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Measuring Spatio-Temporal Variations in Upper Atmosphere via Drag Controlled Nano Satellites and RAMS (RAM-Sensor)

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LONG-TERM GOALS

1) Create an unprecedented capability to predict atmospheric drag in low Earth orbits, by means of novel estimation techniques. These techniques need to be real-time capable, i.e., possible to run onboard an autonomous spacecraft. We have lately added the feature of spatial resolution to the forecast.
2) Design and assembly of a spacecraft hosting a dedicated sensor measuring neutral density, a dedicated maneuverable drag sail, and the algorithms created at point 1. The spacecraft name is PADDLES (Propellant-less Atmospheric Differential Drag LEO Spacecraft).
3) Demonstration of the ability to close the loop, i.e., measuring and forecasting drag and using it to steer the spacecraft without propellant.
4) Contributing with significant advances to current atmospheric models.
5) Obtaining funding for the assembly of a second identical spacecraft, and fly a 2-spacecraft mission demonstrating relative maneuvering based solely on drag forces. Such maneuvers will be base on differential drag, i.e., the ability to change the relative cross-wind surface area between two satellites, thus generating relative forces without the use of propellant (Figure 1).

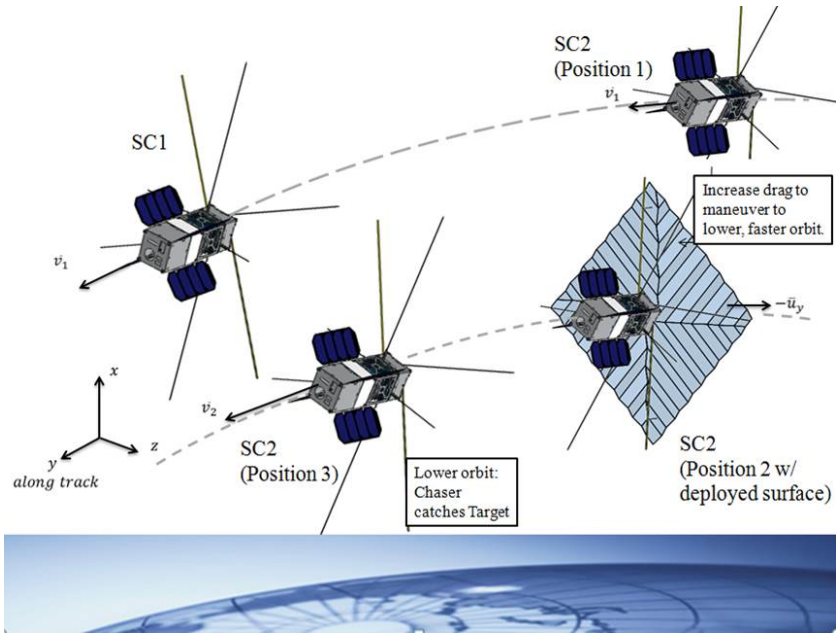


Figure 1: Explanation of atmospheric differential drag. Spacecraft 2 creates and increase in its drag with respect to spacecraft 1, opening a drag sail in the back-end. This lowers its orbit, accelerating its motion, thus driving it at a lower separation (orbital polar angle) with respect to spacecraft 1. Spacecraft 1 has the same ability; opening and closing drag devices appropriately can result in several types of relative maneuvers in the orbital plane.

OBJECTIVES

1) A forecasting technique to predict spacecraft drag along future orbits, in all solar and geomagnetic conditions;
2) a 3U CubeSat hosting a density sensor and a deployable system to control its drag force;
3) the final product (hardware & software) ready for flight by end of 2016. Planning for a two-satellite experimental flight contingent to funding for the second vehicle.

APPROACH

Time series forecasting and techniques such as Artificial Neural Networks are used for drag forecasting. CubeSat format will be used to design and build the PADDLES.

The team is part of the ADAMUS laboratory (ADvanced Autonomous MUltiple Spacecraft). It is formed by the PI, one graduate student (David Guglielmo), and a PostDoc (Dr. David Perez). Several undergraduate students have joined to complete PADDLES. The PI and the graduate student serve as system engineers for the PADDLES, while the student specifically will base his Ph.D. thesis on the drag forecasting and maneuver estimation problems. Undergraduate students will support spacecraft design, assembly and mission analysis performed in STK (Systems Tool Kit). The PostDoc helped with forecasting and Artificial Neural Networks work.

