National Aeronautics and Space Administration

Differential Drag Demonstration: A Post-mission Experiment With The EO-1 Spacecraft

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What is Differential Drag?

- Perturbation force based on a difference in ballistic coefficient
  - Usually considered a force to be counteracted or managed
  - An asymmetric spacecraft tends to yaw
  - Typically countered with reaction wheels or other means
  - Perturbation is strongest at low LEO altitudes
    - Drag force is stronger due to higher atmospheric density
    - Effect is dramatically less above ~600 km

- Can also be exploited to influence orbital location
  - Increase or decrease the drag area of the spacecraft
  - Effectiveness depends on the altitude and the spacecraft design
  - Numerous papers on the theory and control algorithms

Exploitation of Differential Drag

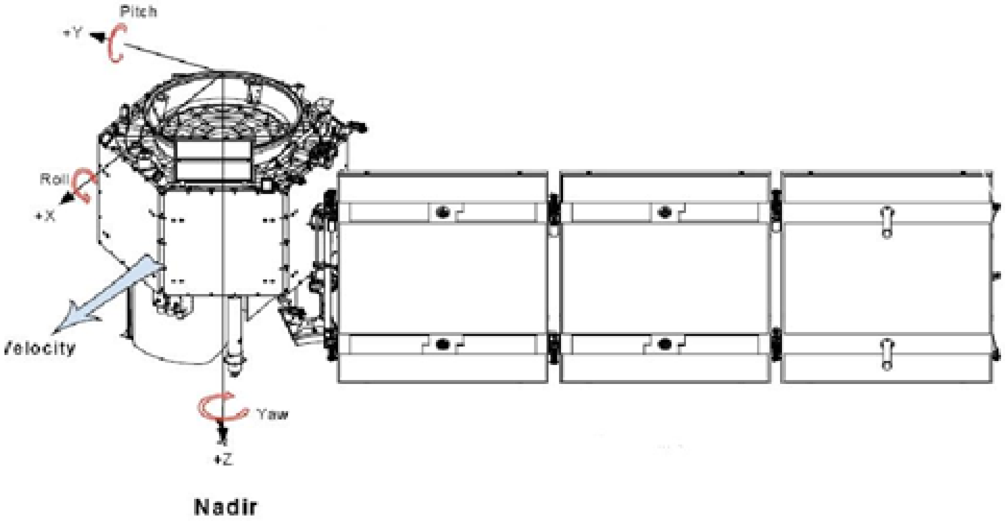
- Examples of current or planned operational use
  - Constellation formation: Planet, CYGNSS, AeroCube-4
  - Formation-keeping: Planet, CYGNSS, ORBCOMM, QB50
    - Solar array position varied during eclipse periods
    - Complex algorithms used to maintain dozens of spacecraft

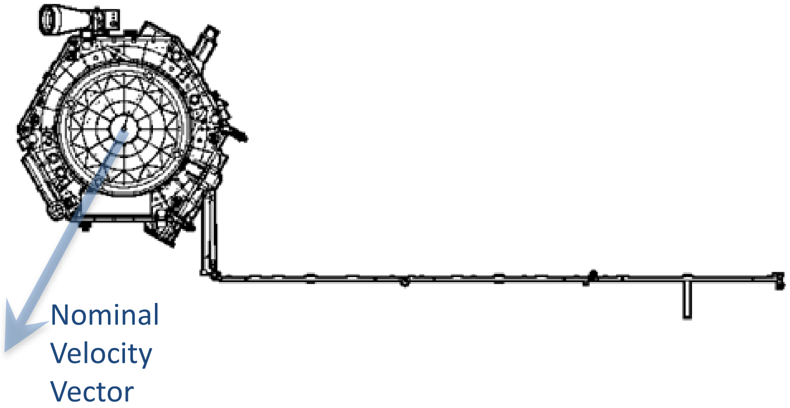
- This experiment differed from these applications
  - Opportunistic use vs. intended/designed use
  - Relatively high ~680 km altitude
    - Most ORBCOMMs are even higher
  - Single-use displacement, akin to collision avoidance
  - Single spacecraft vs. constellation

EO-1 Mission Description

- Earth Observing-1 (EO-1) was launched in November 2000
- Intended to demonstrate and validate new satellite technologies
- High degree of autonomy
- One year primary science mission in the EOS-PM constellation
- ~ 705 km, 98.2° Sun-synch nominal orbit
- Extended to more that 16 years, based on value of the science data
- Small and agile Flight Ops Team: Mission Dir., Lead Systems Engineer (since before launch), three console operators
- Orbit determined three times per week from downlink Doppler shift
- Decommissioned in March 2017
  - 3-4 weeks of shared postmission testbed studies performed

EO-1 Spacecraft Design





- Main spacecraft/instruments assembly ~2 m tall x ~ 1.5 m ‘diameter’
- Solar array is ~ 1.5 m x ~ 4.2 m, 6.1 m^2 face area
- Solar array can rotate nearly 360°
- Nadir direction is always maintained
- Fuel was essentially depleted in 2011
  - Orbit had drifted down to 673 km x 686 km x 97.9°

Differential Drag Experiment

- Three orientations attempted
  - Minimum drag with solar array forward and back
  - 'Maximum' drag with solar array 15° from velocity vector
- Nominal operations orientation before and after each maneuver
- Spacecraft defaulted to safe hold mode if faults occurred

