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Ironbark: Trajectory and Aerodynamic Simulator for High-Power Student Rockets

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Abstract

Accurate apogee prediction is one of the most important ways for student teams participating in rocketry competitions to maximise points. This paper presents USYD Rocketry Team's unique in-house developed trajectory and aerodynamic simulator for high-power rockets, known as Ironbark. Inviscid aerodynamic simulations are conducted in Ironbark using the higher-order panel code PANAIR and the viscous drag contribution is added using common analytical equations. A custom six-degree-of-freedom simulation is used for trajectory modelling. Ironbark is shown to reproduce aerodynamic results to available experimental data confirming its credibility. Finally, Ironbark's apogee prediction for Bluewren, the 2022 winning Spaceport America Cup rocket, is presented and discussed.

1. Introduction

High-power rocketry has become increasingly popular for educational purposes, with many students participating in rocketry competitions worldwide. These competitions provide student teams with an opportunity to design, build, and launch a rocket, requiring optimal design of aerostructures, avionics, propulsion, and recovery systems. A large portion of the competition score is based on the accuracy of the rocket's apogee compared to the target apogee. This significant weighting towards apogee accuracy emphasises the importance of rocket trajectory modelling to design and adjust the rocket to reach the target altitude as closely as possible. Trajectory simulation requires accurately modelling the rocket's aerodynamic, gravimetric, propulsion, and environmental parameters.

Student rocketry teams often use existing trajectory software for apogee predictions, such as OpenRocket[1] and RASAero.[2] However, these software packages often use empirical aerodynamic equations, which make limiting assumptions for transonic and supersonic flight. Using empirical equations also limits the possible geometries that can be modelled by the aerodynamic equations implemented in the software.[1] These assumptions, especially for rockets travelling within the transonic and supersonic flight regimes, often lead student teams seeking greater accuracy to develop their own trajectory simulation, which can use higher fidelity aerodynamic models.

Ironbark, named after the native Australian tree, is an in-house developed flight trajectory software created by USYD Rocketry Team, representing the University of Sydney. Ironbark aims to create high-fidelity flight simulations by coupling its own aerodynamic and trajectory simulation models. This enables rapid prototyping of rocket designs with accurately simulated trajectories without using computational and time-intensive processes such as computational fluid dynamic (CFD) solvers whilst being more accurate than existing trajectory software. The software is developed in Python 3 using a flexible object-oriented programming approach and interfaces with third-party programs. Ironbark was built for, validated, and used for USYD Rocketry Team's rocket Bluewren at Spaceport America Cup in June 2022.

In-house written trajectory simulations for student rocketry teams have been developed in the past. Publicly available software include RocketPy, developed by Project Jupiter, from the University of São Paulo,[3] and Cambridge Rocketry Simulator, developed by Cambridge University Spaceflight.[4,5] Both simulators use six-degree-of-freedom flight models with common verified dynamic equations and implement complex atmospheric modelling based on real weather data from forecasts, which is used for Monte Carlo analysis. However, both simulators require external aerodynamic parameters as inputs for the trajectory analysis. The aerodynamic analysis is the most complex part of flight simulation and the overall trajectory of the rocket depends highly on the aerodynamic parameters.

For a high-fidelity trajectory simulation, accurate aerodynamic coefficients are required. These coefficients are often derived from CFD solvers, which model aerodynamics more accurately than empirical equations, particularly in

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the transonic and supersonic flight regions. However, CFD analysis is time and computationally intensive. CFD data is only available when the rocket's exterior is finalised, and if any changes to the exterior are made, the CFD analysis must also be updated. This makes CFD calculations useful for final design simulations but infeasible for the early stages of design, where the exterior model of the rocket may not be defined.

Ironbark differs from other custom student-made rocket simulators because it has an inbuilt aerodynamic solver that automatically calculates the aerodynamic coefficients given a rocket geometry instead of requiring external input. The aerodynamic analysis is built upon a combination of PANAIR,[6] a panel code solver, and FRICTION,[7] empirical equations for skin friction drag. This combination allows higher fidelity estimates of the rocket's aerodynamics and trajectory than purely empirical equations; however, it does not require the computational intensity of CFD analysis, meaning it is more feasible for early design analysis and comparisons. Ironbark's aerodynamic solver is inbuilt into Ironbark's trajectory simulator so that, given a rocket's design parameters, the aerodynamics is automatically calculated and used to provide an estimated trajectory.

This paper presents an overview of the underlying Ironbark architecture, including the definition of rocket parameters through OpenRocket file inputs, the aerodynamic calculators, environmental models, and trajectory simulation. More detailed discussions of the aerodynamic and environmental model are provided, as well as details about the trajectory simulation and equations of motions used by Ironbark. Validation for Ironbark's aerodynamic models is presented, comparing results against experimental data of a wingless missile. Finally, Ironbark's apogee prediction for Bluewren, the 2022 winning Spaceport America Cup rocket, is presented and discussed.

2. Ironbark Architecture

Ironbark uses OpenRocket[1] files as an input to define parameters such as geometry, gravimetric properties, and motor thrust. The geometry is used to develop a mesh for the aerodynamic panel code solver PANAIR.[6] Combined with estimates of skin friction from Mason,[7] PANAIR provides medium-fidelity aerodynamic coefficients for use in a 6-DOF trajectory simulator. Ironbark also supports atmospheric models based on weather forecasts. Models are generated using NOAA Rapid Refresh (RAP)[8] and Global Forecast System (GFS)[9] forecasts to provide atmospheric conditions. Figure 1 shows a software flowchart illustrating the modules defined by the OpenRocket input and how each interfaces with the aerodynamic solver and trajectory simulation.

