Coupled simulations, ground-based experiments and flight experiments for astrodynamics research

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1. ABSTRACT

Near-Earth satellites undergo complex and poorly understood interactions with their environment, leading to large uncertainties in predicting orbits and an associated risk of collision with other satellites and with space debris. The nature, evolution and behaviour of the growing cloud of space debris in that environment is even less well understood. Significant effort and expenditure is currently being made by governments in Australia, UK, USA, Europe and elsewhere in space surveillance and tracking, in order to mitigate the risk. However, a major gap exists with respect to the science of in-orbit behaviour.

Research is underway in Australia to enable the prediction of the orbits of near-Earth space objects with significantly greater fidelity – for the modelling of atmospheric interactions - than currently possible. This is being achieved by coupling together the necessary parts of the puzzle - the physics of rarefied space object "aerodynamics" and the space physics and space weather that affects it - and employing our capabilities in ground-based and in-orbit experiments, ground-based observations and high performance computing to do so.

As part of the effort, UNSW Canberra is investing $10M to develop a sustainable university-led program to develop and fly affordable in-orbit missions for space research. In the coming years, we intend to fly various CubeSat missions, some in partnership with Defence Science and Technology Group, which will include flight experiments for validating Space Situational Awareness astrodynamics simulation and observation capabilities. The flights are underpinned by ground-based experimental research employing space test chambers, advanced diagnostics, and supercomputer simulations that couple DSMC and Particle-in-Cell methods for modelling space object interactions with the ionosphere.

This paper describes the research underway and planned, with particular emphasis on the coupled numerical/experimental/flight approach.

2. INTRODUCTION

Australia (to the value of at least $8B per year improved GDP alone) and the international community critically and increasingly depend upon services from space-based technologies, to maintain our way of life and to respond to current and future challenges. Earth Observation from Space (EOS) supports key activity such as emergency response, environmental monitoring, natural resources management, agriculture management, urban planning, maritime traffic monitoring, and more [1]. Position, Navigation and Timing (PNT) – employing Global Navigation Satellite Systems such as GPS – supports key sectors of the economy (agriculture, mining, transport, finance, national security) and impacts directly on our culture and way of life. Satellite communications (SATCOMM) play a central role in national security activities, as well as supporting delivery of voice, internet and television communication services. The risk of service disruption or denial, due to space weather events or in-orbit collisions, is significant.

At the same time, space technology is evolving towards the application of resilient, agile swarms of small and miniature satellites with game-changing capabilities. Space-based technologies have traditionally been extremely expensive to develop and launch. Technology has improved in a manner comparable to Moore's Law however, to the extent that the capabilities of small and miniature satellites have increased and the opportunities to deploy them to orbit are now accessible and affordable. The direction of space technology development is trending from large expensive platforms to distributed agile resilient networks/swarms of much smaller and inexpensive platforms employing distributed sensors, sophisticated communications and precision navigation and control.

Addressing these current risks and future opportunities both require advances in our ability to understand and accurately and rapidly predict the physics of the manner in which artificial space objects interact with the space environment – both operational satellites and space debris. For example, in "Continuing Kepler's Quest", US Air Force Space Command was recommended by the US National Research Council to tackle a series of current and pending problems that face the international community in relation to space debris and collision avoidance [2]. These problems include the need for high fidelity physics-based modeling of space objects / space environment interactions.

Near-Earth artificial space objects do not fly the simple orbits that two-body orbital mechanics with uniform gravitational fields would predict. Rather, they fly orbits perturbed by: non-uniform gravity; aerodynamic interaction with the rarefied but non-negligible neutral and charged atmosphere in Low Earth Orbit; forces due to radiation of various wavelengths from, for example, the sun and Earth; and forces due to interaction with the magnetosphere via charging of the space objects from interactions with the space environment. The non-conservative forces depend on altitude, attitude, the physics of gas-surface interactions on the space object, surface charge, time of day, state of the solar cycle, and space weather. Satellite shape, size and attitude with respect to the flight path play a crucial role in determining the atmospheric drag force experienced by a satellite. For example, the effect of aerodynamic forces at altitudes as high as several hundred km were enough to enable qualitative demonstration of formation reversal for a formation of three cubesats, and for the in-track discrepancy between onboard GPS and standard orbit propagation algorithms to grow for that mission by 10-20 km per day, and spanwise discrepancy by 1-3 km per day [3].

Thus the forces generated by the interaction of space objects and the rarefied atmosphere in which they fly are non-negligible, integrate to produce significant orbital perturbations, and are not fully understood or modeled. Typically, orbit predictions assume cannon-ball representations of space objects, a drag coefficient Cd = 2.2, and ignore spanwise forces. As demonstrated numerically [4] and examined with Direct Simulation Monte Carlo (DSMC) simulations in the Los Alamos National Laboratory IMPACT project [5], the drag coefficient can in fact vary by up to 40% for a given shape over altitude ranges typical of LEO; vary by similar levels depending on the shape or aspect ratio of the object; and depend significantly on factors such as solar maximum/minimum. Consideration of the effect of charged particle interactions in the ionosphere (interactions which are more frequent than neutral particles at high LEO altitudes) and spanwise effects are less well understood. Improvement of the state-of-the-art of accurately simulating the interactions between space objects (satellites and debris) and the near-Earth environment is urgently needed to improve orbit predictions and reduce the likelihood of collisions [2].

Following world best practice for aerospace research, UNSW Canberra Space Research is developing an astrodynamics research program that closely couples physics-based supercomputer simulations of the interaction between spacecraft/debris and the near-Earth environment, benchmark-quality ground-based experiments (by means of employing high energy / low density particle sources to create a rarefied gas satellite "wind tunnel"), and orbital flight experiments to validate the ground-based science.

