An Innovative Method for Measuring Drag on Small Satellites

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Background and Motivation

Precise orbit prediction depends on accurate knowledge of atmospheric density and in particular *excursions from the mean state* (up to 800%).

We are data-limited in both density and wind information.

While present models can be accurate on average to below 15%, storm time errors are still estimated to be upwards of 25%.
Satellite drag measurements suffer from errors caused by:

Unknown acceleration contribution from in-track winds

\[ \vec{a} = \frac{A_{sc} \cdot C_D \cdot \rho \cdot \left| \vec{V}_w - \vec{V}_{sc} \right|^2}{2M_{sc}} \left( -\vec{V}_T \right) \]

\[ -\vec{V}_T = (\vec{V}_w - \vec{V}_{sc}) \]

Wind magnitudes have been observed to be as high as 800-1,000 m/s

coefficient of drag accuracy

\[ C_{D,\text{sphere}} = \frac{2s^2 + 1}{\sqrt{\pi} s^3} \exp(-s^2) + \frac{4s^4 + 4s^2 - 1}{2s^4} \text{erf}(s) \]

\[ + \frac{2(1-\epsilon)\sqrt{\pi}}{3s} \sqrt{T_r/T_i} \]

\[ s = \left| \vec{V}_T \right| \sqrt{m/(2k_bT)} \]
To address these challenges a method was devised for multi-instrument observations on a small satellite.

DANDE will test this method and determine atmospheric properties by measuring:

• Horizontal Winds

• Acceleration

• Composition (O,N$_2$)
Measurement Challenges

How do we improve the models and our density/wind monitoring capability?

- **density at 350 km during solar max**: $1.5 \times 10^{-11}$ kg/m$^3$
- **measure to ± 2% of this density**: $3.0 \times 10^{-13}$ kg/m$^3$
- **Mass of spacecraft**: 40 kg
- **Velocity**: 7,800 m/s
- **C_D**: 2.15
- **Spacecraft Area**: 0.20 m$^2$

<table>
<thead>
<tr>
<th>measured acceleration</th>
<th>50,000</th>
<th>ng</th>
</tr>
</thead>
<tbody>
<tr>
<td>acceptable accelerometer error</td>
<td>90</td>
<td>ng</td>
</tr>
</tbody>
</table>

There is a need for a low-cost measurement technique which:

- Can be fielded on missions of opportunity in multiple numbers
- Can measure accelerations on the order of 50 µg
- Can simultaneously measure winds
Problem Description: Satellite Drag

\[ \vec{a} = \frac{A_{sc} \cdot C_D \rho}{2 M_{sc}} \left( \vec{V}_w - \vec{V}_{sc} \right)^2 \begin{pmatrix} -\vec{V}_T \end{pmatrix} \]

\[ -\vec{V}_T = (\vec{V}_w - \vec{V}_{sc}) \]

\( \rho \) – density

\( A_{sc} \) – projected area

\( M_{sc} \) – s/c mass

\( C_D \) – drag coefficient

apriori knowledge

measured

solved
Drag Coefficient – Monte Carlo Method

Bias induced by $C_D$ uncertainty using method of [Moe and Moe, 1996] at solar max

$$(2.22 - 2.12) = 0.10 (4.7\%)$$
Unique Accelerometer Suite

\[ \omega = \frac{\pi}{3} \quad [\text{rad/sec}] \]

Analog Filter Output

\[ F_D \]
Wind and Temperature Spectrometer Schematic
Wind and Temperature Spectrometer Operation

1. Collimator
2. Ion Source
3. Small Deflection Energy Analyzer
4. Micro-Channel Plate
5. Detection Anodes and Electronics (12 detector channels)
Wind and Temperature Spectrometer Simulation

- Wind angle
- O temp.
- O wind mag.
- Energy [eV]

Channel (Anode)
DANDE encapsulates the dual instrument method and maintains a drag coefficient which is constant with orientation.
Measurement Simulation: Accelerometers Only
Conclusions

• $C_D$ of DANDE was predicted with an accuracy of 4.7%. The numerical technique allows for evaluating changes in CD over time and integrating this with the data analysis.

• Horizontal winds can be a significant source (~10-14%) of error at high latitudes and impact precision of the wind measurements – can be successfully mitigated by including measured wind information.

• Modeling demonstrates that this approach of drag measurement is feasible and will improve location specific density measurements by up to 10-14%.