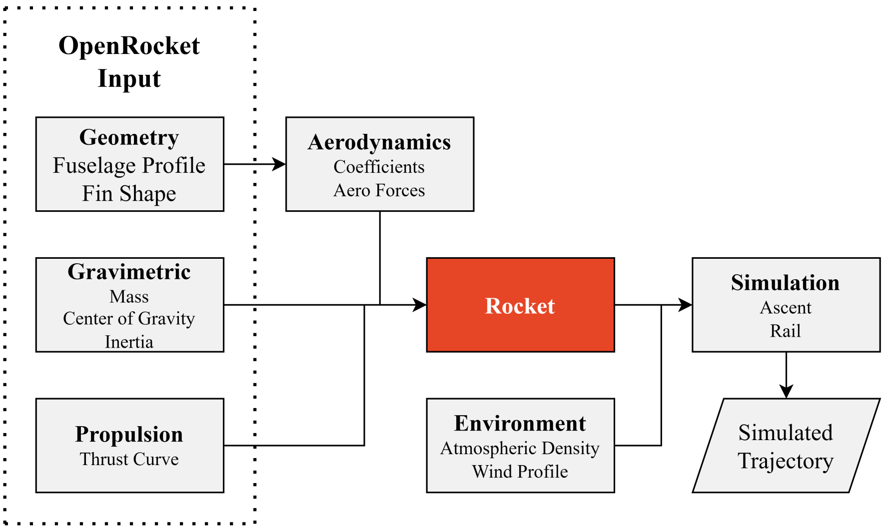

Figure 1: Ironbark software flowchart.

All inputs can be manually initialised inside the Ironbark environment for complete simulation control. However, initialising Ironbark using an OpenRocket file (.ork) as input is more common as many of the Team's rockets are initially designed in OpenRocket.

Geometry parameters, such as fuselage dimensions, fin shapes, nose cone profiles, and transitions, can be imported or manually defined and are used to generate a parameterised rocket geometry. Ironbark's geometry also extends

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the limited fin cross-section shapes and fin boat tail interface in OpenRocket, allowing for the definition of hex-shaped cross-sections and more complex fin planform shapes. Ironbark uses the parameterised rocket geometry in its aerodynamic simulations.

Gravimetric properties such as mass, centre of gravity, and moments of inertia are necessary inputs for Ironbark's trajectory simulation. Again these properties can either be imported from OpenRocket, which uses a component build-up approach, or manually defined from a computer-aided design (CAD) file. Notably, these gravimetric properties must be a function of time to capture the variation throughout the flight as the motor burns. Typically, these time-variant properties are input into Ironbark from OpenRocket. However, at a minimum, if the time-variant gravimetric properties of the rocket motor are known, and either the rocket's overall wet or dry properties, then Ironbark can calculate the total gravimetric properties.

Ironbark's propulsion module requires the input of a thrust curve through an OpenRocket initialisation or manual input. The propulsion module was explicitly written to allow for the future inclusion of hybrid and liquid engines.[10] Ironbark also allows importing thrust curve data of commercial solid rocket motors using the thrustcurve.org's ThrustCurve API.[11] The motor name is taken from the OpenRocket model and can be downloaded as a RockSim (.rse) and RASP (.eng) thrust curve file.

3. Simulation Models and Methods

OpenRocket cannot be used for accurate supersonic rocket simulations because of assumptions and limitations in its aerodynamic modelling. OpenRocket implements semi-empirical aerodynamic models that are only valid in the subsonic regime. Consequently, aerodynamic modelling was the primary focus of improvement for Ironbark. Once the aerodynamic properties of the rocket are simulated, they could be passed back into OpenRocket for trajectory modelling; however, it was decided for complete control of the simulation process that a trajectory model would be implemented in Ironbark instead. For these reasons, OpenRocket was integrated as the primary method to initialise Ironbark but not used for aerodynamic or trajectory simulations. The following sections discuss Ironbark's aerodynamic, environmental, and trajectory simulation models.

3.1 Aerodynamics

Ironbark allows for the input of external aerodynamic results, such as CFD simulations; however, the implemented aerodynamic models are the primary differentiating feature of Ironbark. The aerodynamic module calculates aerodynamic forces and moments given the rocket's current state. Ironbark generates aerodynamic tables by calculating aerodynamic coefficients over a range of expected flight conditions. During a simulation, these coefficients can be interpolated given the actual state of the rocket.

Instead of using theoretical and empirical aerodynamic formulas, Ironbark uses the panel code solver PANAIR, an open-source code that solves subsonic and supersonic flow problems for arbitrary three-dimensional configurations.[6] The program uses a higher-order panel method based on solving the linearised potential flow boundary-value problem at subsonic and supersonic Mach numbers. PANAIR cannot predict flow dominated by viscous and transonic flow effects or flow with different total pressures. To accurately capture the transonic flow regime is difficult, even for CFD solvers. Since student rockets do not spend an extended period in the transonic regime and no better solution exists to capture transonic effects without increasing computational complexity and time, this limitation of PANAIR is considered manageable.

As PANAIR does not have a panel generation code, Ironbark uses a modified version of the Python package, pyPanair, as the pre/post-processor for PANAIR. An automated surface meshing method for rocket geometries was developed using pyPanair as the underlying tool. Ironbark automatically converts a parameterised rocket into a set of networks, creating a Langley Wireframe Geometry Standard (LaWGS) geometry format. The panel network used to analyse one of the Team's rockets, Bluewren, is shown in Figure 2. This LaWGS format is then processed using PANIN to convert to PANAIR's required input format. PANAIR is then run for a given Mach number, angle of attack, and sideslip angle. These results are then processed by reading the output file, which returns the complete rocket configuration coefficients. Ironbark can also process the calculated pressure coefficients and export them for visualisation.

As directly simulating the aerodynamic forces and moments using PANAIR on each time step of the trajectory simulation is too computationally expensive, a table look-up method is instead implemented in Ironbark. PANAIR uses the Mach number, angle of attack, and sideslip angle as inputs to define the flow characteristics; therefore, these parameters are used to tabulate aerodynamic force and moment coefficients. Ironbark conducts a linear sweep over these parameters and a linear interpolation function is constructed for the aerodynamic results. Due to the symmetrical

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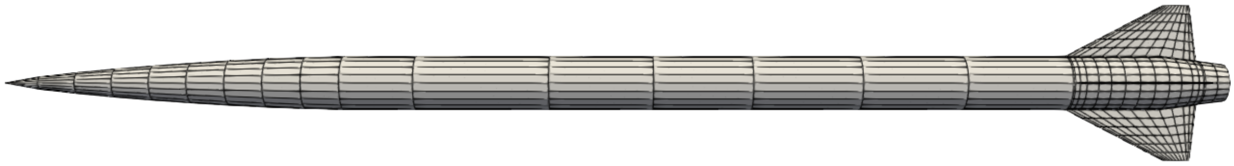

Figure 2: Bluewren PANAIR panel networks.

nature of rockets, Ironbark more commonly considers the forces and moments a function of the polar aeroballistic incidence angles. This allows for a significant reduction in the number of aerodynamic simulations and the computational time, as only a sweep of the angle of attack and Mach number needs to be performed. While the aerodynamic forces and moments are only calculated in the load factor plane, the roll angle is used to rotate the forces and moments into the velocity coordinates. Furthermore, it has been shown that this has little impact, as drag is still accurately captured, which is the primary contributor to the apogee prediction. A typical set of aerodynamic force and moment coefficients as a function of Mach number and angle of attack calculated by PANAIR is shown in Figure 3.