The simulations will guide the development of the ground-based and orbital experiments, and will reconstruct those experiments to develop full insight; the ground-based experiments and associated diagnostics will enable real data on the details of the physics to be obtained, providing partial validation of the simulations; the full performance of the simulations in being able to predict space object motion will be validated by the flight experiments. In turn, the simulations are intended to eventually contribute to the development of advanced orbit propagation and collision-avoidance algorithms for Australian input to space traffic and debris management.

3. NUMERICAL SIMULATION DEVELOPMENTS

The perturbations in artificial space object motion due to interaction with neutral and charged particles in the upper atmosphere and ionosphere arise due to particles exchanging momentum with the surface of the objects. To simulate this numerically for the case of neutral particles, Direct Simulation Monte Carlo (DSMC) approaches are often used. In the work at UNSW Canberra, a DSMC code has been extended by coupling it with a Particle-in-Cell (PIC) method to include the effects of charged particles. The intention is to use this and other codes to study the flow physics and resultant forces and moments on various fundamental building-block geometries of space objects and for the ranges of environmental conditions encountered in those domains – including the significant increases in particle flux during space weather events.

The ability to accurately model the forces and moments imparted on a space object due to Earth's atmosphere at any given point in its orbit first requires an accurate model for the atmosphere itself. UNSW Canberra is leveraging an atmospheric database that spans approximately 2 years, created at Los Alamos National Laboratories (LANL), to provide a high fidelity set of boundary conditions to study the forces exerted on space objects by neutral and charged particles. The dataset was generated as part of the wider IMPACT (Integrated Modeling of Perturbations in Atmospheres for Conjunction Tracking) project [5] and utilised the Global Ionosphere Thermosphere Model (GITM) [6] to perform 3D coupled ionosphere/thermosphere simulations. The dataset will form a basis for a rapid surrogate assisted method to approximate Ionosphere /Thermosphere conditions and will be used in conjunction with the orbital propagator developed in IMPACT to study the orbital perturbations generated by charged and neutral particle interaction with space objects.

UNSW Canberra uses two DSMC codes to study the effect of the neutral atmosphere on space objects. SPARTA (Stochastic PArallel Rarefied-gas Time-accurate Analyzer) [7], an open source DSMC code from Sandia National Laboratories, and dsmcFoamStrath [8], which is a modified version of the dsmc implementation within OpenFOAM by the University of Strathclyde. The codes share similar functionality and can scale efficiently to a large number of processors for large-scale computations. For example, Figure 1 shows the European ATV5 transfer vehicle at a Mach 22, 107km altitude (neutral atmosphere) condition, simulated at UNSW Canberra with SPARTA.

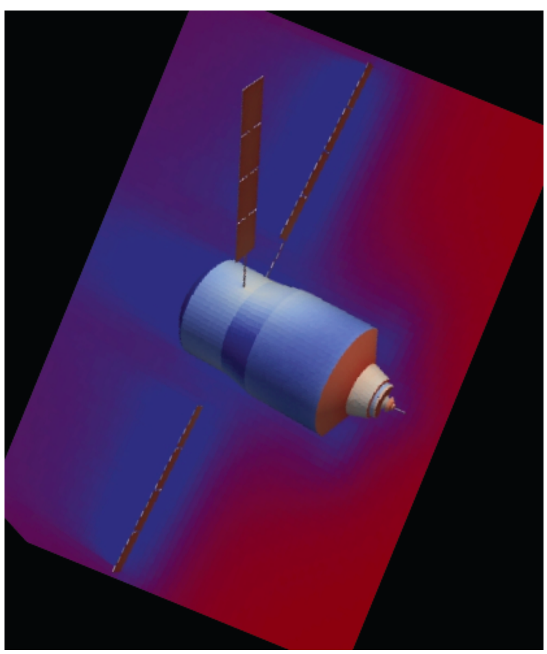
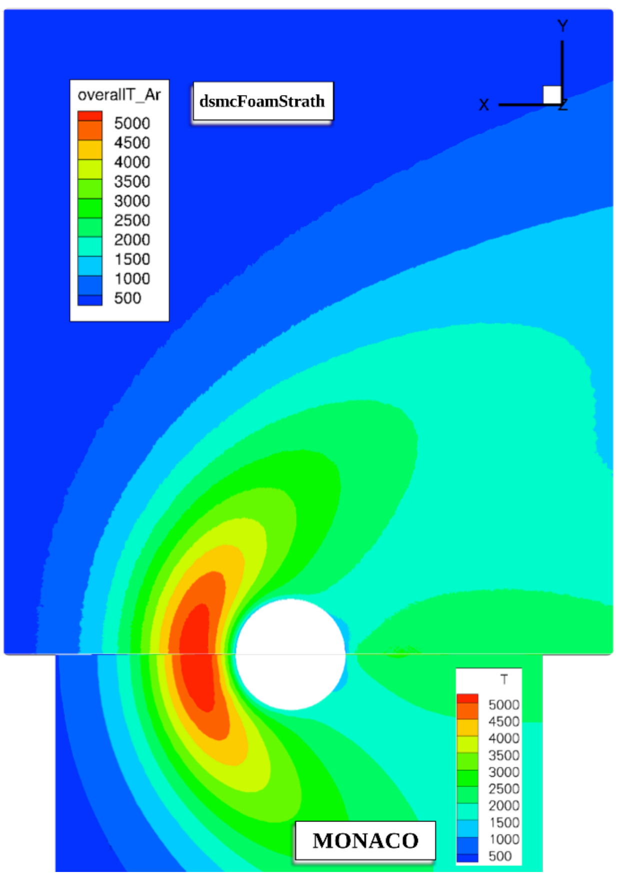


Fig. 1. DSMC simulation using SPARTA, of the flowfield around a re-entering spacecraft (Mach 22 altitude 107km)

The interaction between a near-Earth object and the ionosphere, Earth's local plasma environment, is complex, non-linear and rich in fundamental physics that are difficult to investigate in a laboratory. Development of appropriate simulation techniques to further our understanding of these phenomena is essential. While the Direct Simulation Monte Carlo (DSMC) method has shown to be effective at investigating the contribution of neutral gas-surface interactions to near-Earth object aerodynamics, the DSMC method is unable to capture the coupled nature inherent to plasmas resulting from collective field interactions. The Particle-in-Cell (PIC) technique [9], the plasma physics analogue to the DSMC method, is ideal for exploring the contribution of ionospheric flow physics with near-Earth object aerodynamics.