Orientation	Description	Effective Drag Area (m^2)	Percentage of Nominal Drag Area
Nominal Ops	Nominal science operations as shown above (solar array rotated 30° from velocity vector)	5.37	100%
Minimum Drag 1	Solar array fixed, but spacecraft rotated to place array in the anti-ram direction (trailing the spacecraft)	2.86	53%
Minimum Drag 2	Solar array fixed, but spacecraft rotated to place array in the ram direction (leading the spacecraft)	2.86	53%
Maximum Drag	Solar array fixed, but spacecraft rotated to place array 15° to the velocity vector	8.04	150%
Orbit Decay	Tumbling following passivation	6.29	117%

Experiment Timeline

- Planning
  - Initially considered eight different orientations
  - Primary concern was to ensure the spacecraft was not damaged
  - No high-fidelity simulators available for EO-1
- Minimum drag
  - Array following: ~2 hours; spacecraft became power-starved
  - Array leading: ~12 hours; Star Tracker overheated
  - Spacecraft response both times: Safehold mode; drag area unknown
    - Spacecraft attitude is unconstrained, solar array on the Sun
- Maximum drag
  - 39 hours maintained successfully
  - Appeared long-term stable

Results – Orbit Change

- Minimum drag orientations both caused spacecraft to enter safe hold
  - No way to estimate the physical drag area
  - Ephemeris data equates to 13% increase in drag
  - Comparable to the 17% estimated increase during purely random orientation
- Maximum drag orientation for 39 hours (+ some time in nominal)
  - Ephemeris data equates to 37% increase in drag
  - Comparable to the 50% estimated increase for purely maximum drag
- Estimated displacement
  - Ephemeris data has loose tolerance, so calculations are not certain
  - Data showed an in-track position change of 0.154 km (relative to a simulation with no drag maneuver) during the 39-hour experiment
  - Calculations estimate an additional radial distance decrease of ~7 cm

Operations Lessons

A primary objective of the experiment was to determine the practicality, and to learn what operational factors are important for implementing differential drag maneuvering on existing assets

- Differential drag can be a practical option for propellant-less maneuvers
- Early planning is important
  - Key factor was to ensure spacecraft safety
  - Small, collaborative and flexible team was important
- Adapting an operational mission requires testing before it is needed
  - Identify stable max/min drag orientations
  - Measure the effectiveness, in order to design maneuvers
- Best to design for differential drag before launch if possible
  - Design in stable max/min drag orientations (Safe Hold perhaps)
  - Ensure sufficient attitude control and power storage
- EOM experiments are a useful tool for developing new ideas

Potential Uses for Conjunction Avoidance

- NASA has many satellites without propulsion
  - Differential drag maneuvering may offer an option for collision avoidance
- More practical below about 600 km
- Generally requires deployed solar arrays or large antennas
- Spacecraft design may not support it
  - Sufficient attitude control authority
  - Power storage capacity
  - Thermal concerns
- Simulate different orientations to increase and decrease drag
- Timely decision making is necessary for conjunction avoidance
  - Long duration maneuvers need to be started early
  - Test before it is needed

Theoretical Disposal Scenario

Because of the extended mission (depleted fuel), EO-1 violates NASA-STD 8719.14A Requirement 4.6-1: the 25-year rule

- Reentry is estimated in 38.3 years (random tumbling)

Hypothetically, could differential drag methods have achieved compliance?

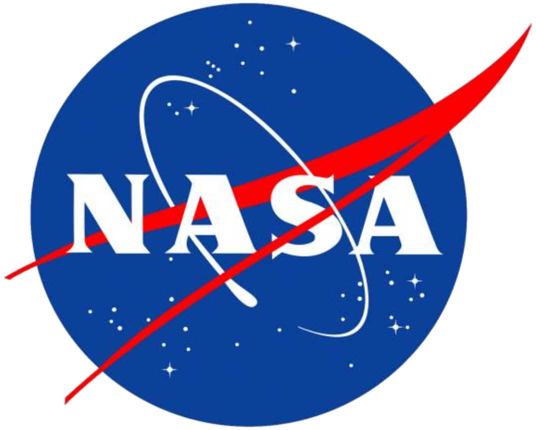
- 28% increased drag area: 8.0 m^2 (maximum) vs. 6.3 m^2 (random)
- 29.0 years postmission reentry; 9.3 years shorter, but not compliant
- Violates passivation requirement by leaving the spacecraft active (EO-1 is already non-compliant for not venting pressurant)

- Reliability risk
  - Assumes that apparent stability is consistent for a very long time
  - EO-1 is already 16 times its design life; another 29 years is unlikely
  - Fails safe, by entering safe mode; equivalent to random tumbling drag

Differential drag could have hastened reentry, but would not have achieved compliance, and **could present other unexpected risks**

Conclusions

- Differential drag has been demonstrated using an existing spacecraft that was not designed for that scenario
- In this instance the spacecraft may have been displaced sufficiently to prevent a conjunction
- Depending on spacecraft and mission design, this technique may be applicable to other existing missions
- Early planning and testing is crucial if differential drag is to be considered as a conjunction avoidance maneuver option
- A hypothetical study shows that reentry could be hastened by using differential drag, but that it may carry unexpected long-term risks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