Human Powered Flight, what can the Past tell us about the Future

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Monday the 18th January 2016 at the RAeS

We want to know how accurate our design calculations for light low speed aircraft are and also if there are places on the speed-power map for all aircraft that give a desirable combination of low power combined with manoeuvrability.

When Gossamer Condor won the Kremer figure of eight prize in 1977 no practical CFD codes existed for the design of low Reynolds number airfoils or aircraft and Larrabee had not yet formulated an algorithm for the design of lightly loaded propellers. It thus seems interesting to have another look at a few of the better documented aircraft to compare calculation using CFD with flight test data and pilot power estimates, in part to construct an accurate map of the design space in which these aircraft operate and in part to see if improvements future designers can exploit are possible.

Gossamer Condor

Paul MacCready produced a set of detailed engineering drawings for the Gossamer Condor which the author redrew from a set in the HPFG archive. (These are available online.) So it was possible to use these to produce a 3 view drawing and hence measure all the bracing wire lengths and angles in order to calculate the total wire drag. (Cda = 0.196) And since a drawing for the propeller existed it was possible to calculate the propeller efficiency using XROTOR and found it close to 80%.

The approach adopted was to use several CFD codes and a lifting line model with the method of images to model ground effect and then put the resulting drag polar into a spreadsheet. Wing Cdo (profile drag) could then be degraded to allow for poor surface accuracy and wrinkled covering, bracing wire, king post, diamond post, bowsprit, gap and cooling drag added and the result multiplied by propeller and drive train efficiencies to produce power and specific power polars. In the case of the Gossamer Condor no flight test data exist but P. Lissamen [6] estimated the power to be between 0.3 - 0.35 hp, 224 - 261 W giving specific power between 3.59 and 4.19 W/kg

We also know the flight time and distance, hence airspeed, of the competition flight as follows:

Gossamer Condor Kremer figure of eight prize 23 August 1976

Pilot Bryan Allan
Take off 07.30

Flight	Time	Distance	Pilot weight	Airspeed
	min	m	kg	m/s
Kremer figure of eight prize	6:22.5	1850	62.27	4.84
Total flight time	7:27.5	2172		4.85

Shafter airport is 129 m above sea level. The air temperature was 18 degrees C, dew point 15 degrees C and pressure 1018 mb at 07.30 on 23.8.1976. These figures give an air density of 1.2103 If the met station data underestimate the temperature on the tarmac then at 21 C the density would be 1.198 and at 25 degrees C 1.18 kg/m^3 (For comparison the standard atmosphere density at sea level is 1.225 kg/m^3) These data are from a nearby weather station.

Since it was not clear how much ground effect is actually present (see later section) or how much the drag was degraded by inaccuracies and wrinkles several polars were calculated corresponding to flight at different altitudes all with 19-25% increase in profile drag and one with fully turbulent flow. These are shown in figure 1. For comparison a polar for a clean wing with no degradation in drag flying in ground effect is shown. It is clear that worthwhile improvement is possible.
Given they only just managed to make the flight these estimates seem realistic.

It is obvious that considerable performance gains are possible by cleaning up the aircraft. These could be exploited by flying at the same speed at much lower power. Given the delight the whole world had from watching the Condor fly - and an academy award for the best documentary the author feels strongly this is a nieche worth flying in.

They chose to fly faster and to cross the channel instead.

Gossamer Albatross

As above with less pessimism about the accuracy of the wing section. The vertical dashed line corresponds to the ground speed measured during the first hour long flight at Harper dry lake and to the calculated still air flight time for the channel crossing. The flight test power polar is from Fig 2-2, Ref. 5

Daedalus 88

It was assumed the aircraft was clean and only a few percent were added to the drag. Drag was calculated at three heights corresponding to those in [9]. And flying out of ground effect. The circles are flight test data from the NASA report. They say that during some flights they encountered lift and the power dropped to zero. This probably accounts for some of the low experimental values.

Mowe 13

The data and drawings for this are from: Nomura [9.] Three points are shown in the plot corresponding to data taken from their flight tests.

Airglow

Polars are calculated at three different weights. What the author thought it weighed and what it actually weighed at Lasham in 2015.

Betterfly

This is where the author started. He had drawn the plan from measurement and photographs taken at Lasham and from notes, calculations and photographs provided by David

Barford and Chris Roper. Then he thought it would be helpful and interesting to add the power polar to the plan. The calculations became quickly more elaborate and detailed in an effort to achieve accuracy and to search for improvements.
Betterfly is interesting because it has nice controllability. Two pilots learned to fly in it, both going solo on their first flights and neither crashing.
The power is high but can be drastically reduced my reducing the weight. The good news being that this should be easy simply by replacing the velair derived structure with an entirely wire braced structure constructed from smaller lighter tubes and by carefully minimising the weights of details.