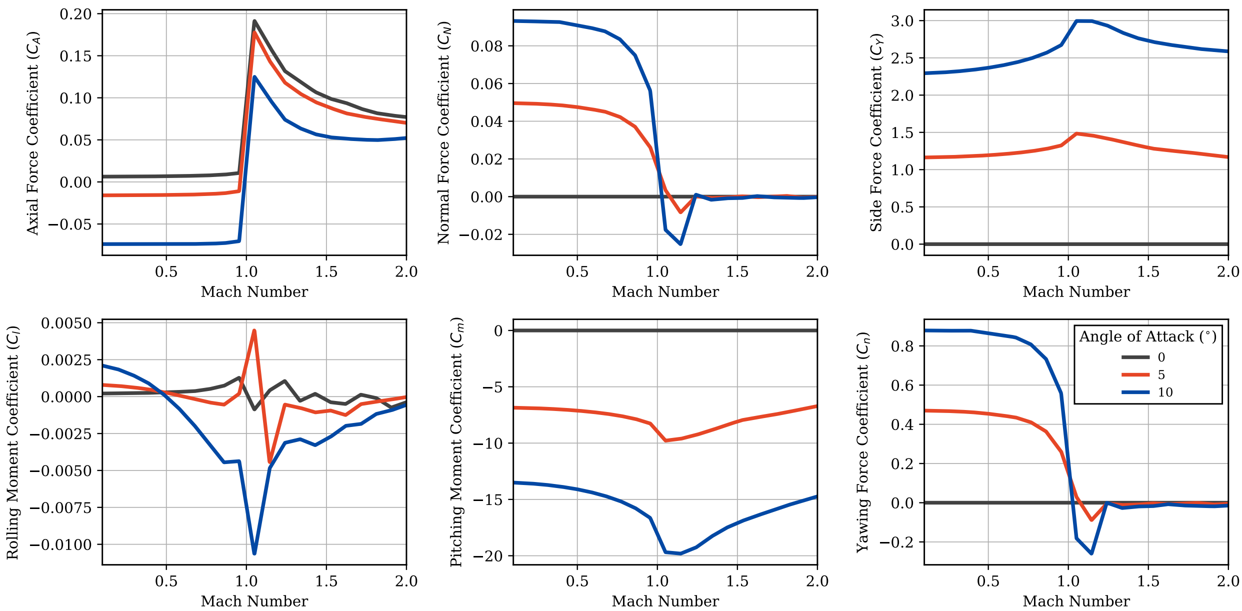

Figure 3: Bluewren aerodynamic coefficients around the centre of gravity in the body frame from PANAIR.

As PANAIR is an inviscid solver, and viscous effects contribute significantly to a rocket's drag force, additional modelling is required to calculate the viscous drag contribution. The methods utilised in FRICTION developed by Mason at Virgina Tech were implemented in Ironbark for this purpose.[7] These equations estimate laminar and turbulent skin friction based on the vehicle's geometric properties and the Mach and Reynolds numbers. The method uses a build-up approach where the skin friction drag of each component is found and then summed to find the total vehicle skin friction drag. The Blasius formula for skin friction, with compression adjustments using the Eckert reference temperature method, is used for laminar flow,[12] while the van Driest II method is used for turbulent flow.[13] Transitional flow is calculated using Schlichting's formula as a composite of the laminar and turbulent skin friction formulas.[14] Since estimating the point of transition is difficult, as suggested by Moore, a transitional Reynolds number is introduced where below the flow is considered to be full laminar and above full turbulent.[15] To further improve the results, additional formulas presented by Barrowman that estimate the critical Reynolds number for skin friction based upon the surface roughness were implemented.[16]

Unlike PANAIR, skin friction can be calculated for each time step of the trajectory simulation given the instantaneous flight conditions. Therefore, given the Mach and Reynolds numbers, Ironbark calculates the skin friction drag coefficient, rotates it to the body frame and adds it to the force and moment coefficients calculated using the PANAIR interpolation function. Typical values of the estimated skin friction drag coefficient are shown in Figure 4.

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The discontinuity in the left figure at a Reynolds number of 5×10^6 is due to the transition from laminar to turbulent flow.

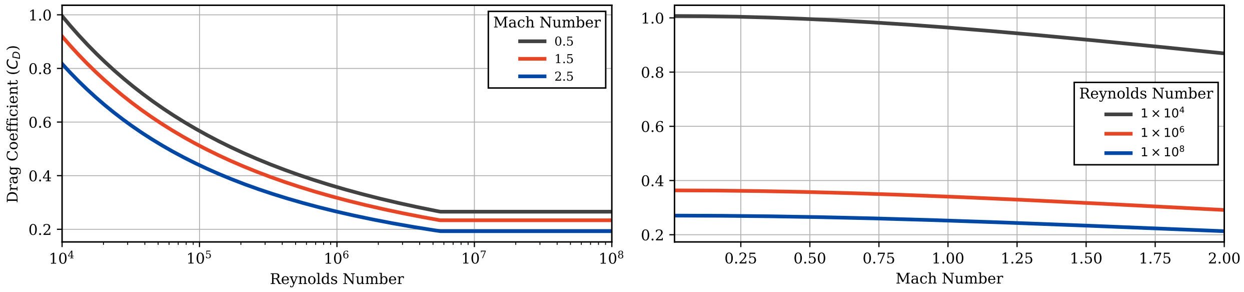

Figure 4: Bluewren skin friction drag coefficient.

