Report for the Submission of Data Supporting World Record Runs in the Dead Downwind Vehicle Category

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12 July 2010

Introduction

On the 2nd and 3rd of July 2010, the ThinAir Designs team made several runs with the wind powered vehicle, the "Blackbird", on the El Mirage dry lake bed in southern California. This was done in a bid to establish the first world records in the newly developed NALSA categories C3 and C4 (top speed for a non-conventional sailing craft and greatest ratio of vehicle speed to wind speed for a dead downwind vehicle).

This document summarizes the case for a vehicle speed ratio of 2.8 times the wind speed and a top vehicle speed of 51.4 mph in accordance with categories C4 and C3, respectively. Bob Dill of NALSA is in possession of all raw data logged from multiple sensors on multiple vehicles and platforms that will support this summary.

Vehicle Description

The Blackbird is a vehicle designed and built with the sole purpose of traveling directly downwind, faster than the wind, powered only by the wind, steady state. It has a tricycle configuration and a 17.5' diameter propeller on the top of a set of pylons over the vehicle's rear axle. The propeller is connected to the rear axle through a simple chain-drive transmission and ratchets. This configuration permits the wheels to turn the propeller via the fixed ratio transmission, while allowing the prop to freewheel during braking. The prop pitch can be controlled by the pilot "on the fly". By design, such a configuration cannot be accelerated through the use of stored energy/momentum. The vehicle makes no use of any controls or actuators other than those operated directly by the pilot with human power.


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Analysis of speed run for NALSA category C3

On 2 July 2010 the DDWFTTW craft reached a top speed of 51.4 mph at 14:19:16 PDT on El Mirage dry lake.

This speed is a three-second average from GPS-Dill-#7 which was attached by Bob Dill to the front deck of the DDWFTTW craft. Secondary measurements were made from the chase vehicle which had three logging GPS receivers (including NALSA provided GPS-Dill-#5 and GPS-DILL-#6) and a MetOne Instruments anemometer.

Chart 1 below shows the DDWFTTW vehicle speed profile for the submitted time period. Time is presented on the horizontal axis, and represents UTC time in seconds from beginning of day. Speed is given on the vertical axis in knots.

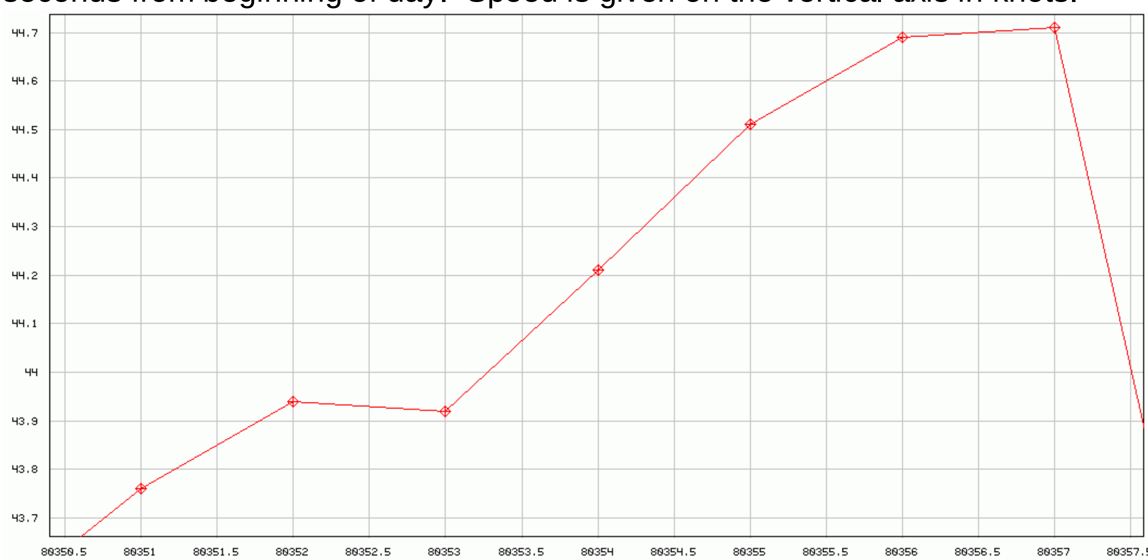

Chart 1: DW Cart speed in knots as measured by GPS-Dill-#7

Analysis of 10 second run for NALSA category C4

The subject run begins from a dead stop at 588959.4 seconds (GPS time in seconds measured from beginning of week). The downwind cart is pushed on foot (by JB) and released at 588977.0 at a ground speed of 11 mph. From this point the DW cart accelerates monotonically, by wind power alone, up to and through the 10 second measurement period from 589060.8 to 589070.8.

