Propellant-less Atmospheric Differential Drag LEO Spacecraft (PADDLES)

Dave Guglielmo, Rosemary Huang, Grace Tilton, Seth Robinson, Joe Spinazola, Riccardo Bevilacqua (PI)
Advanced Autonomous Multiple Spacecraft (ADAMUS) Lab
Contact: dguglielmo@ufl.edu

What is PADDLES?

- PADDLES is a 3U CubeSat that will maneuver using only atmospheric drag instead of conventional thrusters
- Developed at Rensselaer Polytechnic Institute, with parts from Pumpkin, inc.
- The differential drag is created through the use of a repeatedly deployable/retractable drag sail (see other poster)
- PADDLES uses an atmospheric density sensor to predict when to open the sail and estimate the density on future orbits

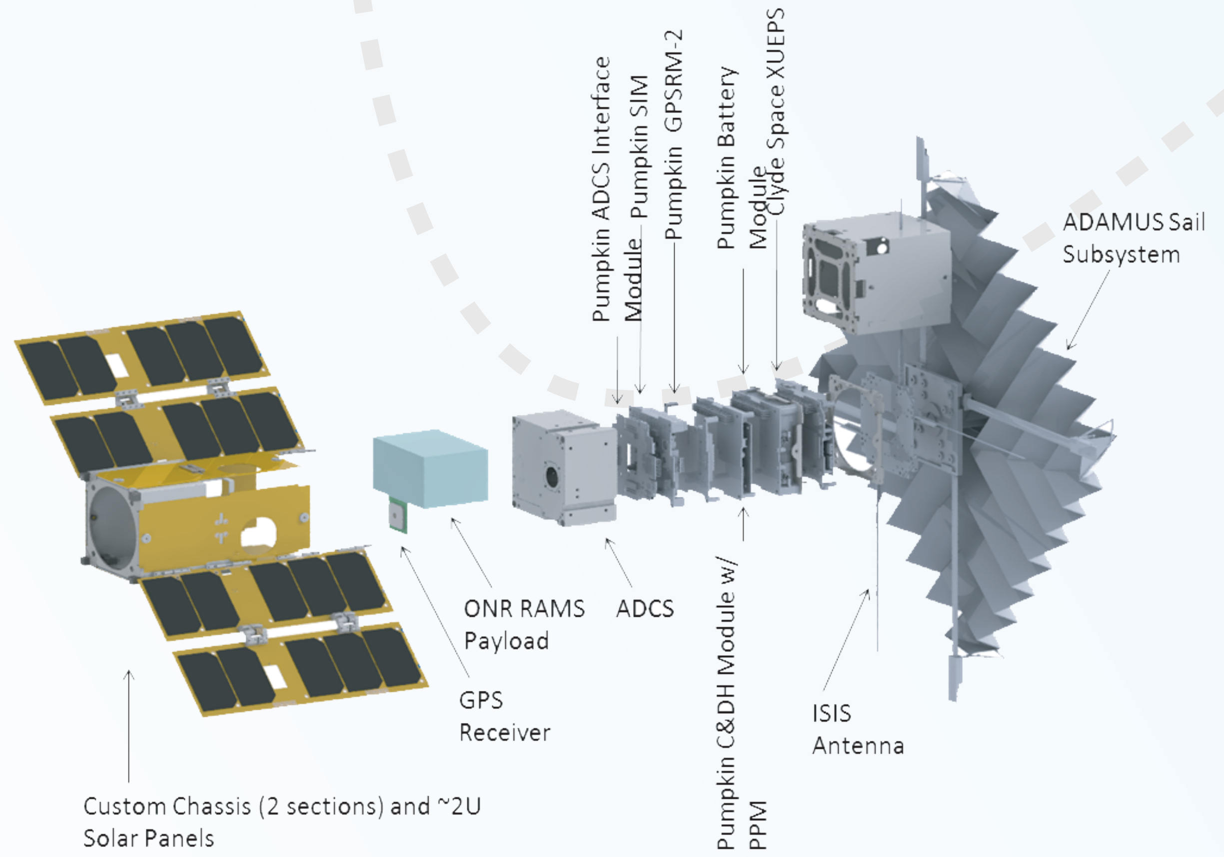
What are CubeSats?