3.2 Environment

Atmospheric attributes, like density, temperature, and pressure, are critical for an accurate trajectory simulation. Air density determines the aerodynamic forces and moments, the temperature is linked to the speed of sound, and while not currently implemented in Ironbark, air pressure impacts the thrust of a rocket engine. Wind speed and direction are also essential for trajectory simulation, particularly at the low speeds immediately after the launch rail, where strong winds could destabilise the rocket. The International Standard Atmosphere (ISA), the most commonly used atmospheric model, is implemented in Ironbark but is not used for a typical simulation. The ISA model is helpful for comparative studies, but a more realistic and localised model must be used for an accurate trajectory simulation. Furthermore, ISA does not include wind models, which require additional modelling to capture.

Ironbark implements two atmospheric models to suit international and North American launch sites. Both models provide up-to-date forecasts for atmospheric temperature, pressure, wind speed and direction. North American launch sites use the Rapid Refresh Model (RAP), which covers continental North America and provides hourly forecast updates with a nominal 13 km grid.[8] The Global Forecast System (GFS) is a weather prediction system used for Australian and international launch sites and provides updates four times a day on a 27 km grid.[9] Typical environmental properties at Spaceport America Cup using the Rapid Refresh Model are shown in Figure 5.

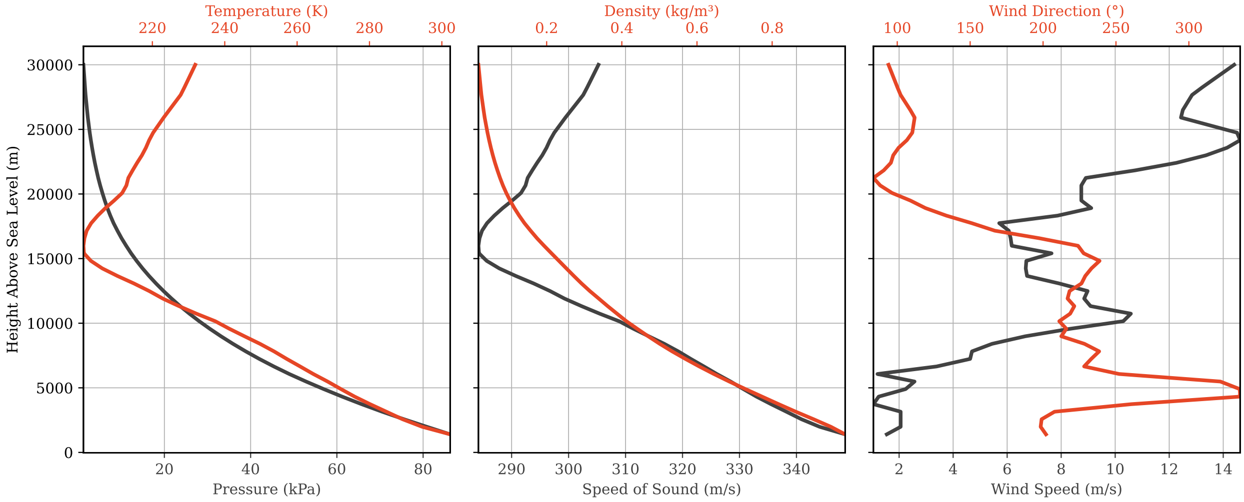

Figure 5: Environmental properties at the 2022 Spaceport America Cup from the Rapid Refresh Model.

3.2.1 Trajectory

Ironbark's trajectory simulation is built upon the equations and methods outlined by Zipfel.[17] The trajectory simulation is split into two phases: rail simulation and flight simulation. A third recovery phase is currently in development.

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The flight simulation is a complete 6-DOF simulation incorporating the rocket's full gravimetric, propulsion and aerodynamic properties to generate a trajectory to apogee. Figure 6 shows a flowchart of the simulation process. The atmospheric and wind velocity conditions are calculated using the set environmental model at each time point and rocket state. These conditions allow parameters such as airspeed, angle of attack and lateral wind conditions to be calculated. Given these parameters, aerodynamic forces and moments are computed using the interpolation functions. The forces and moments are calculated at a pre-defined point, typically the burn-out centre of gravity, and then shifted to the current centre of gravity, creating an additional moment about the centre of gravity. The propulsion and gravimetric forces are calculated in the body axis at the centre of gravity.

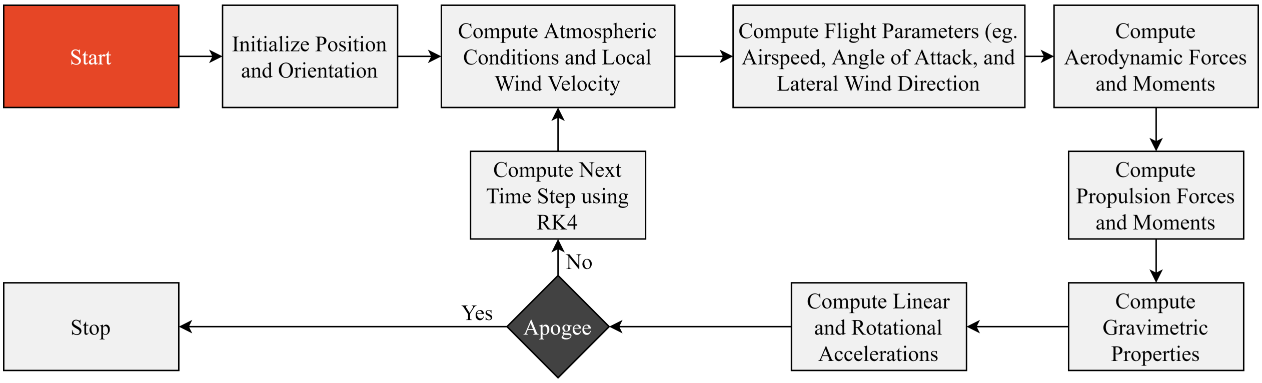

Figure 6: Flow chart of Ironbark's trajectory simulation.