WORK COMPLETED

1) The results obtained using Artificial Neural Networks for drag/density prediction on N future orbits are published on Acta Astronautica
2) The results obtained using Artificial Neural Networks to calibrate existing atmospheric models using spacecraft data are published on Acta Astronautica
3) The results obtained adding spatial resolution to the density forecast have been presented at the AAS conference in Colorado, summer 2015
4) The PADDLES Spacecraft is completely designed and waiting for input from NRL about the RAMS sensor. The drag sail subsystem is tested, and it is under final assembly. A conference paper was presented in Japan on the sail subsystem.
5) Theoretical work on using drag to control both position and orientation of a small S/C will appear on Acta Astronautica. The PADDLES design parameters were used in this study.

RESULTS

1) Successful prediction of drag on future orbits, compared against data from CHAMP spacecraft (Figure 2).

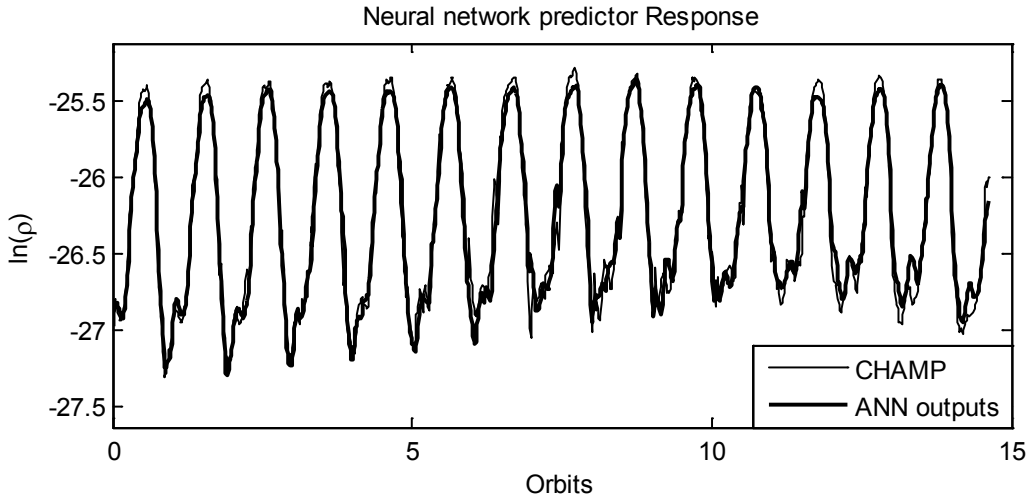


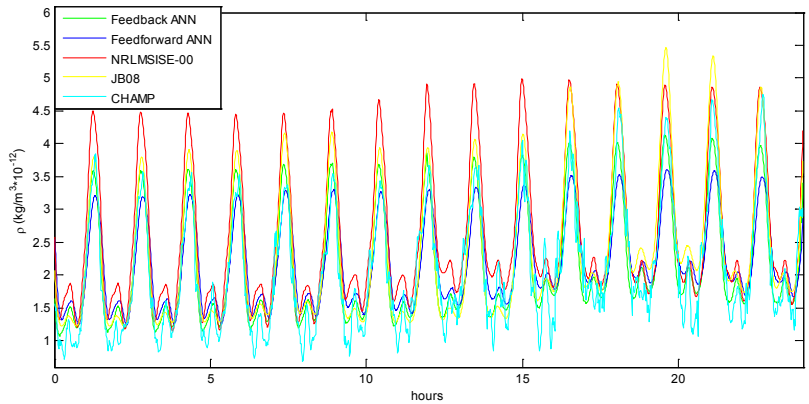
Figure 2: Neural network response for best case one orbit prediction over day 141 of 2002

In addition, the discussion below describe the work recently appeared on Acta Astronautica on a neural network-based calibrator/corrector of existing density models, which uses spacecraft data.

