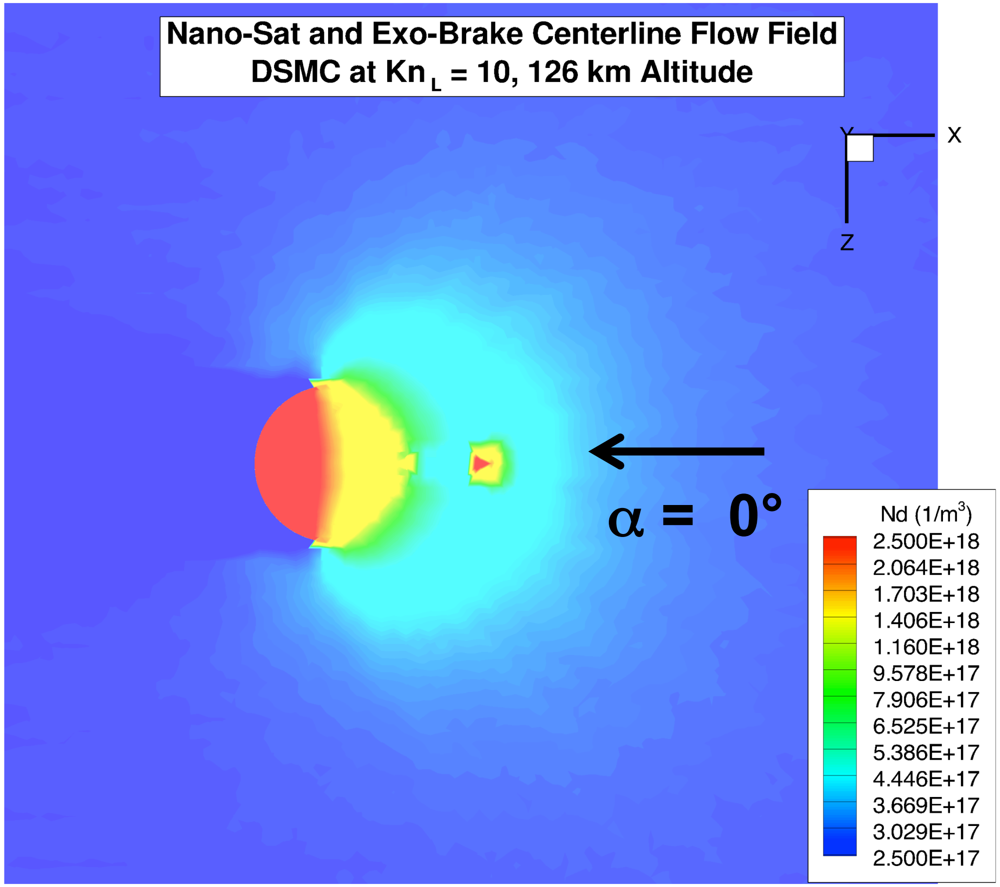
Note: Small-scale work permits techniques that may be different at larger scale

Aero-Coefficients/Data Base



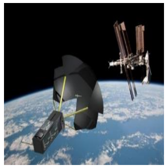
C. Glass, (LaRC)

Sample DAC Results

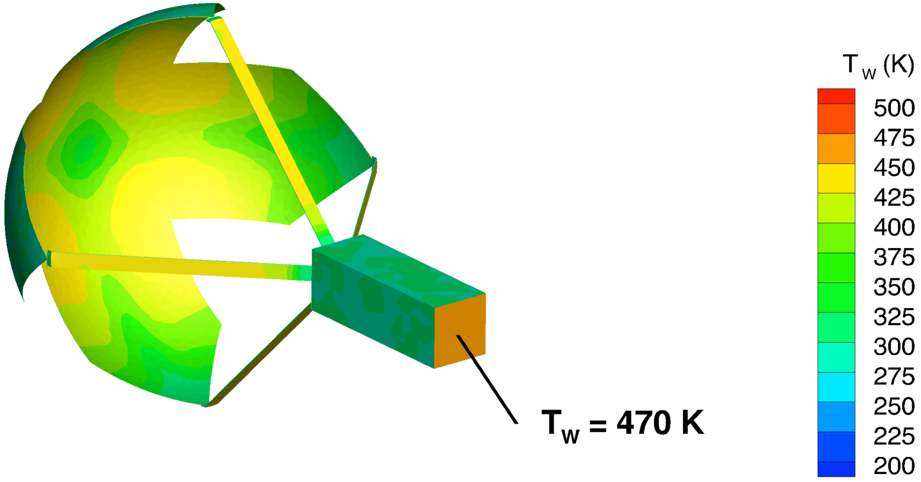


C. Glass, (LaRC)

Sample DAC Results

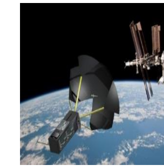


Nano-Sat and Exo-Brake Radiative Equilibrium Temperature
DSMC at Kn_L = 10, α = 0°, ε = 0.85, 126 km Altitude