The rocket's linear and rotational accelerations are calculated by combining all aerodynamic, gravimetric, and propulsion models. The linear accelerations are integrated using Equation 1, which represents Newton's second law in matrix form.[17]

$$m\left[\frac{\mathrm{d}v_B^E}{\mathrm{d}t}\right]^B + m\left[\Omega^{BE}\right]^B\left[v_B^E\right]^B = \left[f_{a,p}\right]^B + m[T]^{BL}[g]^L \tag{1}$$

Here $[v_B^E]^B$ is the linear velocity of the rocket with respect to Earth, $[\Omega^{BE}]^B$ is the angular velocity of the rocket with respect to Earth, and $[f_{a,p}]^B$ is the aerodynamic and propulsive forces. Rotational accelerations are integrated using Equation 2, which is Euler's rotational equation in matrix form.[17] Ironbark propagates the state vector using the 4th-order Runge-Kutta method (RK4) as its numerical integration solver. The integrator propagates the rocket's state until the simulation reaches apogee, which occurs when the rate of change of altitude is negative.

$$\left[\frac{\mathrm{d}\omega^{BE}}{\mathrm{d}t}\right]^B = \left(\left[I_B^B\right]^B\right)^{-1}\left(-\left[\Omega^{BE}\right]^B\left[I_B^B\right]^B\left[\omega^{BE}\right]^B + [m_B]^B\right) \tag{2}$$

Here $[\omega^{BE}]^B$ is the body rates of the rocket with respect to Earth, $[I_B^B]^B$ is the moment of inertia tensor of the rocket, and $[m_B]^B$ are the aerodynamic moments. The rocket's movement whilst on the launch rail is modelled using a 3-DOF simulation, where rotation is set to zero due to the constraint of the rail and the angle of attack is considered zero for aerodynamic calculations. The rail simulation ends when the rocket leaves the launch rail.

4. Model Validation

Ironbark's aerodynamic modelling is validated against available experimental data. As published data is scarce, a complete study comparing only one vehicle is presented here. It was decided to present a supersonic validation case instead of a subsonic validation case, as accurate supersonic aerodynamic predictions were one of the main motivations of this work. The results used are sourced from a NASA technical memorandum which provides an experimental investigation on the effect of fin planform on the aerodynamic characteristics of a wingless missile.[18] This model was chosen due to its resemblance to the geometry of the Team's rockets. Testing was completed at supersonic Mach numbers and a range of angles of attack using the Langley Unitary Plan wind tunnel. Data for four models are provided, identified herein as T9, T10, T11, and T12. The four models are shown in Figure 7. The fuselages of all four models are identical, with only the fins varying between them; however, the fins are designed to have the same exposed area.

Most of a typical sounding rocket's flight is spent at a small angle of attack, often very close to zero. Furthermore, as has already been discussed, drag is the most critical factor for apogee prediction, which is the main aim of

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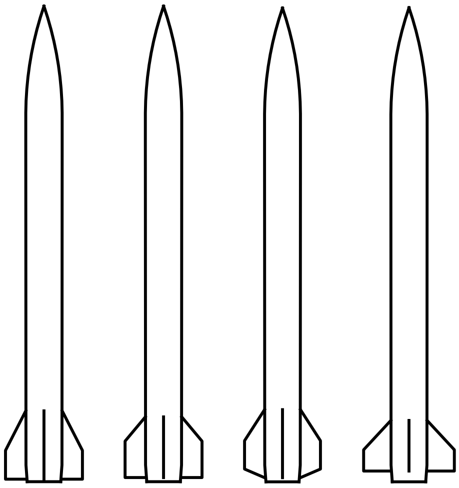

(a) T9 (b) T10 (c) T11 (d) T12

Figure 7: Simulated rocket models.

Ironbark. Therefore, validating the rocket's drag coefficient at zero angle of attack ($C_{D,0}$) is very important for accurate aerodynamic modelling. Table 1 shows $C_{D,0}$ for the four rocket models at three different Mach numbers. All four models show an acceptable error at Mach 1.6; however, the error grows as the Mach number increases. This was somewhat expected as, even though PANAIR is designed to simulate supersonic flow, the formulas implemented to calculate skin friction drag are designed for subsonic flow. More accurate supersonic skin friction drag equations exist and will be investigated in future. However, the Team's rockets do not currently fly faster than Mach 1.6, so this error level is deemed acceptable.

Table 1: Zero angle of attack drag coefficient ($C_{D,0}$)

	T9			**T10**			**T11**			**T12**		
Mach [a]	**Exp** [b]	**Sim** [c]	**Error** [d]	**Exp**	**Sim**	**Error**	**Exp**	**Sim**	**Error**	**Exp**	**Sim**	**Error**
1.60	0.3313	0.3424	3.3	0.3610	0.3440	4.7	0.3326	0.3447	3.6	0.3967	0.3546	10.6
2.38	0.2668	0.3224	20.8	0.2800	0.3234	15.5	0.2790	0.3240	16.1	0.3071	0.3332	8.5
2.83	0.2367	0.3391	43.2	0.2497	0.3401	36.2	0.2390	0.3404	42.4	0.2640	0.3493	32.3

[a] Mach number, [b] Experimental results,[18] [c] Ironbark simulation results, [d] Percentage error

Next, the variation of the aerodynamic forces and moments with the angle of attack is validated, where the three most significant parameters are axial force, normal force, and pitching moment coefficient. The normal and axial forces are the body reference frame's equivalent of lift and drag, while the pitching moment provides stability. Figure 8 shows the results for these three parameters of model T9 at Mach 1.6 as a function of the angle of attack. As can be seen, all three parameters estimated by Ironbark agree with the experimental results at a low angle of attack; however, all three start to deviate at high angles of attack. Again, this is expected as PANAIR does not capture flow separation experienced at a high angle of attack. However, as student rockets mostly fly at a small angle of attack, these results are acceptable.

Finally, the drag and lift coefficient for all four models at Mach 1.6 for a range of angles of attack is validated, shown in Figure 9 as a drag polar. The same trends as the previous two cases can be seen where agreement is good at low angles of attack, corresponding to lift coefficients around zero. At the same time, the simulation starts to diverge from the experimental results at high angles of attack and, thus, high lift coefficients. All four models show good agreement between results, meaning the automated workflow from geometry input to aerodynamic results works as expected.

As presented in this validation study, the aerodynamic simulation models implemented in Ironbark show good agreement with experimental data. For instances where discrepancies arose, the difference in results was identified and explained. This shows that the aerodynamic simulation module is credible, making it sufficient for use in Ironbark.