Within this context, a hybrid PIC-DSMC code, pdFoam, is under development at UNSW Canberra in collaboration with the University of Strathclyde (UStrath). Built within OpenFOAM, an open-source Computational Fluid Dynamics (CFD) library, pdFoam is an extension of UStrath's DSMC code dsmcFoamStrath. pdFoam may be run as a pure DSMC or PIC simulation or a hybrid PIC-DSMC simulation. DSMC capabilities are retained from dsmcFoamStrath, while the PIC portion of the code is limited to electrostatic simulations. Particle orbits are tracked using the Leapfrog method in physical space and self-consistent fields are governed by Poisson's relation applied to Gauss's law. pdFoam accepts structured and unstructured body-fitted grids and transforms physical cells into logical space where a standard linear particle-grid interpolation/assignment procedure is applied. To reconcile the disparate scales inherent in plasma-surface interactions, PIC simulations may be either fully kinetic or apply an electron fluid approximation to significantly reduce computational requirements.

Fundamental validation cases, described below, are used to test the code's capture of the key physics, before employing it to investigate the effect of the ionosphere on satellite charged aerodynamics and its relative importance to neutral aerodynamics under different boundary conditions.



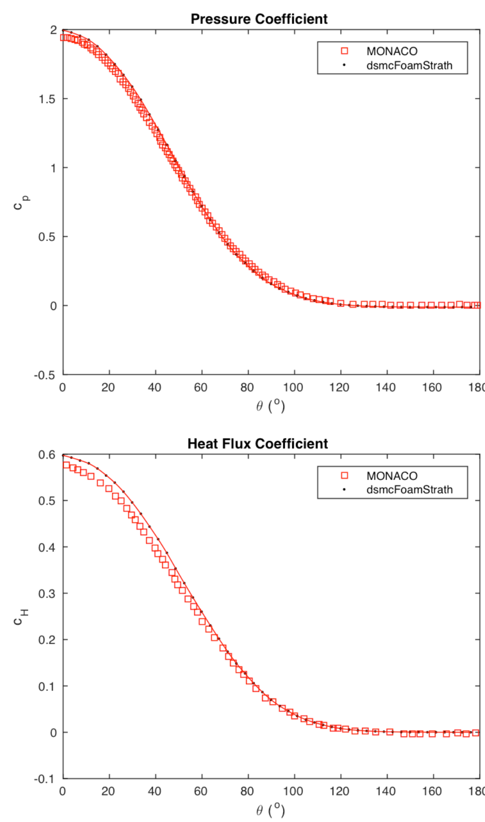


Fig. 2. Comparison between the DSMC part (dsmcFoamStrath) of pdFoam and MONACO, for a Kn=0.25 Mach 10 neutral particle test case [10].

The neutral particle test case employed here, to ensure that pdFoam retains the integrity of dsmcFoamStrath, is a Mach 10 flow of Argon (Ar) over a 12 inch (0.3048 m) diameter, infinitely long cylinder i.e. 2D flow. The cylinder wall temperature is held constant at 500 K, while the freestream velocity and number density is 2624 m/s and 1.699 x10^{19} m^{-3} respectively. The Knudsen number (Kn) based on the Hard Sphere (HS) mean free path (λ_{HS}) is 0.25 and the case is designed to replicate the DSMC benchmarking case done by Lofthouse et al using the established DSMC code MONACO [10]. The purpose of this study is to compare surface heat flux and pressure coefficients calculated made by MONACO and pdFoam. To remain consistent with Lofthouse, the Variable Hard-Sphere (VHS) collision model is used with temperature exponent Ω = 0.734, and a reference diameter of 3.595x10^{-10} at a reference temperature of 1000 K. MONACO uses a virtual sub-celling method for collision partner selection, whereas the technique applied here more closely reflects that used by Bird's DS2/3V codes [11]. A fine mesh constructs conglomerated cells such that collision cell maximum dimensions are 1/3 of the local mean free path and contain 20 particles per cell. The conglomerated collision cells then preferentially select collision partners based on the nearest populated cell, effectively minimising mean collision distance. Figure 2 shows comparisons between the two codes for this case, for the overall temperature fields and the surface pressure and heat flux. Excellent agreement between the codes is seen for the overall flow fields, except in the upstream region ahead of the cylinder where collisions first begin to accumulate. Excellent agreement is also found for the pressure coefficient, while there is a slight under-prediction of peak heat flux. The cause of the small discrepancies observed is currently under investigation, with the most likely candidate being relative mesh resolution. The mesh for the current simulation is more resolved than in the original MONACO simulation.