- CubeSats are small satellites intended for research and student missions. Most are about the size of a football
- Each unit, denoted U, is 10x10x10cm, with a weight limit of 1.33 kg. CubeSats that are less than the full 3U can be stacked in the launcher to fill the 3U length
- Most CubeSats are far cheaper than full-size satellites. A CubeSat can be on the order of $100,000 vs. $1,000,000 for a full-size satellite

Mission Motivation and Goals

- Spacecraft need an alternative to thrusters to reduce fuel usage and costs
- Eliminating thrusters makes satellites much harder to track due to lack of emissions
- Measuring density during flight allows closed-loop control of maneuvering
- A successful mission will use the drag sail to produce maneuvers using drag
- Measuring the atmospheric density while in orbit is an additional success

PADDLES Exploded View



(ADAMUS Drag Sail Control Board not shown)

Key PADDLES Hardware

- **Drag sail subsystem:** The sail opens and closes to increase or decrease atmospheric drag.
- **ADCS (Attitude Determination And Control System):** Determines whether PADDLES is pointed in the correct direction and uses reaction wheels to control pointing. Different ADCS models can use either a star tracker or horizon sensors to determine the attitude while in orbit.
- **EPS:** Controls the distribution of power (collected by solar panels and stored in the barrery) to all systems and boards.
- **GPS:** Provides location data for PADDLES while it is in flight. PADDLES contains an onboard algorithm to convert this into different frames.
- **Motherboard and Processor:** The CubeSat "brain". The software necessary for operation is stored on this board.
- **Radio:** Used to relay information to the ground station on Earth, minimizing the processing power necessary in orbit.
- **RAMS (RAM Sensor):** A sensor used to measure atmospheric density. Under development by the Naval Research Lab (NRL), it will feed density information to the other systems on board PADDLES.
- **Chassis:** This is the "skeleton" of the satellite that keeps all hardware protected and in alignment.
- **Drag Sail Control Board:** Under development, will control the drag sail directly and monitor the open/close state.

Details of the Drag Sail Subsystem for PADDLES

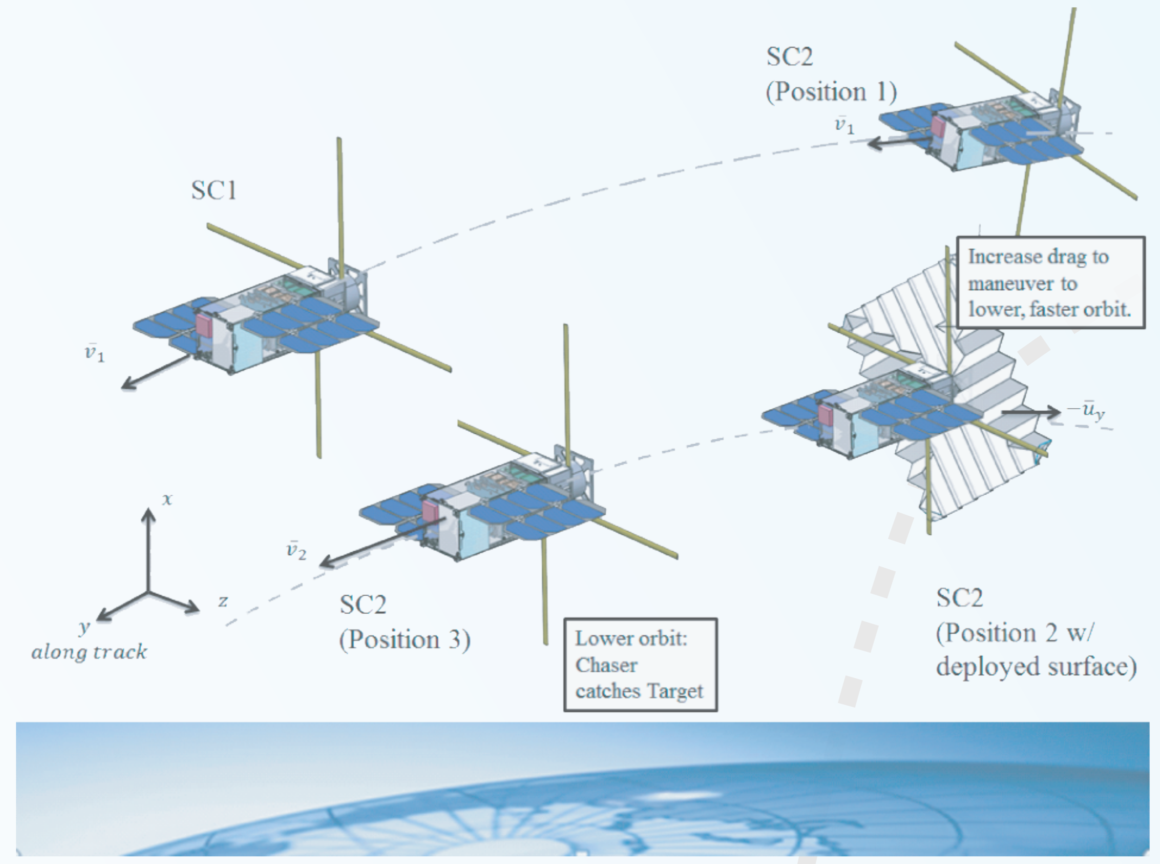
Dave Guglielmo, Rosemary Huang, Grace Tilton, Seth Robinson, Joe Spinazola, Riccardo Bevilacqua (PI)
Advanced Autonomous Multiple Spacecraft (ADAMUS) Lab
Contact: dguglielmo@ufl.edu