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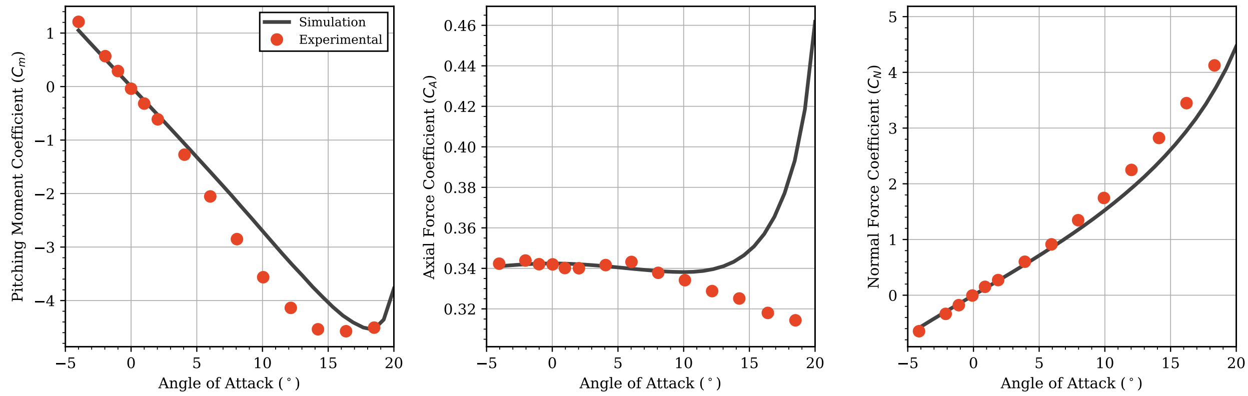

Figure 8: Angle of attack validation using geometry T9 at Mach 1.6.

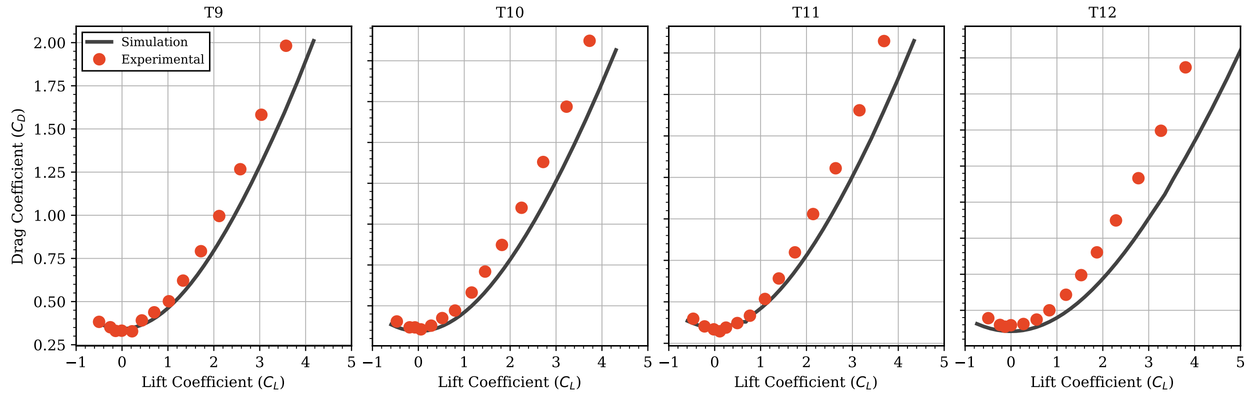

Figure 9: Geometry validation at Mach 1.6.

5. Results

Ironbark was initially developed to allow the Team to accurately predict the apogee of Bluewren, which was USYD Rocketry Team's entry into the 30,000ft category at the 2022 Spaceport America Cup (SAC). Bluewren is 3.2 m long with a 0.143 m diameter and was designed to fly on a Cesaroni Technology Incorporated (CTI) O3400; their most powerful 98 mm motor. Bluewren was the Team's second design for a 30,000ft rocket, building upon the previously designed Firetail, designed for the 2021 SAC, but was ultimately never flown because of the COVID-19 pandemic. Consequently, when Ironbark was initially developed, the Team did not have access to any complete supersonic flight data for validation. While these results look specifically at the application of Ironbark to Bluewren for the 2022 SAC, they are also representative of the typical 30,000ft category rocket, which flies in the subsonic, transonic, and supersonic regimes. Analysis of Bluewren's test flight and competition flight using Ironbark is presented and compared to results generated by the open-source simulation tool OpenRocket.

Initially, it was unclear if Ironbark's inbuilt aerodynamic simulation would be sufficient for the desired apogee prediction accuracy. Therefore, aerodynamic force and moment coefficients for Bluewren over the expected flight regime were also obtained using a full RANS CFD simulation in Ansys Fluent. As Ironbark can import aerodynamic coefficients, this allowed for both the CFD-derived and inbuilt coefficients to be analysed. Simulations using Ironbark's internally derived aerodynamic results and these externally generated CFD results are investigated.

Bluewren was first flown in a test launch at Tolarno Station in New South Wales, Australia. The test flight allowed for the validation of Ironbark as a trajectory simulation and prediction tool. Precise gravimetric properties of the rocket were recorded before the flight and the atmospheric model was derived from the Global Forecast System (GFS) closest to the launch time.

Figure 10 compares the three flight simulations and the flight data the two onboard flight computers recorded. The comparison indicates that Ironbark, using both the inbuilt aerodynamic solver and CFD coefficients, can closely fit the recorded apogee with only a minor deviation from the ascent trajectory. At the same time, OpenRocket over-estimates the expected flight trajectory. All simulations closely match the recorded flight velocity after the maximum

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velocity but typically overestimate the expected peak velocity. Similarly, all simulations closely match the recorded acceleration but tend to have a larger deceleration following motor burnout. A comparison of key flight parameters is shown in Table 2.