During this period, the DW cart achieved a 10-second average speed of 27.665 mph while the wind had a 10-second average speed of 10.01 mph.

During this period the DW cart maintained a 10-second averaged heading within less than 5 degrees of the 10-second average of the true wind direction.

Over this same period, the DW cart averaged a 2.77 multiple of true wind speed, while it's absolute speed increased from 26.84 mph to 28.81 mph.

Charts 2, 3, and 4 detail the performance of this run.

In each case, time is given on the horizontal axis as GPS time in seconds from beginning of week. The curves on the chart are as follows:

Red	10-second averaged cart speed (mph)
Yellow	Non-averaged cart speed (mph)
Blue	10-second averaged cart heading (deg.; 0: East; 90: North)
Black	10-second averaged wind TO direction (deg.; 0: East; 90: North)
Green	10-second averaged speed ratio (cart speed / wind speed)

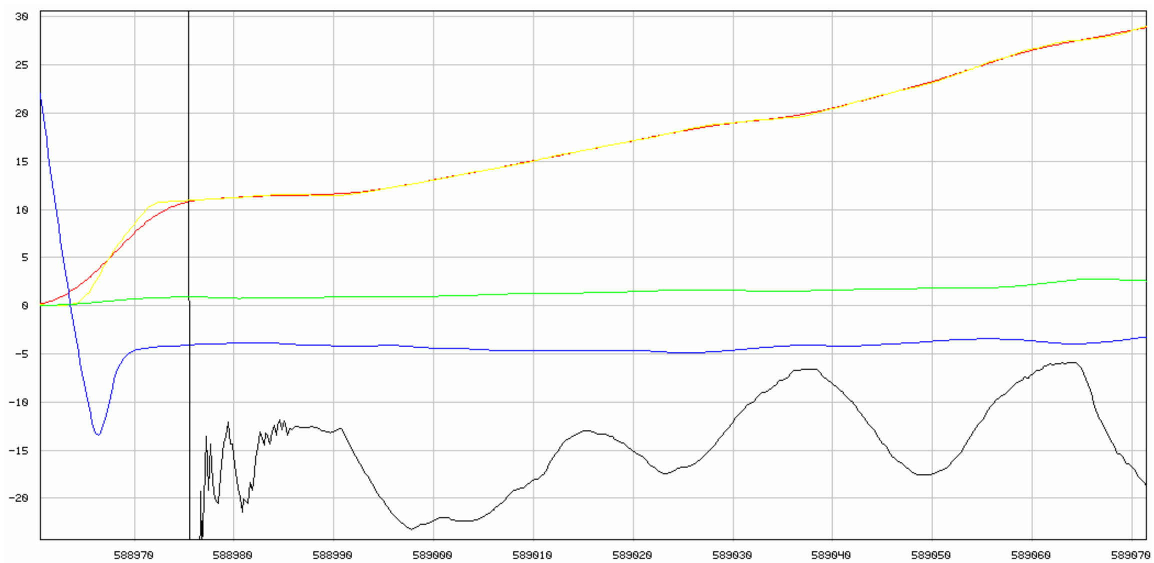

Chart 2: Overview of data supporting submission in record category C4

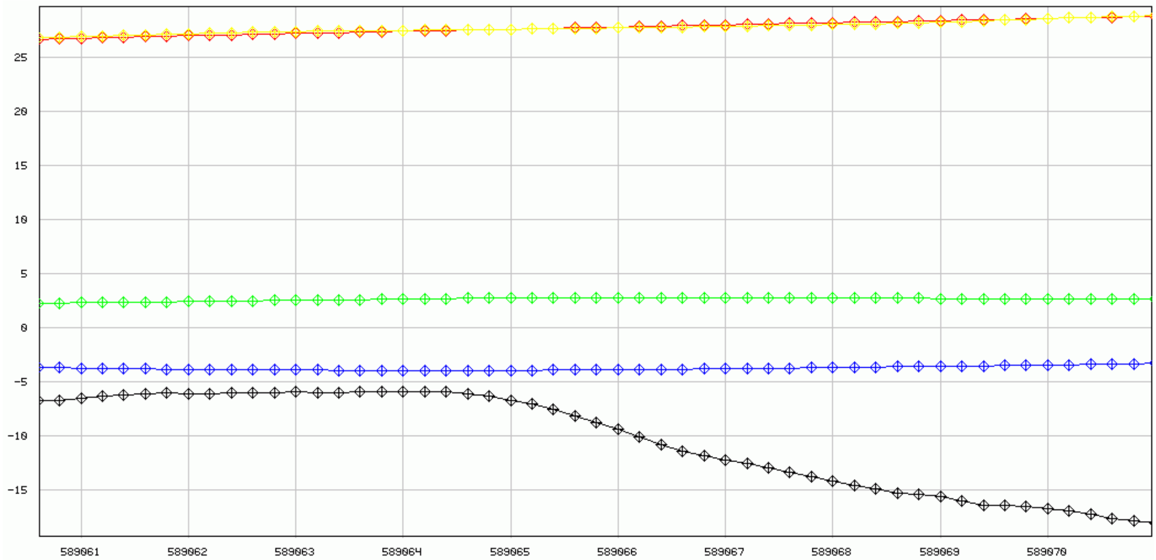

Chart 3: Measurement period data supporting submission in record category C4

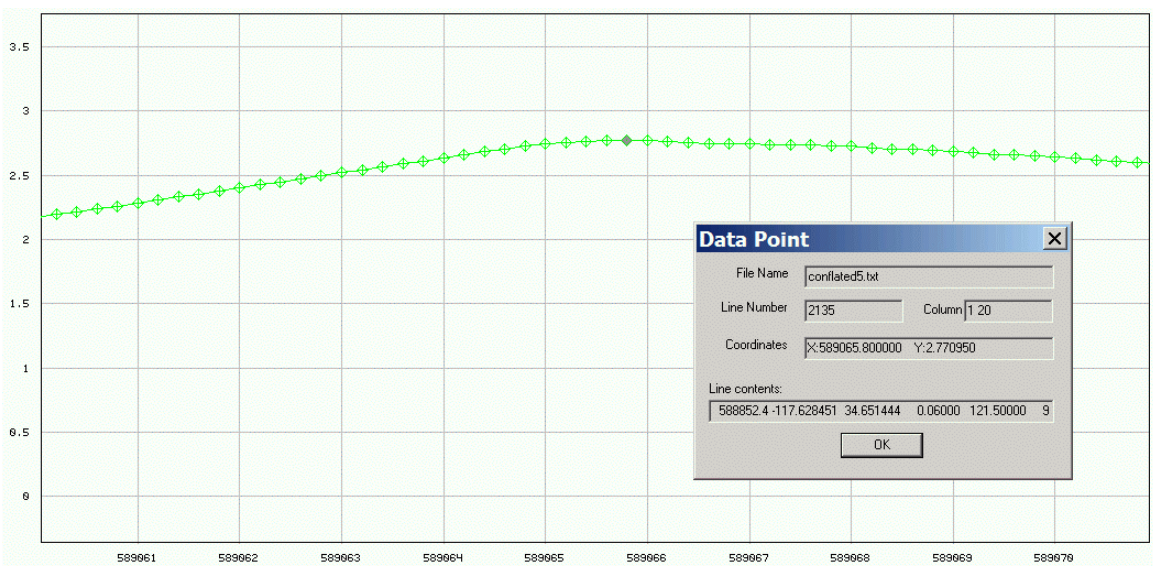

Chart 4: Speed ratio data during 10 second measurement period

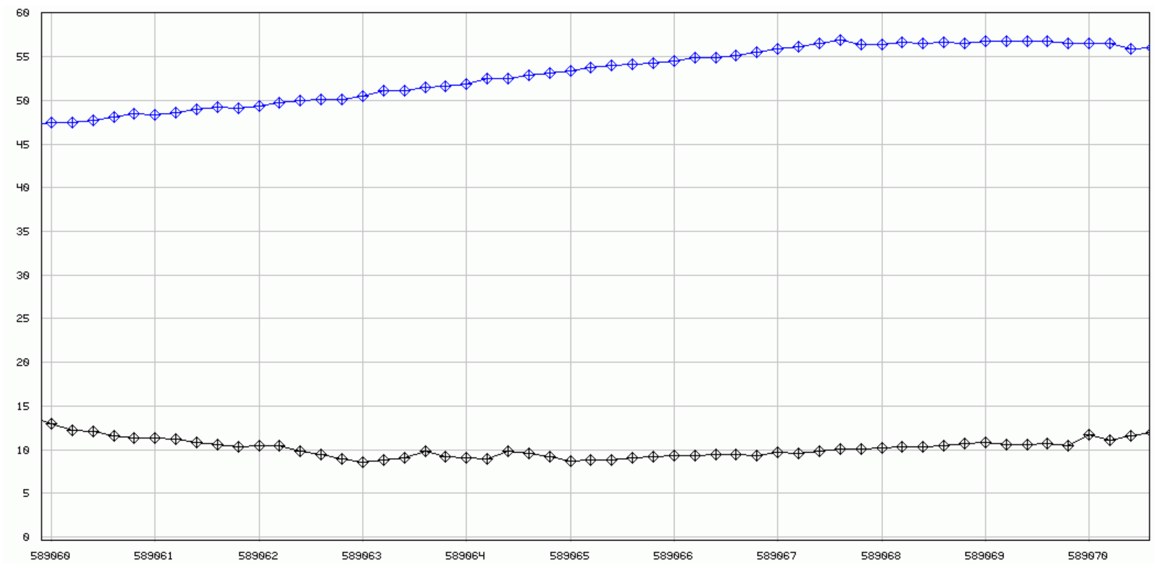

Chart 5: Distance in feet between chase vehicle and downwind vehicle during 10 second measurement period (blue curve)