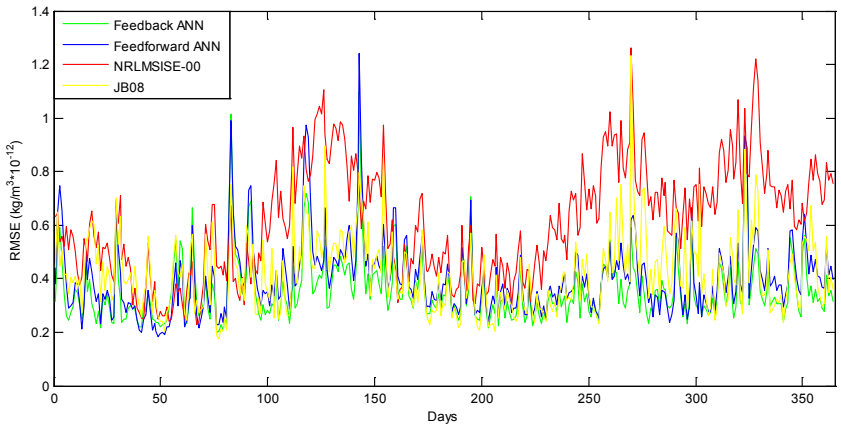
Accurate atmospheric density estimation is critical for precise orbit estimation of spacecraft at LEO. Available atmospheric model are affected by bias. As means to mitigate this bias, Artificial Neural Networks (ANN) are been developed that take as input the estimated density by atmospheric models, such as Jacchia Bowman 2008 (JB08) and NRLMSISE-00, and output a corrected value for the density. The ANN's can be trained using density estimated by missions such as CHAMP or GRACE.

As a proof of concept a feedforward and a feedback ANNs have been trained and validated using the density available from the GRACE-A satellite's orbit as targets and density estimated by JB08 and NRLMSISE-00, over that same orbit, as inputs. Both ANNs have two layers, with one nonlinear neuron at the input layer and one linear neuron at the output layer. The feedforward ANN has two delays and the input layer and the feedback ANN has five delays at the input layer and one delay in the feedback loop. A few different number of neurons and delays were tested, for the feedforward and a feedback ANN density correctors, the ones shown in this document provided the best results so far. The data used for training and validating covered the month of January of 2003, with a sampling rate of 60 secs.

The resulting ANN density correctors were tested over the orbit of the CHAMP satellite during 2007. As an illustration of the estimated densities the first figure below shows the value for the density estimated, for January the first of 2007, by JB08 and NRLMSISE-00, the feedforward and a feedback ANN density correctors; and the density estimated from CHAMP's accelerometers, which for the purpose of this work is assumed to be the true value for the density. The second figure shows the daily root mean squared error (RMSE) of the density estimated by JB08, NRLMSISE-00, and the feedforward and a feedback ANN density correctors during the whole year of 2007. The table shows the correlation coefficient (r) between the targets and the outputs, and the RMSE for JB08, NRLMSISE-00, and the feedforward and a feedback ANN density correctors for the test over the orbit of CHAMP during 2007.



Estimated densities and CHAMP density as estimated from its accelerometer for January first 2007



Daily value for the root mean squared error of the estimated density over year 2007

Performance metrics for test over CHAMP's orbit during 2007

Model	r	RMSE($kg/m^3 * 10^{-12}$)
Feedforward ANN	0.9087	0.4243
Feedback ANN	0.9122	0.3778
MSISE-00	0.8987	0.6480
JB08	0.9075	0.4419

The results of the tests show the ANN density correctors are capable of significantly improving the accuracy of the estimated density by JB08, NRLMSISE-00 over a completely different time period than the original training and validating period (trained and validated with the data of GRACE-A during January 2003 and tested with the data of CHAMP during 2007).

2) We have added spatial resolution to the density forecast, by forecasting several (up to 3 for the time being) trajectories in the future at various decay rates. This enables interpolation among them when designing a guidance, and this guidance will be more realistic than when based on a single trajectory forecast. A new finding consists in the fact that high solar activity shows a higher benefit in adding spatial resolution to the forecast (see Lyapunov function below for several types of guidances, when performing a rendezvous maneuver – the image is extracted from our paper presented at the latest AAS conference).