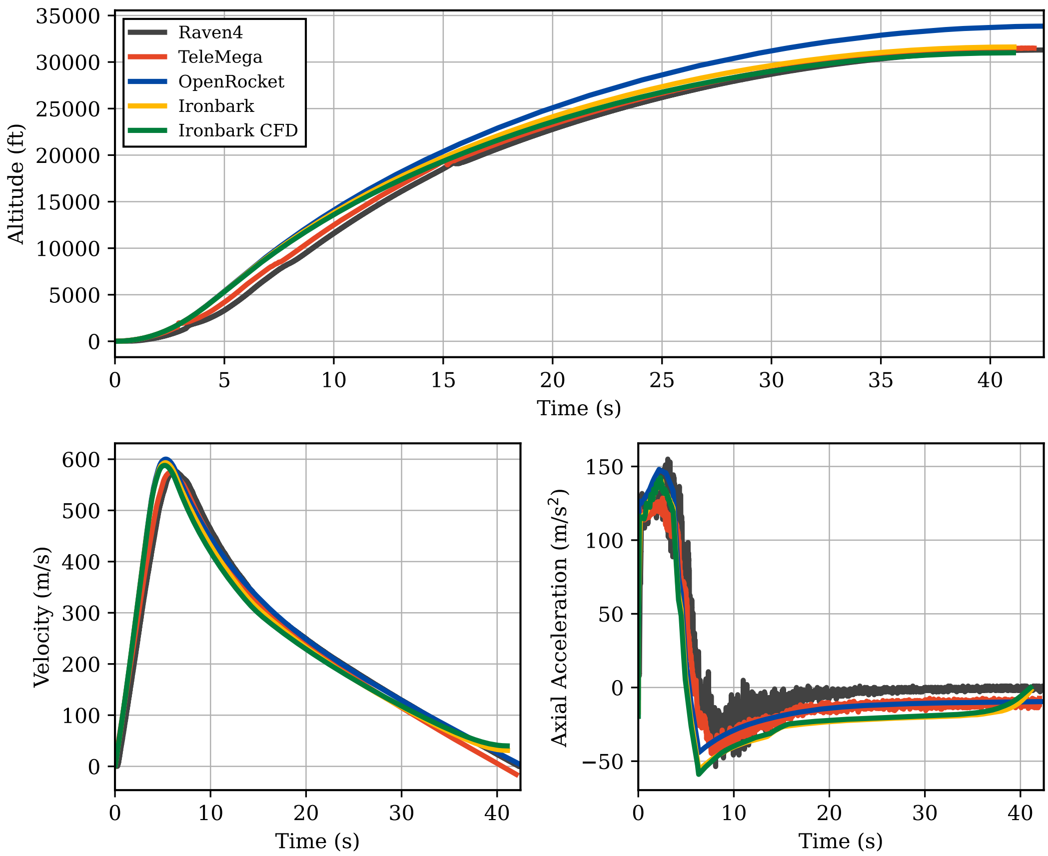

Figure 10: Tolarno test flight data compassion.

Table 2: Tolarno test flight data compassion.

Data Source	**Apogee, m (ft)**	**Apogee Time, s**	**Maximum Velocity, m/s**	**Maximum Acceleration, m/s^2**
Raven4	9 539 (31 297)	42.9	576	155
TeleMega	9 604 (31 509)	42.0	575	128
Ironbark	9 636 (31 615)	41.1	593	140
Ironbark with CFD	9 447 (30 993)	41.1	588	142
OpenRocket	10 320 (33 857)	42.6	600	148

Compared to the apogee measurement from the TeleMega and Raven4 flight computers, the Ironbark simulation with CFD coefficients had relative errors of 1.64 % and 0.97 %, respectively. The Ironbark simulation with internal aerodynamic results had better relative errors of 0.34 % and 1.02 % compared to the TeleMega and Raven4 results, respectively. Ironbark simulations had significantly better apogee errors than the OpenRocket simulation, which had errors of 7.45 % and 8.18 %. Therefore, after the test flight, it was proven that Ironbark could predict Bluewren's apogee significantly better than the available open-source simulation tools, thus achieving its initial goal.

An important note is the discrepancy in results between the two onboard flight computers. While the TeleMega and the Raven4 recorded similar flight profiles, their differences become important when producing the most accurate apogee predictions. The difference in recorded values could be due to several factors, such as the type of sensor used, sensor quality, sensor fusion, filtering, post-processing, or even their physical location in the rocket. The TeleMega is considered the more reliable data source by the Team and is the flight computer used by the Team for the official competition apogee. Therefore, Telemega is considered the primary benchmark for Ironbark; however, the true flight

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profile is most likely between the two.

The test flight, whilst validating Ironbark, also demonstrated that the impulse provided by the O3400 motor resulted in an apogee overshoot of 460 m (1 509 ft) at the Tolarno launch site with an elevation of 57 m (187 ft) above mean sea level (AMSL). Spaceport America has a higher elevation of 1 401 m (4 595 ft) AMSL, which due to the lower atmospheric density, results in an increase in the apogee overshoot. Ironbark was used to re-evaluate the performance of Bluewren for its SAC flight, using a range of suitable motors.

Ironbark simulations predicted that a flight using the O3400 at SAC would result in an apogee of 10 518 m (34 510 ft), resulting in the Team losing half of its apogee points. Ultimately it was decided that Bluewren would fly on a CTI N3301 at SAC, which was predicted to have an apogee of 9 512 m (31 208 ft). While this is still an overshoot of the target apogee, Bluewren was designed with a variable mass ballast system that could be used to adjust its apogee. Around apogee, there is an almost near-linear reduction in height with additional mass added to the rocket.

Ironbark was used on the day of launch at Spaceport America with the latest available RAP atmospheric model to determine the mass ballast required to get the closest apogee possible to the target. It was decided that while Ironbark's internal aerodynamic results provided a better estimate for the Tolarno test flight, the Team had more confidence in the accuracy of the CFD results, so they were used for the final SAC simulation. The variable mass ballast was set for a predicted apogee of exactly 30,000ft in Ironbark. Ultimately, Bluewren flew to an apogee of 29 933 ft, representing a difference of 67 ft or 0.2 % from the target and prediction. The accuracy of Ironbark is one of the main contributing factors to Bluewren's win at the 2022 Spaceport America Cup.

Figure 11 compares the Ironbark flight simulations, OpenRocket, and the flight data the two onboard flight computers recorded. A comparison of the key flight parameters for Bluewren's flight at Spaceport America Cup is shown in Table 3.