C. Glass, (LaRC)

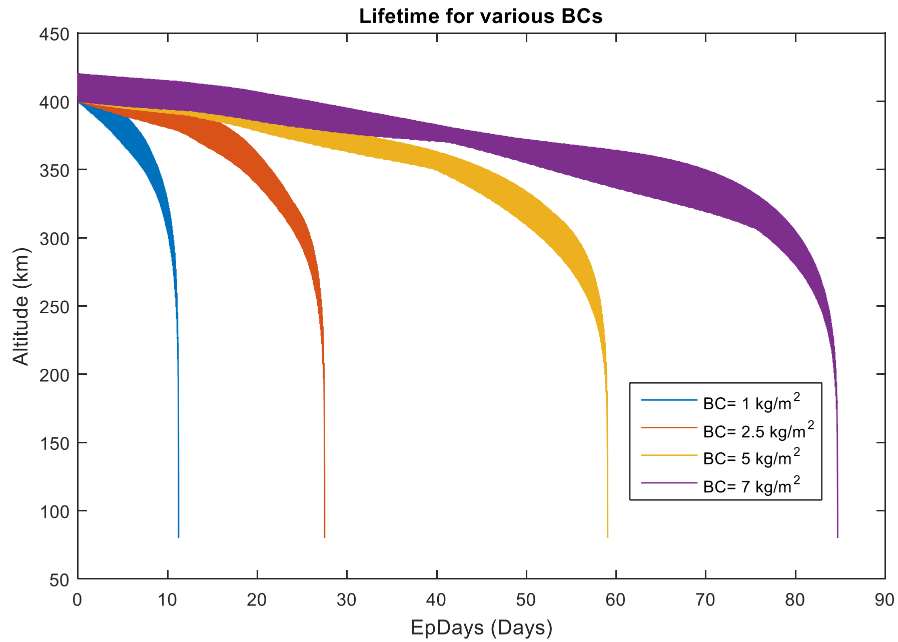
Lifetime Simulation (STK)



❑ Assumptions:

- M=2.85 kg
- Deployment from ISS
- Epoch 16th May 2016
- Initial altitude= 404.13 km
- 1m/s in the antivelocity direction
- Different BCs

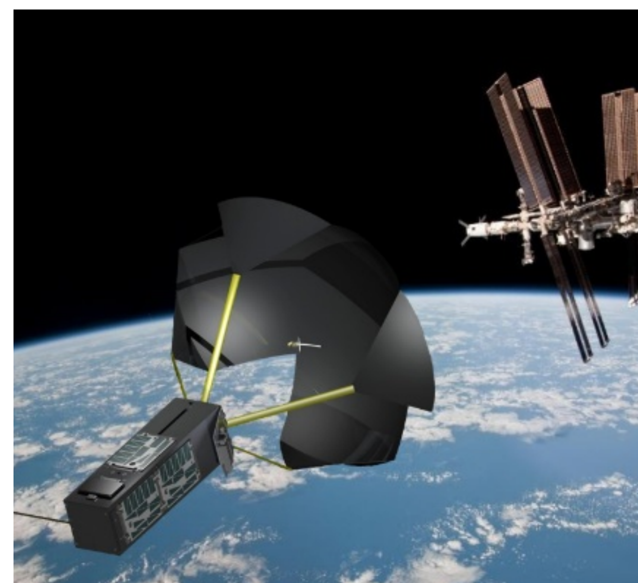
- If BC=1 kg/m^2 Cd=2.2 and M=2.85 kg
  A=1.295 m^2
- If BC=2.5 kg/m^2 Cd=2.2 and M=2.85 kg
  A=0.5182 m^2
- If BC=5 kg/m^2 Cd=2.2 and M=2.85 kg
  A=0.2591m^2
- If BC=7 kg/m^2 Cd=2.2 and M=2.85 kg
  A=0.1851 m^2



Sample Targeting Results

- **End-to-End Simulation**
  - ISS orbit to UTTR
- **Allowed for POST2 to select 7 time & drag modulation combinations to meet UTTR landing constraint**
  - Drag Area Modulations options: 75% to 100% (Lref = 60 to 100%)
- **Monte Carlo dispersions (2000 cases, 860 finished/shown)**
  - Atm: JB2006, Earth GRAM +/-3 sig
  - Aero: No Exobrake aero dispersion
  - Does include REBR aero dispersions
- **Switches to REBR vehicle at entry**
  - Sphere cone properties “appear” at 90 km