For the PIC part of pdFoam, and for hybrid PIC-DSMC simulations, initial validation work is currently in progress. A preliminary example of the former is presented in Figure 3, which compares a pdFoam PIC simulation of the classic two stream instability problem investigated in detail by Birdsall [12]. Here, two counter streaming 1D electron beams in the presence of a stationary background ion field, develop unstable, non-linear behaviour in position-velocity phase space in response to a small disturbance. The qualitative performance of pdFoam's PIC algorithm is very good. Further validation work has been conducted by simulating the development of a plasma sheath about a Faraday probe at -5V relative to freestream conditions in the wake of a Hall effect thruster [13]. A hybrid PIC-electron fluid simulation, where the electron fluid is described according to the non-linear Boltzmann relation, has been compared against the Bohm Sheath model and experimental current collection. Very good agreement is observed between pdFoam and the Bohm Sheath model for potential, electron and ion number densities (electron and ion densities presented in Figure 4) in the sheath regions, while variations in the freestream are a result of the development of a pre-sheath region not modelled in the Bohm Sheath approximation. Very good agreement is also found with the experimental measurement of ion current.

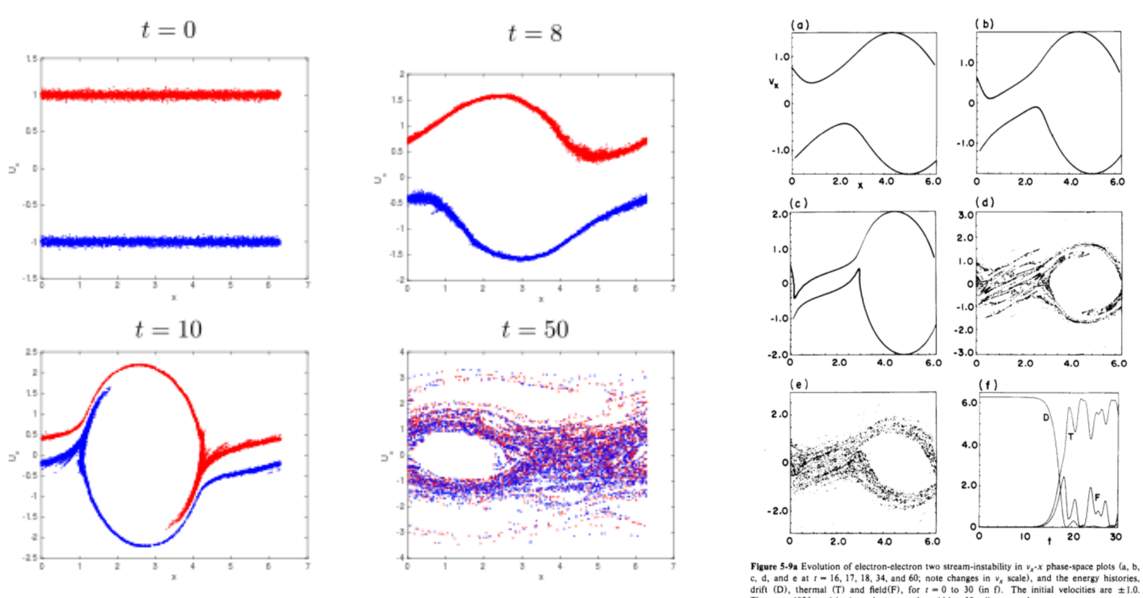


Fig. 3. PIC capability. Left : pdFoam PIC simulation of two stream instability problem. Right : results for the same problem from Birdsall [12]

The simulations will over time build a significant database of space object/environment interactions for a variety of fundamental geometries, attitudes and environmental conditions. To perform such simulations for each point along space object orbits in order to provide high fidelity propagation through predicted and/or observed non-uniform space environment distributions is not a tractable task however. On the other hand, by applying neural-network-trained surrogate modelling [14] to both the atmospheric model database and astrodynamic database, the possibility for rapid yet physics-based orbit predictions of higher fidelity than currently available, is opened up. To that end, an effort to develop such surrogate models, for the IMPACT space environment database and for astrodynamics databases, is being developed. The ultimate aim is to couple high fidelity gravity / atmosphere / space weather / rarefied gas-dynamic and solar radiation modelling tools within a surrogate-assisted framework for the rapid high accuracy propagation of space objects under the action of non-conservative forces and torques.

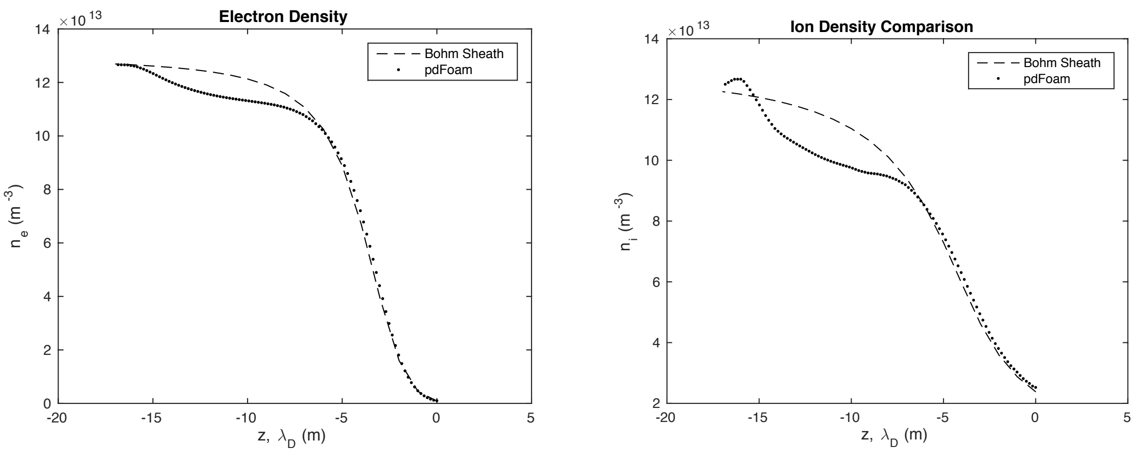


Fig. 4. pdFoam PIC simulation of electron and ion densities near a Faraday probe, compared with the Bohm Sheath model

4. GROUND-BASED EXPERIMENTS: SATELLITE WIND TUNNEL

A satellite wind tunnel is being developed to enable the study of rarefied aerodynamics of LEO spacecraft on the ground. To facilitate this research an ion source will be coupled to a vacuum chamber to simulate the high energy/low density particle environment experienced by spacecraft in LEO.