• The DANDE spacecraft will implement this technique in the 2011 timeframe.
Questions

Many Thanks to

• Dr. Scott Palo – academic advisor
• Dr. Brian Argrow – academic co-advisor
• Chris Koehler – DANDE Investigator
• Dr. Kent Miller – AFOSR Program Manager
• Dr. Jeff Forbes – DANDE Co-Investigator
• Dr. Fred Herrero – wind and temperature spectrometer mentor
• Drs. Kenneth and Mildred Moe – drag coefficient mentors
• Bruce Bowman – DANDE Collaborator
• The entire DANDE student team!
Backup Slides

- Science Requirements
- End-to-End Model Description
- Model Inputs
- Model Results
- Accelerometer Detail
- WTS Testing Results
- Drag Coefficient Detail
- Starshine Satellites
- ANDE
- Measurement History
- Effects on Antennas
## Science Requirements

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Precision (1-σ)</th>
<th>Accuracy</th>
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<tbody>
<tr>
<td>Density</td>
<td>$2E - 13kg/m^3$</td>
<td>$1E - 12kg/m^3$</td>
</tr>
<tr>
<td>Wind*</td>
<td>100 m/s</td>
<td>100 m/s</td>
</tr>
<tr>
<td>Drag Coeff.</td>
<td>0.1</td>
<td>0.2</td>
</tr>
<tr>
<td>Composition</td>
<td>Composition measurements with resolution of $0.30 \Delta m/m$</td>
<td></td>
</tr>
<tr>
<td>Cadence</td>
<td>Horizontal resolution of 500 km or approx 64 seconds flight time in 350 km circular orbit</td>
<td></td>
</tr>
</tbody>
</table>

*Wind refers to both the along-orbit and cross-orbit components*
End-to-End Model

- **WIND (HWM 93)**
- **DENSITY (NRLMSISE-00)**
- **USER INPUTS**

**SPACECRAFT MODEL**
- **Velocity**
  - \( C_v \)
  - \( A_{ref} \)
- **Acceleration**
- **Wind**
- **Density**

**ACCELEROMETER**
- Analog Filtering
  - Scale Factor
  - Bias
- **ACCELERATION MEASUREMENT**

**ON-BOARD COMPUTER**
- **CLOCK**
- **TEMP SENSOR**

**GROUND PROCESSING**
- Orbit Propagation based on state estimate
- **Acceleration Measurement**

- **WIND SENSOR**
  - 30 m/s 1-\( \sigma \) error

**USER INPUTS**

- **Density**
- **Temperature**
- **Orientation**
- **CLOCK**
- **TEMP SENSOR**

The model integrates various inputs and data sources to provide a comprehensive understanding of spacecraft dynamics and environmental factors.
Accelerometer Simulation

USER INPUTS

- Accelerometer Position Vectors
- Analog to Digital Converter Properties
- Accelerometer Scale Factor and Bias Properties (apriori measurements)

Accelerometer System Simulator

- Mass Spectrometer Geometry and Error Properties
- time-averaged accelerometer data value

Mass Spectrometer System Simulator

- Wind and Composition Minute Data Products (MDPs)

Attitude Dynamics

- NRLMSISE-00
- HWM-90
- Cₜ and Aₜₜ Solver

Spacecraft Bus Simulation

- Spacecraft Time Generator

Orbital Dynamics

- Simulator Time Keeping
- Initial orbital parameters

Start Date End Date

Ground Processing Simulation

- Density, Wind, Composition Data Products

̃ρ(̃tₛ, lat, lon)

̃n_O(̃tₛ, lat, lon)

̃n_N₂(̃tₛ, lat, lon)

̃V_Wₜₜ(̃tₛ, lat, lon)

̃Tₜₜ(̃tₛ, lat, lon)
Coefficient of Drag Determination

User Inputs: Surface Geometry, Altitude, Bulk Velocity, Number of Impacts (N)

- Accommodation Coefficient Polynomial Fit
- Quasi-Specular Fraction Polynomial Fit
- NRLMSISE-00 Executable

Initialize Simulator Environment

- Initiate particle velocity
- Initiate particle position
- Initiate particle mass, m

Construct projected area map for facet vertices

Is this a secondary reflection?

Is projected position within projected sphere area?