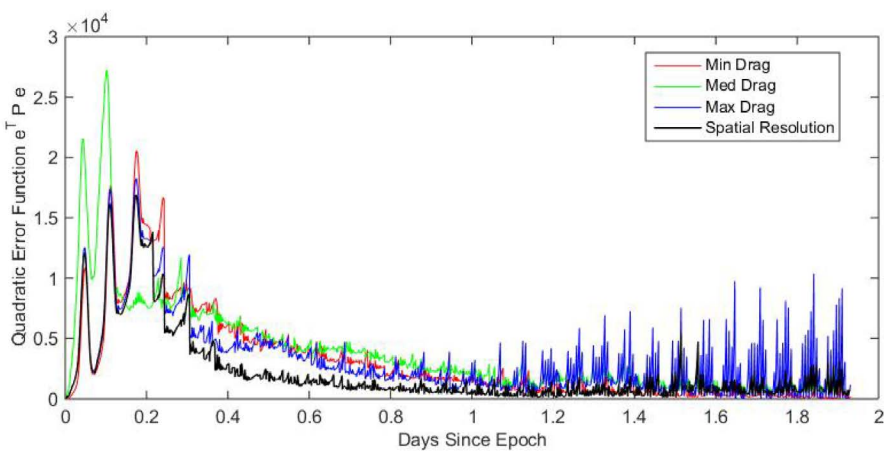
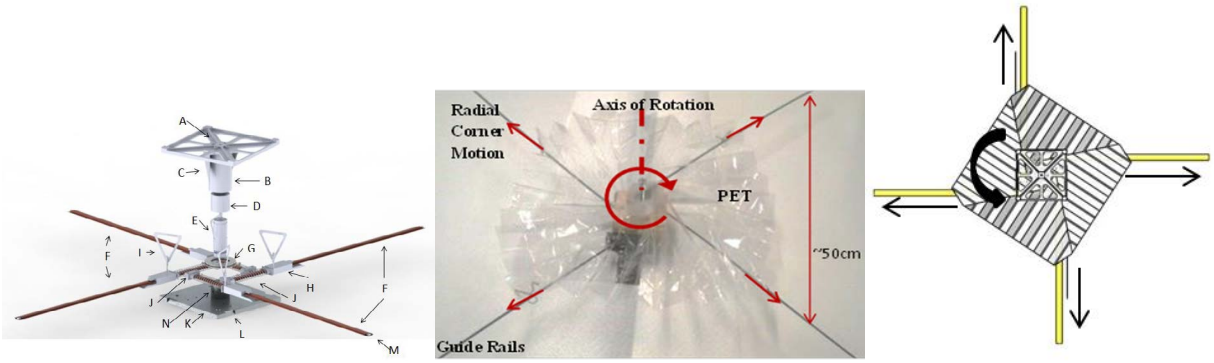


Figure 10. Quadratic Error Function $\vec{e}^T \underline{P} \vec{e}$ for All Cases, High K_p.

3) 1/2U Drag sail subsystem designed and under final assembly (Figure 3).



A: Top Plate B: Support Column C: Sail Attachment D: Sleeve Bearing E: Motor
F: Guide Rails G: Thrust Bearing H: Guide Rail Slides I: Sail Attachment Rings
J: Guide Rail Mounting Blocks K: Mounting Plate L: Guide Rail Bending Guide
M: Optical Position Detector N: Motor Attachment

Figure 3

4) The PADDLES spacecrat is completely designed (Figure 4).

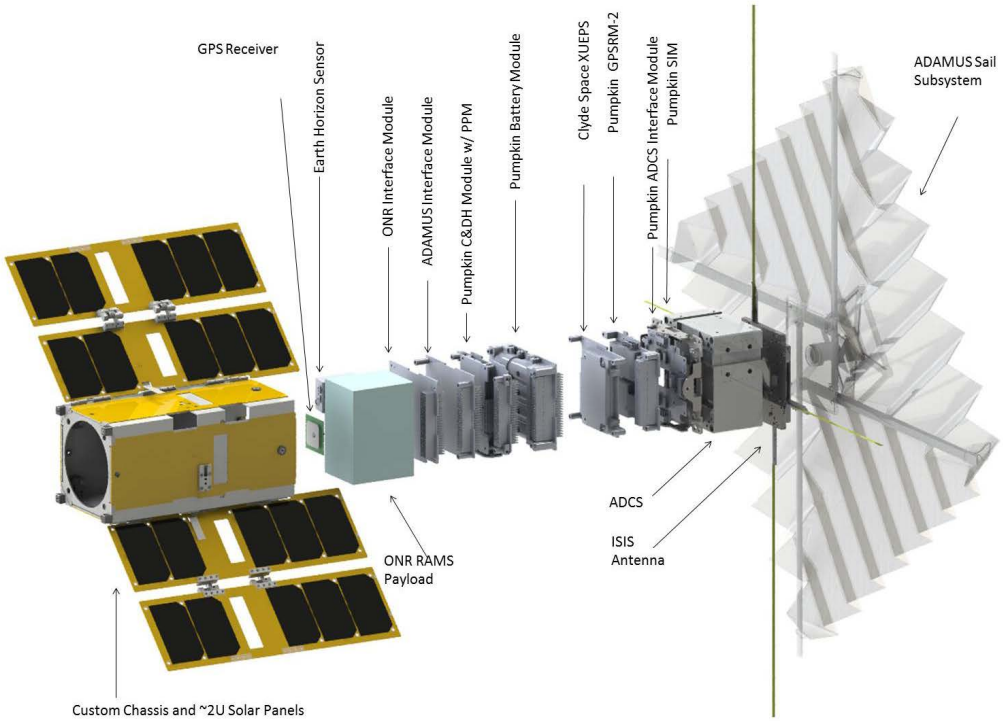


Figure 4: PADDLES exploded view.