A three-dimensional section view of the vacuum chamber with the ion source installed is presented in Figure 5a. The chamber, known as SPECTRE, is actually a thermal-vacuum chamber soon to be commissioned as part of UNSW Canberra's spacecraft R&D capabilities. The stainless steel vacuum chamber has an internal length and diameter of 2.3m and 1.3m, respectively, and is equipped with multiple ports to allow for optical access and connection of data and power feed-throughs. Access to the inside of the vacuum chamber is provided via a hinged door at the front of the vacuum chamber. A combination of rotary vane and turbo-molecular pumps are used to achieve a vacuum with an ultimate pressure of less than $1x10^{-5}$ mbar prior to the operation of the ion source. A plume capture system, provided by means of a cryo-pump, will be utilised to maintain a background vacuum as the plasma, generated by the ion source, expands into the vacuum chamber.

The initial design for the ion source is that of an inductively coupled plasma discharge, which will be positioned in the satellite wind tunnel using an aluminium support stand. The inductively coupled source uses an inductive circuit element wrapped around a borosilicate tube (60 mm diameter and 300 mm long). This design allows for the radio frequency (RF) power to be coupled to the plasma across a dielectric window, rather than direct connection to an electrode in the plasma, which could introduce extraneous metal impurities.

An inductively coupled plasma discharge works like a transformer whereby the RF coil acts as the primary winding and the plasma acts effectively as the secondary winding. The RF coil will be driven at a frequency of 13.56 MHz or below, using a 50 Ω RF power supply through a capacitive matching network. The matching network is necessary to match the amplitude and phase of the RF power supply to the plasma impedance and avoid reflection of power back into the generator. When electron heating in the plasma results primarily from the inductive fields of the coil, the discharge is then operating in the so-called H-mode since the changing magnetic field of the coil induces a current in the plasma. At low RF powers the discharge can operate in a capacitive E-mode. The prototype ion source will be driven at applied RF powers up to several kW in a pulsed mode (~10 % duty cycle) to limit excessive heating. This allows for a range of plasma densities ($n > 10^8$ cm^{-3}) to be created in the ion source for various gases and their mixtures (H_2, He, O_2). Lower plasma densities are achieved in the plume of the ion source created in the larger thermal vacuum chamber chamber.

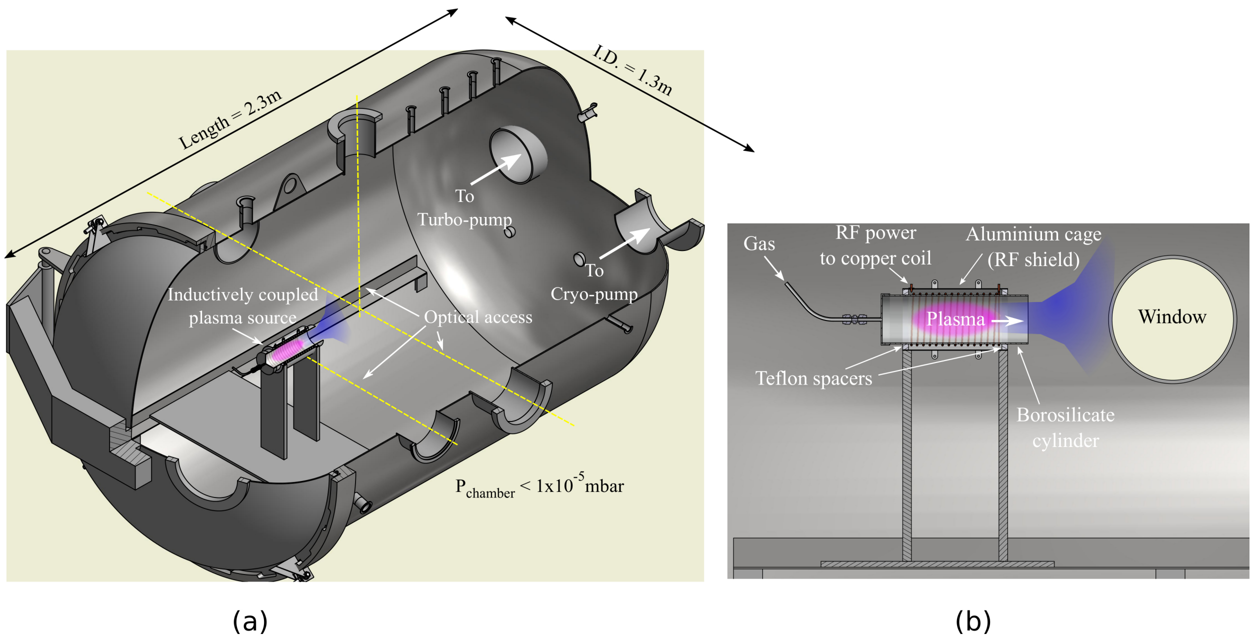


Fig. 5. Concept for a LEO satellite wind tunnel. a) ion source within UNSW Canberra's thermal vacuum chamber SPECTRE. b) Details of the ion source

The plasma production region is shielded from the surrounding vacuum environment using an aluminium cage. As shown in Figure 5b, gas is injected through one end of the source tube while the other end is open to allow plasma expansion into the large vacuum chamber. A set of solenoids will be positioned at the source exit to produce a magnetic field (up to a few hundred Gauss) to further control the plasma plume into the expansion chamber. The design can lead to supersonic plasma flow resulting from the due to the higher-pressure source plasma expansion into the lower pressure thermal vacuum chamber.