Calculate impact position and normal

Choose reflection type statistically

Calculate reflection velocity

Compute momentum difference along reference vector(s)

\[ dp = dp + dp_e \]

\[ M = M + m_e \]

\[ k = k + 1 \]

Compute Drag Coefficient

\[ C_D = f(dp, M) \]
Accelerometer Simulation

\[ a = \frac{I}{SF} - Bias \cdot 10^{-6} \]

\[ SF = C_{S1} + C_{S2}A + C_{S3}A^2 + C_{S4}A^3 + C_{S5}A^4 \]

\[ Bias = C_{B1} + C_{B2}A + C_{B3}A^2 + C_{B4}A^3 + C_{B5}A^4 \]

Scale factor and bias correlation
### End-to-End Model Inputs

<table>
<thead>
<tr>
<th>Variable Name</th>
<th>Value</th>
<th>Precision</th>
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<tbody>
<tr>
<td>S/C Mass</td>
<td>40.0 kg</td>
<td>0.00 kg</td>
</tr>
<tr>
<td>S/C Frontal Area</td>
<td>0.1963 $m^2$</td>
<td>0.0002 $m^2$</td>
</tr>
<tr>
<td>Drag Coefficient</td>
<td>2.12</td>
<td>0.00</td>
</tr>
<tr>
<td>Acceleration</td>
<td>0.60 $\mu g$</td>
<td>0.07 $\mu g$</td>
</tr>
<tr>
<td>Temperature Sensor</td>
<td>53.5 $\mu A$mps</td>
<td>0.1 $\mu A$</td>
</tr>
<tr>
<td>Velocity Magnitude</td>
<td>7800 m/s</td>
<td>0.04 m/s</td>
</tr>
<tr>
<td>Velocity Direction</td>
<td>0-180°</td>
<td>0.0003°</td>
</tr>
<tr>
<td>Spin Axis Direction</td>
<td>0-5°</td>
<td>1°</td>
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<tr>
<td>Perigee Altitude, $h_p$</td>
<td>350 km</td>
<td>0.08 km</td>
</tr>
<tr>
<td>Apogee Altitude, $h_a$</td>
<td>350 km</td>
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<tr>
<td>Inclination, $i$</td>
<td>96.9°</td>
<td>0.00°</td>
</tr>
<tr>
<td>RAAN, $\Omega$</td>
<td>99.9°</td>
<td>0.00°</td>
</tr>
</tbody>
</table>
Density Error and the Effect of Wind Information
End-to-End Model: Space Module

Latitude [deg]

acceleration [\textit{g}]

true drag acc.
measured drag

Wind [m/s]

North Component
East Component

M. Pilinski, University of Colorado, Boulder
8/12/2009
Measurement Predictions

Latitude [deg]
Unique Accelerometer Suite

- Analog Filtering
- A/D Conversion
- Least Squares

Low frequency bias
Spin rate

70 ng

PSD [g²/Hz]

Frequency [Hz]

1.6x10⁻¹⁰
1.0x10⁻¹²
4.0x10⁻¹⁵
1x10⁻⁵ 1x10⁻³ 1x10¹ 1x10²
Unique Accelerometer Suite

STAR accelerometer

Cost: ~$3,000,000
Precision: 30 ng
Bandwidth: 10 mHz – 100mHz

QA-2000 accelerometer

Cost: ~$3,000
Precision: ng*
Bandwidth: 6 μHz – 10 KHz**

**must be able to reject the larger noise outside of 6 μHz - 1 Hz to achieve 79 ng

Method to reduce this drift

- Flip one accelerometer in positive and negative directions and remove bias
- Modulate measurement to 6 μHz - 1 Hz range
- 6 reduces the noise through averaging independent measurements by 0.41 (1/√6)
- Provides redundancy
Wind and Temperature Spectrometer Testing

\begin{figure}
\centering
\includegraphics[width=\textwidth]{spectrometer_data.png}
\end{figure}

- \( \Phi = 0.10781 \), \( \nu_{\text{max}} = 1.1453 \), \( \nu = 0.16957 \)
- \( \Phi = 0.4187 \), \( \nu_{\text{max}} = 2.3566 \), \( \nu = 0.18876 \)
- \( \Phi = 0.39138 \), \( \nu_{\text{max}} = 3.7922 \), \( \nu = 0.27567 \)
- \( \Phi = 1.2262 \), \( \nu_{\text{max}} = 5.2261 \), \( \nu = 0.39776 \)
- \( \Phi = 1.7533 \), \( \nu_{\text{max}} = 0.0241 \), \( \nu = 0.6018 \)

Legend:
- \( \text{blue} \) averaged data
- \( \text{red} \) low-pass filter
- \( \text{black} \) Gaussian fit
- \( \text{diamond} \) peak center
- \( \text{circle} \) half-peak width
Wind and Temperature Spectrometer Testing

REQUIRED RESOLUTION

Resolution, dV/Vm

Ionizer Potential, V (V)

E_x = 10.0 V
E_x = 5.0 V
E_x = 0.5 V
Technology Development: Mass Spectrometer

- Measures Wind, Composition, and Temperature
- Preliminary Testing Complete
  - Electronics tested
  - Ion Optics Tested
  - Firmware at 75%
- TRL 3 → TRL 6
- Important addition to observing the atmosphere

![Graph of SDEA Voltage (V) with data points and labels: Vmax = 3.7922, dV = 0.27567, PHI = 0.39138.]