S. Dutta, A. Cianciolo, R. Powell , (LaRC)



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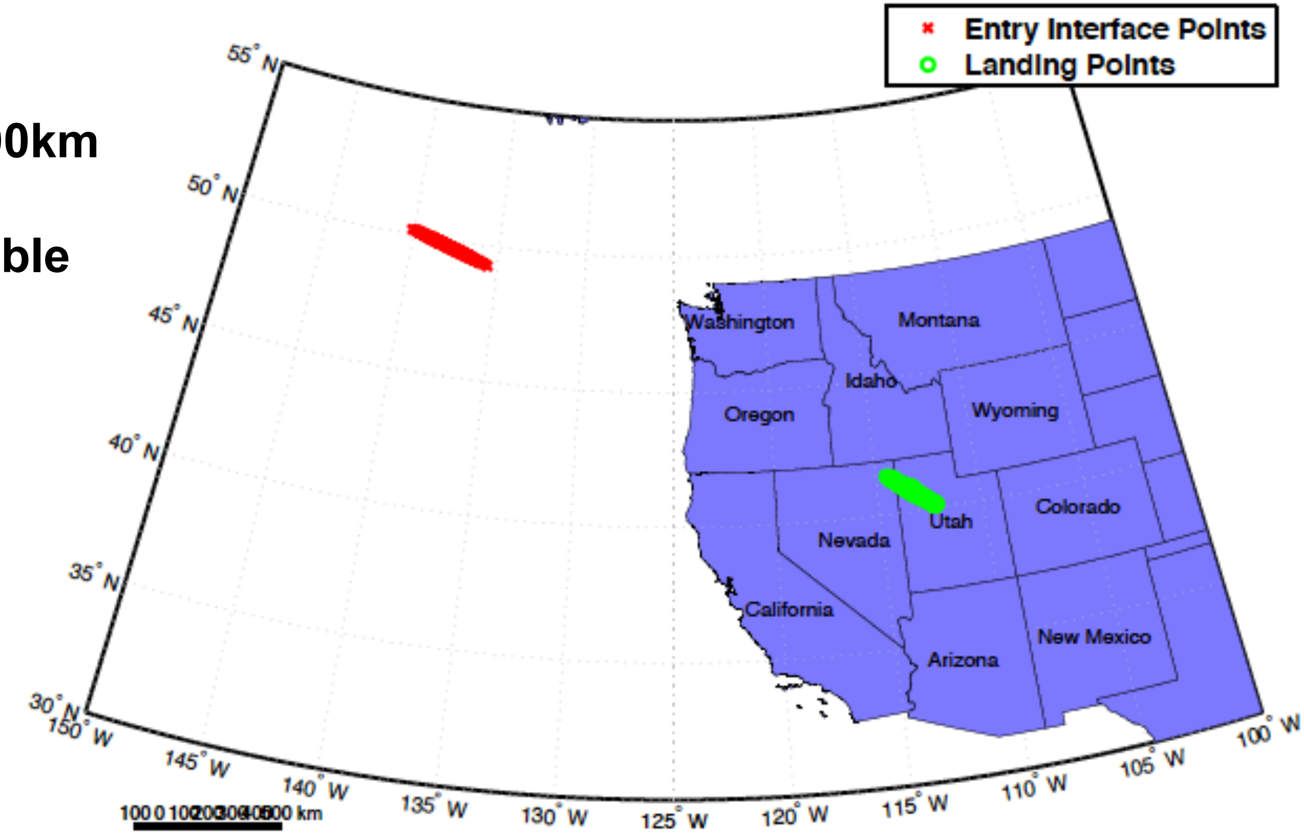
Sample Targeting Results - UTTR

Notes:
860 cases

Landing in 200km with capsule appears feasible



S. Dutta, A. Cianciolo, R. Powell , (LaRC)

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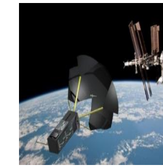
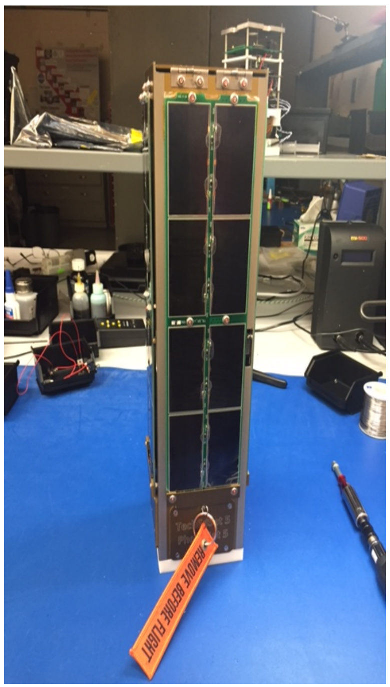
Exo-Brake Test Flight #3 (TES-5; Modulated)



Finished - Ready for OA-5 Launch.



TES-5

After TES-5:

TES-6 (Summer 2016)

- Improved 2^{nd} tier s/w
- Fine modulation control
- Experimental GNC
- Improved targeting/CONOPS

TES-7(Summer 2017)

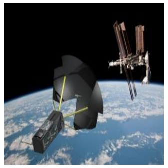
- High beta
- More control authority
- GNC
- Improved structure/TPS

SOAREX 10

- Full scale test #2

(Patent disclosures filed)

Summary



- The TES/SOAREX Team has a good deal of relevant flight experiments (7 and counting; 3 Exo-Brakes).
- Small (.25m^2) and full-scale (~5m^2) have been built/flown.
- Analysis codes and tools are in place.
  - Aero-data base is presented (DSMC results)
  - Modeling of prior data showed good agreement
  - Modulations schemes are being developed
- Next flight tests have been defined and prepared for flight
- It appears feasible to target a 100km area with nominal control of the Exo-Brake modulation

We just need to ..practice!!