The science of the space environment interaction with materials is an extremely difficult problem as the irradiation creates a dynamic surface with an evolving interface and changing surface morphology and chemistry.
The interaction of plasma species with suitable materials for spacecraft applications will be investigated in the plume of the ion source using a range of electrical and optical diagnostics. Electrical diagnostics consist of Langmuir probes to measure plasma density and electron temperature, and retarding field energy analysers (RFEA's) will be employed to determine the ion energy. RFEA's will also be used to determine axial ion flow. Optical emission spectroscopy, fast imaging and laser diagnostics will enable spatially and temporally resolved measurements of plasma species, gas temperatures and species resulting from the interaction with the material surface. The research will provide experimental insight into changes to the materials of space objects, informing the motion simulations and improving understanding of how space objects and therefore the space population evolve.

5. FLIGHT EXPERIMENTS

Scientifically designed astrodynamics flight experiments are required and are being developed in order to provide the in-orbit validation of the ground-based astrodynamics research. These flights, and others that focus on space-based technologies, are the vehicle for the development of a sustainable university-led program to routinely conceptualise, develop and fly affordable responsible in-orbit missions to perform innovative research in space.

UNSW Canberra will develop and fly a CubeSat formation that will provide benchmark-quality validation of our simulation capability. A formation of several (ideally 3-4) fundamentally different aerodynamic shapes will be flown, deployed from miniature satellites – for example, inflation of a sphere, unfurling of a square sail. Their relative motion (translational and rotational), measured accurately by on-board differential GPS and complemented by ground-based surveillance including the Falcon Telescope Network, will be used to validate the simulation capability. Simultaneously, local space environment parameters will be measured on the spacecraft, and input obtained from ground-based space weather observations, to provide the boundary conditions for the simulations. Comparison will be made of the predicted and measured 6DOF orbits.

To enable these developments, as well as the numerical and experimental ground-based research, UNSW Canberra is investing $10M over the coming years to establish capability. These capabilities currently include

- **Flight team** – Spacecraft Project Lead / Systems Engineer; Flight Software Engineer; Spacecraft Electronics Engineer; Spacecraft Mechanical Engineer; Test & Evaluation Engineer (50%); Space-based Instrumentation Scientist; Space-based Instrumentation Electronics Engineer (50%)
- **Research team** – Computational simulations (astrodynamics, orbits) research fellow; space object / space environment interactions (experimental) research fellow (50%); space surveillance (optical, RF) research fellow; formation flying research fellow (to be appointed); currently 4 PhD students
- **Academic team** – UNSW Canberra Space lead (Chair for Space Engineering); eleven other academic staff ranging from Lecturer to Full Professor and from part-time to full-time engagement with UNSW Canberra Space
- **Space mission and experimental facilities** – Class 100 cleanroom for spacecraft assembly and integration; thermal vacuum chamber laboratory with two chambers; 6.6kN shaker table; electronics workshop; space-based instrumentation laboratory; satellite ground station (UHF/VHF/S-band); Falcon Telescope (part of the global Falcon Telescope Network); and access to and experience with the state-of-the-art spacecraft test facilities at ANU Advanced Instrumentation Technology Facility
- **Computational facilities** – 64-core workstation for small-scale simulation developments; access to 57k core NCI National Facility supercomputer for large-scale high-fidelity simulations

The combined orbital, sub-orbital and deep space mission experience amongst the team exceeds 50 years.

Figure 6 shows images of: spacecraft component testing underway using the thermal plate of a small thermal vacuum chamber in UNSW Canberra's thermal vacuum chamber laboratory (which will also house the soon-to-be-commissioned larger chamber SPECTRE); the Falcon telescope; and the satellite ground station.

The first two missions under development are those of the joint DST Group / UNSW Canberra Buccaneer missions. The Buccaneer main mission will fly a 3U CubeSat and High Frequency radio receiver and antenna, to make in-orbit calibration measurements for Australian Defence's Jindalee Over-the-horizon Radar Network (JORN) (see Figure 7). Prior to the main mission, the Buccaneer Risk Mitigation Mission (BRMM) will be flown, minus the HF receiver but employing an on-board camera, to test the deployment of the HF antenna and the in-orbit operation of various sub systems and flight and ground control software. This flight will additionally provide a platform to conduct photometric experiments with the UNSW Canberra node of the Falcon Telescope Network and provide data for the validation of astrodynamic simulations. BRMM is currently scheduled for launch in late 2016.

Other space-based technologies are under development at UNSW Canberra for flying on CubeSat (and larger) satellite missions, including technologies to enable miniature satellite formation flying. The short term goal of the latter is the astrodynamics in-orbit research described above, while the long term goal is to develop the capability for robust formations with distributed sensors across multiple platforms. With these goals in mind, formation flying research is also underway at UNSW Canberra.

Fig 6. A selection of UNSW Canberra space flight related capabilities. Top left : battery testing on the thermal plate of UNSW Canberra's small thermal vacuum chamber. Top right : the UNSW Canberra node of the global Falcon Telescope Network. Bottom : UNSW Canberra's UHF/VHF/S-band satellite ground station (support electronics housed within the adjacent rooftop hut).