What is Differential Drag?

Drag maneuvering leverages variations in drag to produce variations in acceleration. Normally, thrusters are used to maneuver spacecraft into different orbits. Using a drag sail has the effect of using a low-power thruster that can only remove energy from the orbit.

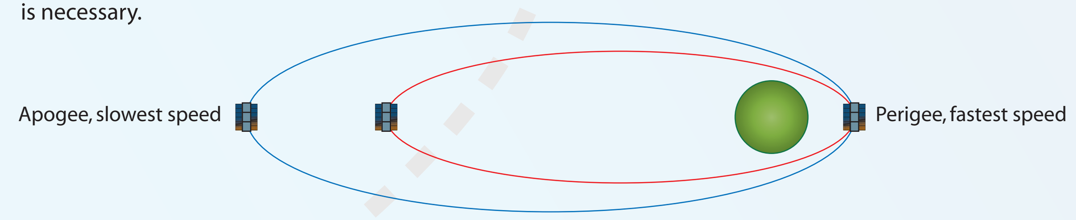
Differential drag, which leverages a difference in drag between two bodies, can be used to create relative maneuvers between two spacecraft. This is used when the absolute position of both bodies is not as important as the position of one relative to the other.

A Sample Chase Maneuver Using Differential Drag



How Does PADDLES Maneuver With Differential Drag?

Spacecraft do not maneuver directly from one orbit to another due to the high velocities involved, requiring too much fuel. Direct maneuvering is only done occasionally, and even then only when a single maneuver is necessary. Spacecraft maneuver by leveraging orbital parameters. First, some orbital mechanics background is necessary.



Only in-plane maneuvers will be discussed. Out-of-plane maneuvers are possible, but not when using drag to maneuver. The method for changing an orbit can be found using conservation of energy.

$$\frac{d}{dt}(KE + PE) = 0$$

This holds true as long as there are no orbital perturbations. As can be seen above, when the spacecraft is at the highest point (the apogee), its kinetic energy is at a minimum and its potential energy is at a maximum. More simply, it is not moving fast enough to stay in a circular orbit at that height. As it falls, potential energy is converted into kinetic energy, so as the spacecraft falls further, it moves faster and faster. At the lowest point (the perigee), its kinetic energy is at a maximum and its potential energy is at a minimum. At the perigee, the spacecraft is now moving too fast to stay in a circular orbit of that height, meaning it will then go back to the apogee. As a special case, if the energy and height are just right, a circular orbit can also result. Other orbits are possible but are not discussed here.