![Image of Mass Spectrometer device.]
Neutral Mass and Wind Sensor

1. Neutral particle (blue) enters the collimator. (Ions rejected)
2. Neutral particle is ionized inside of a field free electron bombardment region
3. Neutral particle enters the energy selector and undergoes acceleration towards the exit
4. Outside the selector, the particle is accelerated abruptly by a -3kV potential towards the Micro-Channel Plate (MCP)
5. The impact on the MCP causes a cascade of electrons to travel towards one of the anodes which measures the impact. Which anode is triggered depends on the angle at which the neutral particle entered the collimator.
Coefficient of Drag Analysis

Calculate the momentum exchange between simulated particles and the spacecraft geometry

\[ dP = m \left( \vec{V}_r - \vec{V}_i \right) \cdot \frac{\vec{V}_{ref}}{\|\vec{V}_{ref}\|} \]

\[ \alpha = \frac{E_i - E_r}{E_i - E_w} \]

\[ T_r = \frac{m}{3k_b} v_i^2 (1 - \alpha) + \alpha T_w \]

\[ dp = \sum_{k=1}^{N} dp_k \]

\[ M_{\text{gas}} = \sum_{i=1}^{\infty} \sum_{k=1}^{N} m_i N_k \]

only O and N\textsubscript{2} considered in this analysis

Sum the momentum and mass over over N collisions
Gas-Surface Interactions

Diffuse Reflection

Use measured accommodation coefficients [Bowman and Moe, 2005] adjusted for solar cycle.

Reflected Velocity distribution is Maxwellian [Sentman, 1961].

Quasi-Specular Reflection

[Schamberg, 1959]

Use empirical model of accommodation coefficient.

\[ \cos \left( \theta_{qs} \right) = \cos' \left( \theta_i \right) \]

[Goodman, 1967]
Accommodation Coefficients

Estimated Energy Accommodation Coefficients

- Solar maximum \( \alpha \) fit
- Solar minimum \( \alpha \) fit
- Pardini et. al.
- Bowman and Moe
Starshine Satellites
Starshine Satellites

Starshine Geometry

The DSMC Model
Starshine Satellites
ANDE

- **Atmospheric Neutral Density Experiment (ANDE)**
  - Smooth outside surface
  - Flying three neutral mass sensors with no attitude control to measure wind and density
  - No photovoltaics – launches from shuttle (54 degrees inclination) fully charged (100 day lifetime)

- **DANDE-ANDE connection**
  - Collaboration with Andrew Nicholas at NRL
  - Design: spherical receive antennas
  - Manufacturing: Spin-cast aluminum shells

- **CU’s DANDE is a complementary and unique mission**
  - DANDE measures drag and density with accelerometers (in situ measurement)
  - DANDE measures wind and composition in different orbits - scientifically very relevant!

- **DANDE-ANI**
  - Collaboration:
  - Design:
  - Manufacturing:
  - DANDE-ANI is designed for ESPA launch with discharged batteries and still compatible with shuttle requirements
# Atmospheric Research Satellites

<table>
<thead>
<tr>
<th>mission</th>
<th>date</th>
<th>Accel./Drag</th>
<th>composition</th>
<th>pressure</th>
<th>cross-track winds</th>
<th>in-track winds</th>
<th>large structure</th>
<th>small structure</th>
<th>temp.</th>
<th>$C_D$</th>
</tr>
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</tbody>
</table>
6 inch whip antennas modeled as cylinders 0.1 inch diameter on an 18 inch sphere

$\beta$ changed from 0 to 90 degrees
Antenna Model Results: Drag Coefficient

Numerical Solutions to the Drag Coefficient

- DSMC Antenna
- DSMC Sphere
- FMF Sphere
Antenna Model Results: Ballistic Coefficient

Numerical Solutions to the Ballistic Coefficient

- DSMC Antenna
- DSMC Sphere