IMPACT/APPLICATIONS

1) New generation of spacecraft able to maneuver without propellant in LEO
2) The ability at point 1 implies lighter vehicles and also less detectable vehicles
3) Ability to forecast drag autonomously onboard, thus a better planning of future manevers

4) Improving currrent atmospheric modeling, thus raising the accuracy of orbital decay prediction, as well as orbital long term propagation

5) We foresee the ability to train Neural Network-based models on old spacecraft data, able to work for potentially any future satellite. Our current work is focused on new methods to create a final capability that will potentially replace existing atmospheric models, being also real-time feasible.

TRANSITIONS

None.

RELATED PROJECTS

Air Office Office of Scientific Research, Young Investigator Program, "Propellant-free Spacecraft Relative Maneuvering via Atmospheric Differential Drag" (2012-2015). – http://afosr-yip.riccardobevilacqua.com/

COMPLETED

This project is a theoretical study on control algorithms enabling differential drag maneuvers. In particular, the research objectives more relevant to the ONR project here reported are: 1) to create a theoretical framework for understanding and designing analytical, DD-based guidance trajectories for new multi-spacecraft missions; 2) devise a feedback control strategy for accurate tracking of the guidance in a real flight environment.

The ONR and AFOSR projects complement each other, as the AFOSR work will provide the control logic actuating the drag sail, while the ONR project will provide the ability to sense and predict the environment, information of significant utility for a controller. The ONR project will close the loop on the controllers developed under AFOSR sponsorhip. Without this ability, the differential drag maneuvering may remain only a theoretical concept, while adding measurements and prediction it can be implemented on a real flight. Also, the AFOSR project does not involve equipment, while the ONR project will convert the concepts of maneuvering with drag, forecasting it, and closgin the loop into a real satellite.

PUBLICATIONS

Leonel Mazal, David Perez, Riccardo Bevilacqua, Fabio Curti, "Rendezvous via Differential Drag with Uncertainties in the Drag Model", 2015 AAS/AIAA Astrodynamics Specialist Conference, Vail, CO, August 9-13 2015

David Guglielmo, David Perez, Riccardo Bevilacqua, "DIFFERENTIAL DRAG-BASED GUIDANCE FOR SPACECRAFT RELATIVE MANEUVERING USING PREDICTED DENSITY", 2015 AAS/AIAA Astrodynamics Specialist Conference, Vail, CO, August 9-13 2015

David Perez, Riccardo Bevilacqua, "NEURAL NETWORK based calibration of atmospheric density models", Acta Astronautica 110 (2015) 58–76. doi:10.1016/j.actaastro.2014.12.018

David Pérez, Brendt Wohlberg, Thomas Lovell, Michael Shoemaker, and Riccardo Bevilacqua, "ORBIT-CENTERED ATMOSPHERIC DENSITY PREDICTION USING ARTIFICIAL

NEURAL NETWORKS", Acta Astronautica 98C (2014), pp. 9-23. Doi: 10.1016/j.actaastro.2014.01.007.

Colin Mason, Grace Tilton, Nomita Vazirani, Joseph Spinazola, David Guglielmo,Riccardo Bevilacqua, Johnson Samuel, "Origami-based Drag Sail for CubeSat Propellant-freeManeuvering", for 5th Nano-Satellite Symposium, November 2013, Tokyo, Japan.

A paper describing the PADDLES spacecraft is in preparation for the Journal of Small Spacecraft

Mirko Pastorelli, Riccardo Bevilacqua, and Stefano Pastorelli. 2015. Differential-drag-based Attitude and Position Control for Propellant-less Spacecraft Rendezvous. *Acta Astronautica.* To appear.

PATENTS

None

HONORS/AWARDS/PRIZES

David Guglielmo, graduate student on the project, won the UF REEF AFRL summer fellowship, Summer 2015.