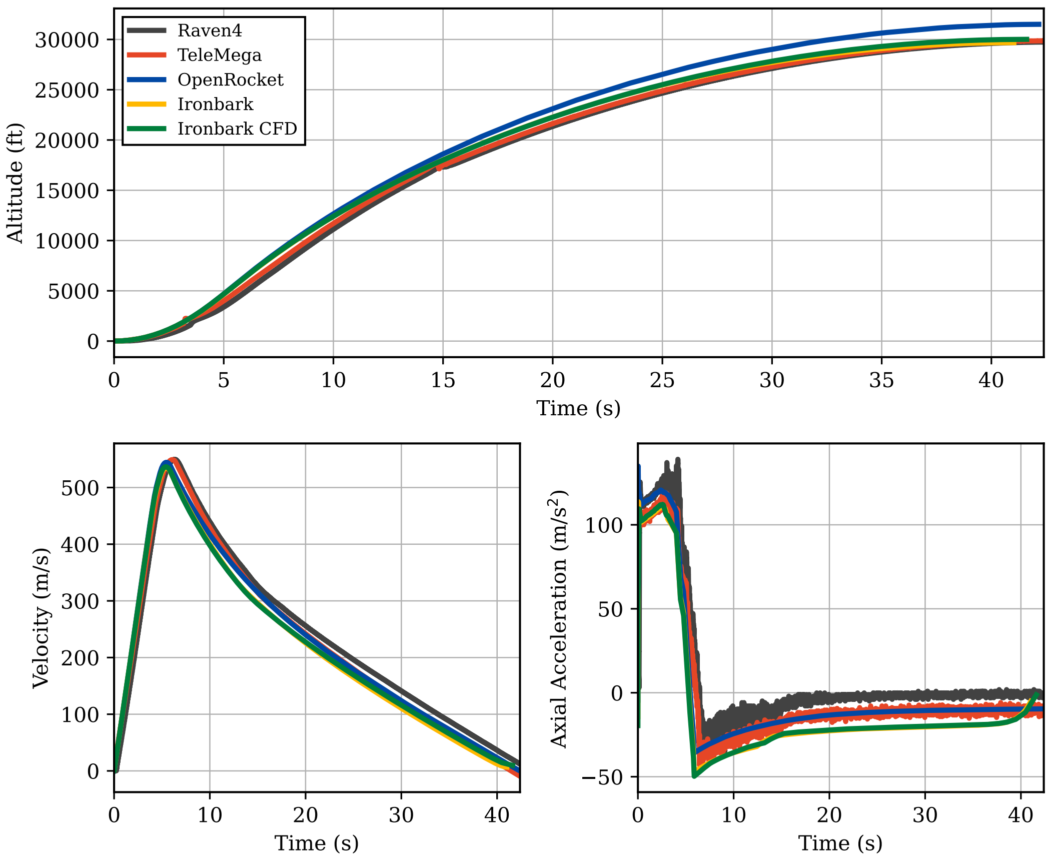

Figure 11: Spaceport America Cup flight data comparison.

Again it can be seen that both Ironbark simulations performed very well in predicting the apogee of Bluewren, with the internal aerodynamic method having an error of 0.85 % and the CFD-based simulation having an error of 0.26 % when compared to the TeleMega value. The percentage errors for all flight parameters, as predicted by all three simulations for both flights, are shown in Table 4. The sensitivity of these simulations to input parameters is evident with the more accurate Ironbark method changing, depending on which flight is considered. The only substantial

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Table 3: Spaceport America Cup flight data compassion.

Data Source	Apogee, m (ft)	Apogee Time, s	Maximum Velocity, m/s	Maximum Acceleration, m/s^2
Raven4	9 076 (29 777)	43.7	550	155
TeleMega	9 124 (29 933)	43.9	549	127
Ironbark	9 046 (29 680)	41.0	535	114
Ironbark with CFD	9 147 (30 009)	41.6	537	112
OpenRocket	9 603 (31 506)	42.2	544	157

difference in modelling between the two flights was the use of a RAP-based atmosphere for the SAC, which has a finer spatial and temporal grid than the GFS-based model that was used for Tolarno, meaning that the atmosphere used for the SAC simulation was likely more accurate than the atmosphere used in the Tolarno simulation.

Table 4: Simulation percentage error compared to TeleMega data.

	Apogee		Apogee Time		Maximum Velocity		Maximum Acceleration	
Simulation	Tolarno	Spaceport America	Tolarno	Spaceport America	Tolarno	Spaceport America	Tolarno	Spaceport America
Ironbark	0.34	0.85	2.28	6.46	3.18	2.63	8.97	10.13
Ironbark with CFD	1.64	0.26	2.34	5.13	2.26	2.31	10.53	11.47
OpenRocket	7.45	5.26	1.24	3.87	4.39	0.88	15.25	24.23

While Ironbark simulations using CFD-derived results were used for SAC, the results produced by Ironbark's internal aerodynamic modelling methods are still very accurate. Notably, the CFD results require a deep understanding of the problem and a lot of computational and setup time to generate. Comparatively, Ironbark can quickly and automatically generate aerodynamic results for typical rocket configurations given only a geometry input. The entire run time for a typical Ironbark simulation with 84 aerodynamic data points, using a computer with an eight-core Intel i9-9900, is shown in Table 5. It can be seen that while the aerodynamic simulation is the most computationally expensive, it is significantly quicker than CFD.

Table 5: Ironbark simulation run time.

Simulation	Run Time (s)
Aerodynamic	137.2
Trajectory	5.8
Total	150

This short run time allows Ironbark to be used as part of a design optimisation study or a statistical analysis. Typically, these studies are limited to parameters that do not impact the aerodynamic results, as creating new results using CFD is not possible in the design time frame. The Team has already used Ironbark for design sensitivity studies and statistical analysis using the Monte Carlo method. The Team plans to use Ironbark as the foundation of future design optimisation studies and a preliminary design tool for new rockets.

6. Conclusion

Ironbark was initially developed to provide USYD Rocketry Team with the capability to accurately predict the apogee of all its future competition rockets, which was not possible with existing tools. Ironbark was validated with experimental data available in literature and showed good agreement. As noted, the skin friction modelling method needs additional work to address Mach numbers above 1.6. The results of using Ironbark to predict the apogee of Bluewren at the 2022 Spaceport America Cup were presented. Overall, Ironbark fulfilled the goals it set out to achieve and provided an adequate foundation for further expansion.

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