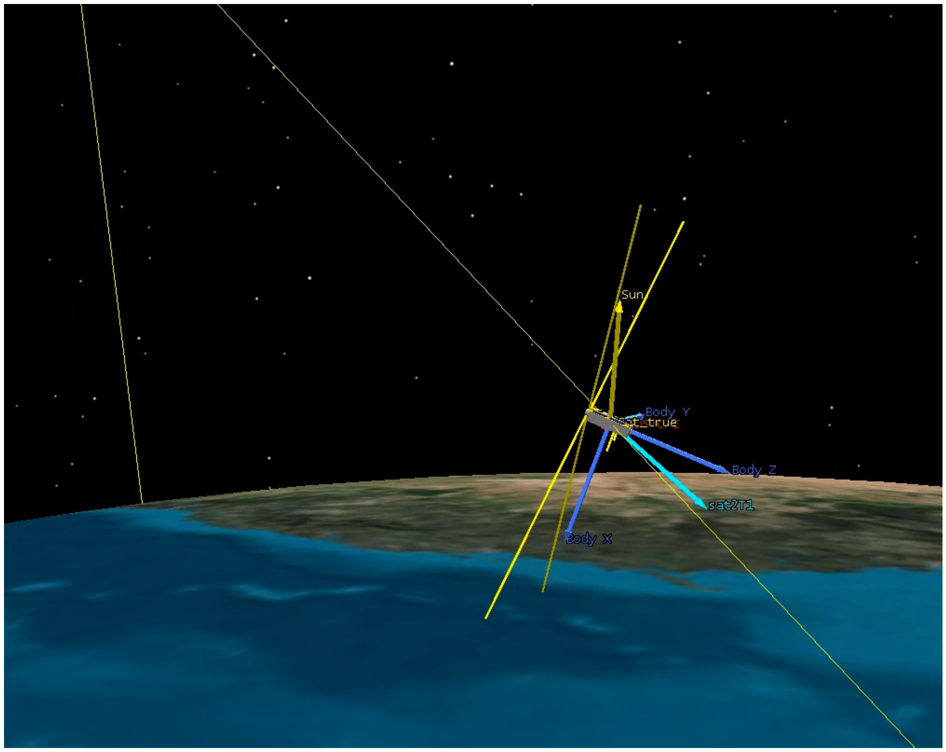
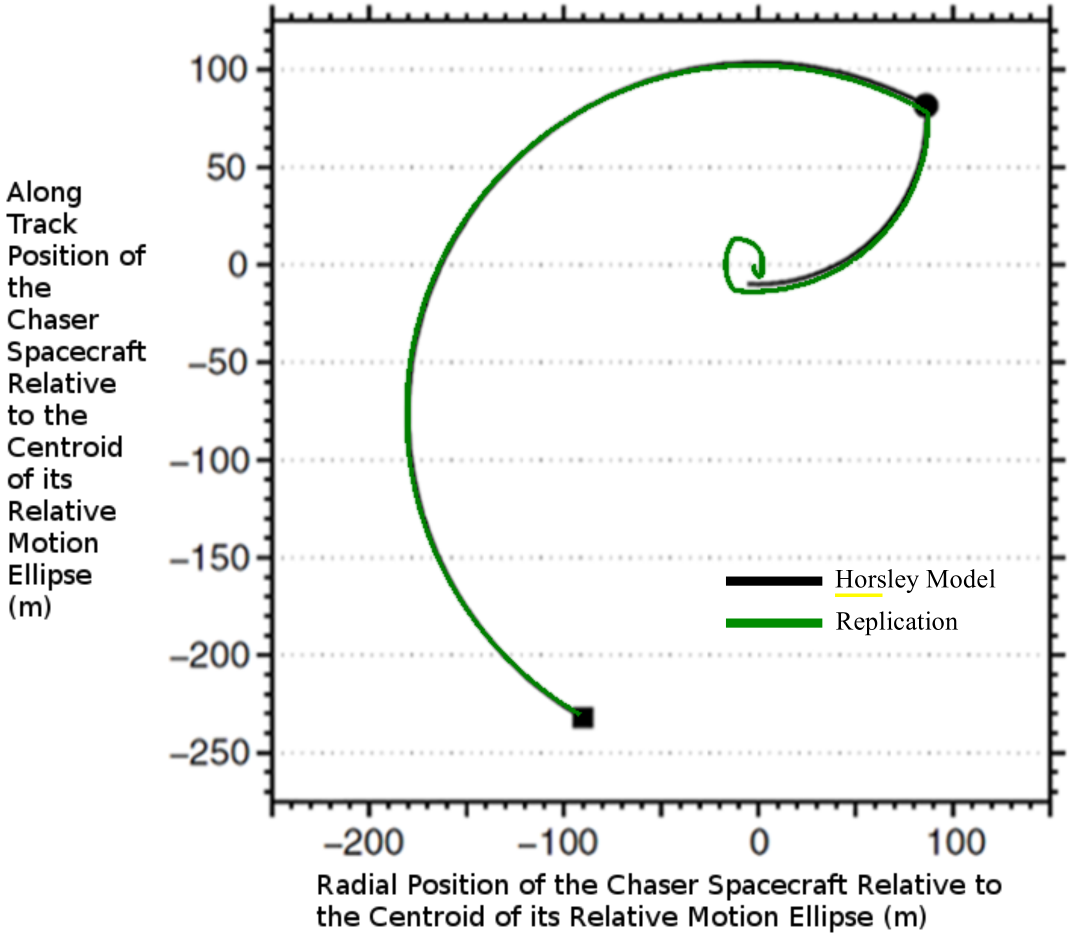


Fig. 7. The Buccaneer joint missions with DST Group – 3U cubesat with HF radio receiver and antenna