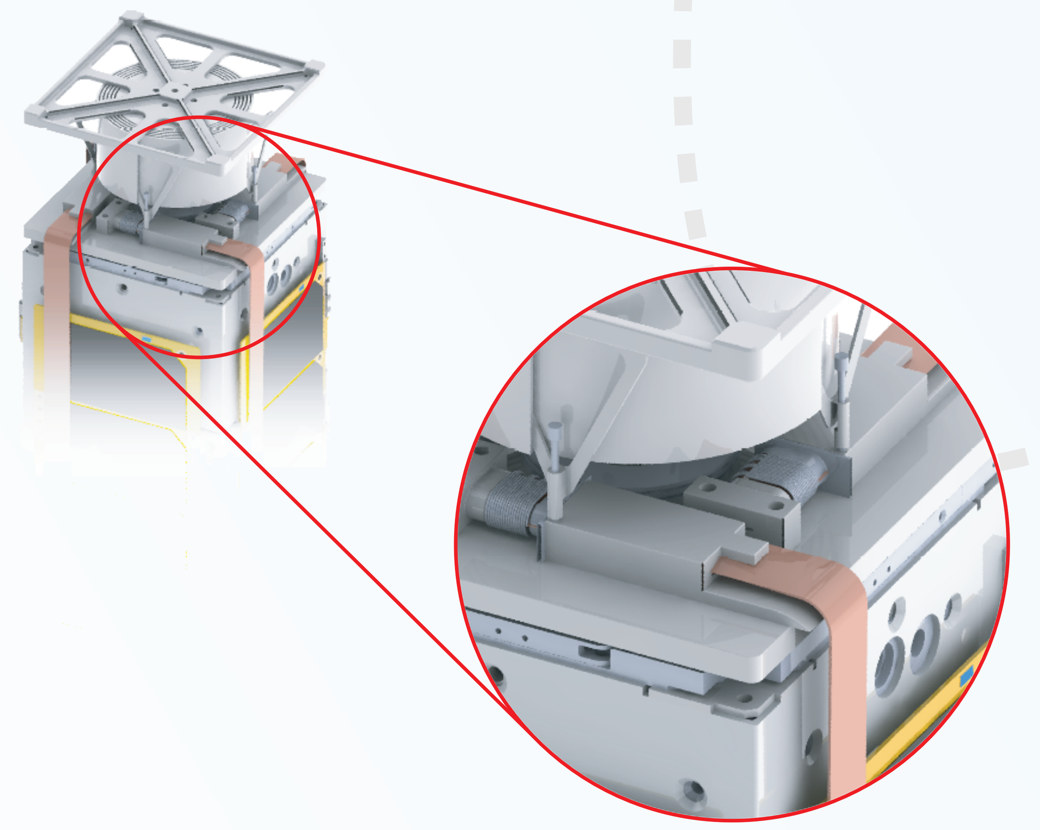
Changing the orbit requires disrupting the process of moving form apogee to perigee. Differential drag only allows for moving to lower orbits. To use it to move from the elliptical orbit (blue) to a more circular orbit (red), the drag sail needs to remove energy from the orbit. Opening the sail at the perigee slows down the spacecraft without affecting its perigee height by much, causing the apogee to decrease, making the orbit both more circular and lower.

A frequently-used effect of going to a lower orbit is that the orbital sidereal period will be shorter.

$$T = 2\pi\sqrt{\frac{a^3}{\mu}}$$

As the orbital semi-major axis decreases, so will the orbit time. This effect can be used to perform chase maneuvers. Since the lower orbit takes less time, normally a spacecraft will drop to a lower orbit, decrease its angular separation relative to the target, then use thrusters to return to the same orbit. Since drag can only maneuver to lower orbits, a different method must be used. Instead of the chaser spacecraft using thrusters to return to its original orbit, the target spacecraft will open its drag sail and drop into the same orbit as the chaser. This puts both spacecraft in a lower orbit, but in the same position relative to one another as would have been achieved using thrusters. An example of this is shown in the opposite poster.

Drag Sail Subsystem Hardware



Student-designed radial constraints for the booms (detail view shown) are used to reduce friction while allowing repeated actuation of the the sail. Custom springs and 3D-printed parts are used to achieve the complex shapes in the slider mechanisms.

Sail Actuation Algorithm

- PADDLES has an onboard atmospheric density prediction algorithm
- As PADDLES passes through LEO, it compiles a series of atmospheric data points
- The atmospheric density points are fed into a neural network, which predicts the density in future orbits
- As PADDLES flies, it continually builds up a density map
- The onboard controller uses the density prediction to estimate when to actuate maneuvers
- Density prediction is used to improve the accuracy of the maneuvers and reduce the time taken