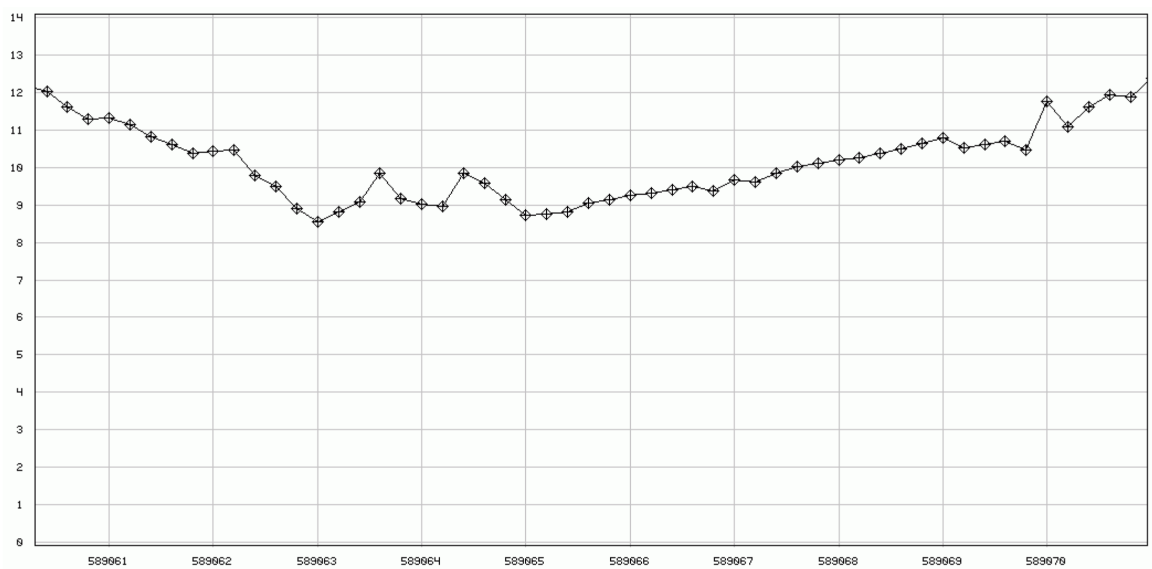

Chart 6: True wind speed (mph) measured at chase vehicle during 10 second measurement period

Attendees:

Representing ThinAir Designs:

Rick Cavallaro:	Vehicle designer, builder, and driver
John Borton:	Vehicle designer and builder
Steve Morris:	Aerodynamics consultant
Chris Fields:	SJSU student contributor

Representing NALSA as official observers:

Bob Dill:	NALSA secretary
Kimball Livingston:	Editor of SAIL magazine

Others on site included Richard Jenkins (world land speed sailing record holder), four engineers representing Joby Energy (primary sponsor of the Blackbird), David Glover (independent photographer/videographer), and several others who had been following the project.