Perturbing forces in space, such as solar radiation pressure and non-spherical gravity, cause formation flying spacecraft to deviate from their desired position. Such aberrant motion has to be corrected using actuation. Power, weight and volume constraints of miniaturised satellites limit the possibility of using long duration thrusting. However, aerodynamic lift and drag forces are a propellant-free means of actuation which offers the potential to provide limitless duration actuation in the lower altitude ranges of LEO. Currently, differential drag and lift are two independent strategies for aerodynamic formation control. Differential drag forces are typically one to two orders of magnitude greater than lift and, therefore, offer greater control authority. As a result, as in-house developed simulations have shown, differential drag rendezvous at 300km altitude has a maximum range 3 times that of differential lift for a given spacecraft. A differential lift simulation is contrasted with published results [15] in Figure 8 – the comparison is excellent, and the in-house code is currently being used to explore the use of differential drag and lift in various mission scenarios. For example, despite the low control authority of lift, it may still be a more efficient means of formation maintenance compared to differential drag. The application of differential drag will deplete the orbital energy of the spacecraft at different rates, causing differential orbital energies between spacecraft. Spacecraft with different energies have different periods, causing the spacecraft to drift apart. Increased correctional fuel or drag use will decrease the mission life. On the contrary, differential lift manoeuvres, where each spacecraft produces the same lift force in opposite directions, do not cause differential energy because the drag force on each spacecraft is balanced. Such a formation control method could offer more stable and longer duration formations.

6. CONCLUSION

Research is underway in Australia to enable the prediction of the orbits of near-Earth space objects with significantly greater fidelity – for the modelling of atmospheric interactions - than currently possible. This is being achieved by coupling together the necessary parts of the puzzle - the physics of rarefied space object “aerodynamics” and the space physics and space weather that affects it - and employing our capabilities in ground-based and in-orbit experiments, ground-based observations and high performance computing to do so. As part of the effort, UNSW Canberra is investing $10M to develop a sustainable university-led program to develop and fly affordable in-orbit missions for space research. In the coming years, we intend to fly various CubeSat missions, some in partnership with Defence Science and Technology Group, which will include flight experiments for



. Fig. 8. Application of differential lift to enable a docking manouevre – in-house code compared with published results [15].

validating Space Situational Awareness astrodynamics simulation and observation capabilities. These flights are underpinned by ground-based experimental research employing space test chambers, advanced diagnostics, and supercomputer simulations that couple DSMC and Particle-in-Cell methods for modelling space object interactions with the ionosphere. The development of a coupled DSMC/PIC code pdFoam is well underway, with initial validation efforts producing very good results. Use of the code to explore ionospheric spacecraft interactions is beginning. Simultaneously a satellite wind tunnel concept has been developed in which a thermal vacuum chamber coupled with a suitable ion source will be used to subject simple shapes to high velocity rarefied streams for astrodynamics studies. Finally, the atmospheric interactions being studied numerically are being applied to the development of formation flying approaches that utilise differential drag and lift to maintain control authority.

7. ACKNOWLEDGEMENTS

The authors gratefully acknowledge the supercomputing resources provided by Australia's National Computational Infrastructure.

8. REFERENCES

1. Surrey Satellite Technology, *Applications of Earth Observation*, 2014
2. Committee for the Assessment of the US Air Forces Astrodynamic Standards, et al. *Continuing Kepler's Quest: Assessing Air Force Space Command's Astrodynamics Standards*. National Academies Press, 2012.
3. Gangestad, Joseph, Brian Hardy, and David Hinkley. "Operations, Orbit Determination, and Formation Control of the AeroCube-4 CubeSats." Proc. 27th Annual AIAA/USU Conference on Small Satellites, 2013
4. Moe, Kenneth, and Mildred M. Moe, "*Gas–surface interactions and satellite drag coefficients*." Planetary and Space Science, 53.8, pp: 793-801, 2005
5. Linares, Richard, Alexei Klimenko, Sean Brennan, Humberto C. Godinez Vazquez, David M. Higdon, Josef Koller, Earl C. Lawrence et al. *A Framework for Integrated Modeling of Perturbations in Atmospheres for Conjunction Tracking (IMPACT)*. No. LA-UR-14-23694. Los Alamos National Laboratory (LANL), 2014.
6. Ridley, A. J., Y. Deng, and G. Toth., 2006, The Global Ionosphere-Thermosphere Model (GITM). J. Atmos. Solar-Terrestr. Phys. 68, 839-864.
7. Gallis, Michael A., et al. "Direct simulation Monte Carlo: The quest for speed." *PROCEEDINGS OF THE 29TH INTERNATIONAL SYMPOSIUM ON RAREFIED GAS DYNAMICS*. Vol. 1628. AIP Publishing, 2014.
8. Scanlon T, Roohi E, White C, Darabandi M, Reese J, "An open source, parallel DSMC code for rarefied gas flows in arbitrary geometries", *Computers and Fluids*, 39(10):2078-2089, 2010
9. Birdsall CK, Langdon AB, "Plasma physics via computer simulations, volume 42" Adam Hilger Press, New York, 1991
10. Lofthouse, AJ, Scalabrin LC, Boyd ID, "Velocity Slip and Temperature Jump in Hypersonic Aerothermodynamics", AIAA 2007-208, 2007.
11. Bird GA, "Sophisticated DSMC", Proc. DSMC07, 2007
12. Birdsall CK, "Particle-in-cell charged-particle simulations, plus Monte Carlo collisions with neutral atoms", PIC-MCC, *IEEE Transactions on Plasma Science*, 19(2):65 85, 1991
13. Boerner J,Boyd I, "Numerical Simulations of Probe Measurements in a Non-equilibrium Plasma using a Detailed Model Electron Fluid", AIAA Aerospace Science Meeting and Exhibit, 2007-995(1), 2007
14. Ogawa H, Boyce RR, "Nozzle Design Optimization for Axisymmetric Scramjets by Using Surrogate-Assisted Evolutionary Algorithms", *AIAA Journal of Propulsion and Power*, Vol.28, No.6, pp. 1324-1338, 2012
15. M. Horsley, S. Nikolaev and A. Pertica, "Small Satellite Rendezvous Using Differential Lift and Drag," Journal of Guidance, Control, and Dynamics, vol. 36, no. 2, pp. 445-453, 2013