How CubeSats are Helping Address the Space Debris Problem: Results from the Polar Orbiting Passive Atmospheric Calibration Spheres

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Space Debris and Satellite Drag

Satellite drag errors degrade capability to:

- Maintain accurate catalog of all space objects including debris
- Predict and avoid space collisions
- Predict satellite reentry time & location
- Atmospheric calibration efforts were lacking atmospheric data at high latitudes

This is not a small satellite problem vs. big satellite problem, it is an issue for all space assets

At the start of 2016

<table>
<thead>
<tr>
<th>Total Number of CubeSats Launched</th>
<th>Total Number of Debris Generated by DMSP Satellites</th>
</tr>
</thead>
<tbody>
<tr>
<td>417</td>
<td>346</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Total Number of Debris Generated by Cosmos-Iridium</th>
<th>Total Number of Debris Generated by Fengyun ASAT</th>
</tr>
</thead>
<tbody>
<tr>
<td>1296</td>
<td>3428</td>
</tr>
</tbody>
</table>

from Picone et al. 2005
What is POPACS

- Polar Orbiting Passive Atmospheric Calibration Spheres
- Launch 9/29/2013 into a high inclination elliptical orbit by Falcon 9
  - ~340 km perigee altitude
  - ~1510 km apogee altitude
  - ~0.08 eccentricity
  - 81.0 deg inclination
- Investigate thermospheric density variability
- Calibrate satellite drag models to improve orbits
What is DANDE

• Drag and Atmospheric Neutral Density Explorer built by COSGC and CU, Boulder and funded by AFOSR and AFRL as part of the University Nanosat Program
• Launched into nearly identical orbit as POPACS
• Investigate thermospheric density variability
• Calibrate satellite drag models to improve orbits
• Test design of atmospheric instruments
Numerical prediction of the orbital decay of the POPACS orbits three years after launch

image credit: Wes Bradley, Willowhill Precision.
Orbit Evolution

Apogee and Perigee Altitudes

Perigee Latitude

Perigee Local-Time and Latitude Sampling Superimposed on Atmospheric Density Structure

Date: 12/20/2015
Geographic Coverage

Latitude Separation

Local Time Separation

Total Angular Separation

Maximum Angular Separation of Perigees in the Equatorial Region

Latitude Separation

Maximum Local Time Separation of Perigees in the Equatorial Region

Total Angular Separation

Maximum Angular Separation of Perigees in the Equatorial Region

Year

Latitude Separation

Local Time Separation

Total Angular Separation

Maximum Angular Separation of Perigees in the Equatorial Region

Year
# Aerodynamic Properties (ballistic coefficients)

<table>
<thead>
<tr>
<th>Satellite</th>
<th>$A$ (m$^2$) $[\text{min, median, max}]$</th>
<th>$C_D$ $[\text{min, median, max}]$</th>
<th>$M$ (kg)</th>
<th>$C_D A$ (m$^2$) $[\text{min, median, mode, max}]$</th>
</tr>
</thead>
<tbody>
<tr>
<td>DANDE-LAB</td>
<td>[0.180, 0.219, 0.243]</td>
<td>[2.205, 2.281, 2.364]</td>
<td>46.495 ± 0.115</td>
<td>[0.420, 0.496, 0.529, 0.549]</td>
</tr>
<tr>
<td>DANDE</td>
<td>[0.172, 0.175, 0.177]</td>
<td>[2.260, 2.287, 2.319]</td>
<td>37.168 ± 0.131</td>
<td>[0.394, 0.400, 0.400, 0.404]</td>
</tr>
<tr>
<td>POPACS-1</td>
<td>0.00784 ± 0.00001$^b$</td>
<td>2.287</td>
<td>0.999 ± 0.000$^+$</td>
<td>0.01794 ± 0.00003$^+$</td>
</tr>
<tr>
<td>POPACS-2</td>
<td>0.00780 ± 0.00006$^b$</td>
<td>2.287</td>
<td>1.498 ± 0.000$^b$</td>
<td>0.01784 ± 0.00014$^b$</td>
</tr>
<tr>
<td>POPACS-3</td>
<td>0.00783 ± 0.00004$^b$</td>
<td>2.287</td>
<td>2.005 ± 0.000$^b$</td>
<td>0.01790 ± 0.00008$^b$</td>
</tr>
</tbody>
</table>

$^a$Mode computed assuming the satellite is randomly tumbling

$^b$Based on preflight measurement uncertainties

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**accurate ballistic coefficients...**

[Graph showing atmospheric density measurements]

...lead to accurate atmospheric density measurements

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from Pilinski et al., JSR, 2016

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Aerodynamic Analysis, DANDE Separation

from Pilinski et al., JSR, 2016
Atmospheric Measurements

Observed Densities

F107 solar flux
Ap Geomagnetic Index

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Atmospheric Assimilation for Improved Conjunction Analysis

Resident Space Objects (LEO)
- Satellite drag and density observations
  - Orbit observations
  - GPS
  - Accelerometers
  - O/N₂
  - Mass Spectrometer

Results
- Improved satellite orbit nowcast and 72h forecast
- Improvements over HASDM and J808
- Up to three-fold improvement during storms and solar minimum
- Densities, winds, and composition outputs
- Covers altitudes from 30 km to 1500 km
- Improved performance during geomagnetic storms

Dragster Architecture
- High Latitude Forecast
- Solar Forecasting
- Super-Ensemble of Full-Physics Models
- Lower Boundary Forcing
- Nowcast and Forecast Output Processing, Validation

Dragster

Orbital Analysis

Super-Ensemble Approach

Output information feeds into existing orbit prediction and determination tools

Image credit: NASA, TerreMetrics, Google

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Dragster model (blue) assimilates data from a number of objects including POPACS.

The DANDE satellite was used as a validation object to check on the assimilation results.

Proximity of POPACS to DANDE as well as their excellent aerodynamic characterization greatly improves the results over the other models.

<table>
<thead>
<tr>
<th>Satellite</th>
<th>Perigee Altitude [km]</th>
<th>MSIS Standard Deviation</th>
<th>JB08 Standard Deviation</th>
<th>HASDM Standard Deviation (no POPACS)</th>
<th>Dragster Standard Deviation (with POPACS)</th>
</tr>
</thead>
<tbody>
<tr>
<td>DANDE (39267)</td>
<td>338</td>
<td>29.3%</td>
<td>17.3%</td>
<td>18.8%</td>
<td>10.9%</td>
</tr>
</tbody>
</table>

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Conclusions

• CubeSats can be used as atmospheric calibration objects to improve orbit determination and tracking for the whole space community.

• More POPACS-like spheres would be great but documenting the orientations, mass, and size of other CubeSats can still make them useful for atmospheric calibration.

• The initial proximity of the POPACS satellites presents opportunities for studying spatial variability of the atmosphere at various scales.
Solar Conditions

Cycle 24 Sunspot Number (V2.0) Prediction (2016/08)

Hathaway NASA/ARC

POPACS & DANDE
Initial Orbit Evolution

(a) Altitude of Perigee

(b) Latitude at Perigee

(c) Local Solar Time

(d) Drift from DANDE’s Perigee time

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Spatial Variability in the Atmosphere

Standard Deviation of [(Observed - Mean Observed)/(Mean Observed)]

(14 day window)

Min
Mean
Median
Max
Spatial Variability in the Atmosphere

Standard Deviation of \[ \frac{[(\text{Observed} - \text{Mean Observed})/(\text{Mean Observed})]} \]

(121 day window)