Appendix 1

Analysis demonstrating that the vehicle is capable of DDWFTTW

In order to run in this NALSA category it must be demonstrated that the vehicle is capable of going directly downwind, faster than the wind, powered only by the wind, steady state. While this has been a hotly debated topic on the internet, the principle has been demonstrated many times with working models and has been analyzed both by the ThinAir Designs team as well as by noted aerodynamicist Mark Drela. See “Drela Power Analysis.pdf” and “Drela DDWFTTW Analysis.pdf”

The following case study will demonstrate the principle in simple terms:

Consider a cart with an electric generator driven by the rear axle and a propeller driven by an electric motor. We’ll assume the following reasonable set of parameters:

Electric generator efficiency: 85%
Electric motor efficiency: 85%
Propeller efficiency: 85%
Coefficient of rolling resistance: 0.02
Vehicle gross weight: 650 lbs
Coefficient of aerodynamic drag: 0.3
Projected frontal area: 20 sq-ft

For the purpose of this analysis we won’t consider the issue of accelerating to speed, but rather the cart’s ability to maintain faster-than-the-wind speed and further accelerate from that point. Thus we’ll tow the vehicle up to a speed of 20 mph in a 15 mph tail-wind and then let it loose. In this situation the vehicle will experience a relative head-wind of 5 mph. We’ll adjust the generator output such that it produces 20 lbs of retarding force at the wheels. This tells us the wheels will be putting power into the generator at a rate of 20 mph x 20 lbs (400 mph-lbs). But the generator will only produce 340 mph-lbs due to its 85% efficiency.

We deliver that power to the electric motor. But we get only 289 mph-lbs at the motor's shaft due to the motor's 85% efficiency. This power is working to spin the propeller, but the propeller does only 245 mph-lbs of work on the air due to its 85% efficiency. Given the vehicle’s relative airspeed of 5 mph, we can see that the prop will be producing 49 lbs of thrust.

Given our vehicle gross weight of 650 lbs and coefficient of rolling resistance of 0.02, we can calculate that we’ll lose 13 lbs of thrust to rolling resistance. We lose another 20 lbs at the wheels due to the retarding force caused by the electric generator. This leaves us with an excess of 16 lbs (49-13-20).

Finally, we have to consider the aerodynamic drag we experience in this state:

Aero_drag = Drag_coeff * frontal_area * ½ * rho * Vel * Vel

In which rho is air density and vel is the relative air velocity experienced by the vehicle.

Aero_drag = 0.3 * 20 * ½ * 0.002329 * 7.333 * 7.333 = 0.376 lbs

Where 0.002329 is the air density in slugs/ft^3 and 7.333 is our velocity in ft/sec.

Subtracting our aero drag of 0.376 lbs from our excess thrust of 16 lbs, gives us a remaining excess thrust of 15.6 lbs. This shows that the vehicle will continue to accelerate from this state.

The simple explanation is that the vehicle acts as a lever between two media (the ground and the air). Like any lever we can trade a small force over a large distance for a larger force over a smaller distance. This is how we get more thrust from the prop than we create drag at the wheels (since the wheels are moving over the ground faster than the prop is moving through the air –due to the tailwind).

Appendix 2

Proof that the vehicle performs best Dead Downwind

As can readily be seen from the above analysis, the vehicle performance is driven significantly by the prop efficiency. This of course is primarily a function of the Lift/Drag ratio of the propeller airfoil at its operating angle of attack. The propeller on the Blackbird is based on the NACA 6412 airfoil which has it's maximum L/D at 4.0 degrees, and has a twist such that the airfoil at each spanwise station is presented at that angle of attack (AOA). When the relative flow is aligned with the propeller axis, that AOA can be maintained at all spanwise stations throughout the complete rotation. As the prop rotates counter-clockwise when viewed from in front of the vehicle, any cross-wind component from the right will cause the AOA for the top blade to increase while the angle of attack of the bottom blade is decreased. A cross wind component from the left will have the same effect in the opposite direction. In both cases the AOA will depart from its optimum value to varying degrees over the full rotation of the prop in this case – reducing the propeller performance – and thus the overall performance of the cart. The cart employs no other aerodynamic surfaces that can take advantage of a cross-wind component.

Appendix 3

Instrumentation configuration

Dill-5, Dill-7, and Dill-9 are self-contained logging GPS receivers placed on the downwind cart by Bob Dill

Steve's car (stationary for all runs on 7-3-2010)
DAPS Unit #28
Wind vane with tail straight forward: 92.8 92.8 92.8

Ground station (stationary for all runs on 7-3-2010)
DAPS Unit #62
Wind vane with tail straight forward: 87.2 90.0 88.6 91.4

JB's car
DAPS Unit #7 (active chase-vehicle for all runs on 7-3-2010)
Wind vane with tail straight forward: 264.4 264.4 261.6 263.0 264.4
Avg: 263.56

Steve’s car arrived at: -117.61553071, 34.65265540
At DAPS time: 590334
At a heading of 239.5 deg (DAPS format)