Daedalus flight test and the effects of atmospheric turbulence on drag

Sullivan and Zerweckh [9] observed an inverse ground effect during flight tests of the Daedalus 88 and make the following observations and suggestions regarding the cause of this.

"There is some subjective data that also supports this theory. When Kanellos Kanellopoulos flew the Daedalus aircraft from Crete to Santorini, Greece, he observed that when flying at 12 meters (39 ft), the required power was less than when flying closer to the surface of the water. Also, during the crossing of the English Channel by the Gossamer Albatross, Bryan Allen was almost forced to abort the flight due to the high power required when flying at an altitude of 1.5 meters (5ft), However when he increased his altitude to 4.5 meters (15 ft), he found that the required power decreased and he was thus able to complete the flight [9]. Although most of the upper surface of the Albatross wing was probably turbulent (judging from the particular air foil on the Albatross), it is possible that the atmospheric turbulence during Alien's flight was of sufficient intensity to trip the laminar boundary layer on the bottom surface of the wing. This could explain the higher power at the lower altitude." [ref. 9 p76]

And *"The data from sections of Flights 307D and 307E (see Table 4-2) have not been plotted in Figure 4-21 due to the widely varying power estimates. The decision to ignore these results was made only after carefully examining the time histories of the energy input., the altitude, the airspeed, the rudder deflections, and the sideslip angles. Flights 307D and 307E were the last flights performed on the day the power measurements were made; as a result, they may have been performed during a time of increased thermal, activity and therefore greater turbulence. This increase in turbulence has been observed to start quite abruptly on Edwards Dry Lake bed and to wary considerably from location to location on the lake bed. This second effect has been attributed to the damp condition of the lake bed, a result of the frequent rains. The damper portions tended to be darker and therefore tended to exhibit greater thermal effects; furthermore, the water vapour rising off the damper portions also tended to create vertical air movements. The effect of these air movements can be seen in the data from these two flights (see Appendix C for the raw data from Flights 307D and 307E). In Figure 4-22, the energy time history for Flight 307D shows that the power input is very inconsistent; data from previous flights exhibited a much more linear behaviour. It is clear that between 80 and 100 seconds, the power required to fly the aircraft is nearly zero, as indicated by the nearly horizontal slope. This event is also accompanied by a rapid increase in altitude. Consequently, it appears that the aircraft was flying through a upward moving thermal. However, after the aircraft leaves this thermal, the associated sink is encountered, thereby increasing the power required to fly the aircraft. This explains the high power estimate for the first section of Flight 307D. Because of these disturbances, this data point was deleted from Figure 4-21. The power estimate for the second section of this flight is not unreasonable; however, the thermal effects clearly cause abrupt changes in the slope of the energy time history. These effects raise doubt as to the accuracy of the power estimate made during this time; as a result, this estimate has also been deleted from Figure 4-21. Similarly, data from Flight 307E appears to be significantly distorted by thermal effects as demonstrated by the short term changes in the slope of the energy plot and by the poor fit in the energy error plot (Figure 4-23). To demonstrate these effects, the data from this fright have been evaluated over nine separate intervals (Table 4-2). This analysis shows that the power drops significantly as the aircraft gains altitude and increases greatly when altitude is lost; however, the decrease in power with altitude is too large to be explained by the inverse ground effect theory. This implies that strong air currents are being generated that cause the aircraft to gain and lose altitude. The lower power estimates occur during periods of updrafts; the higher power estimates occur during periods of downdrafts."* [ref. 9 p83]

While this seems plausible the author wonders if in the case of Gossamer Albatross the aircraft was flying through some wave like structure in the flow over the water. Even in calm conditions there is usually a swell running that is not obvious in photographs which the wind must blow over. The resulting flow field will depend on the relative angle and velocity of the wind to the swell and to amplitude and wavelength of the swell. The author speculates this will impose a span wise unsteady load distribution on the wing that will increase the induced drag.

It is known from flow visualisation of the DAE 1335 section used on the MLE that the wing had the extensive laminar flow predicted by XFOIL: "After it was towed to altitude without the propeller. Flow visualisation tests were performed by applying a mixture of kerosene and black powder dye to the wing at various span wise locations and towing the aircraft at one airspeed for several minutes. The high shear stress of turbulent flow caused the powder dye to flow into a streaked and mottled pattern, while in laminar regions the powder remained in the same smooth, featureless layer as at the time of application. Although the kerosene did not evaporate completely in flight, the powder dye pattern persisted for a sufficiently long time after landing to permit its measurement and photography. Three tests were performed at lift coefficients of 1.04, 1.20, and 1.40. Photographs of the flow patterns on the upper wing surface of the $C_l = 1.04$ test are shown in Fig. 13. The bottom surface of the wing was found to be fully laminar at all operating lift coefficients as expected." [Drela ref. 3]

R. Lean has also confirmed this with wind tunnel tests of a full size piece of wing in the Gastor and Markham wind tunnels at Cambridge.

The author suggests investigation of these effects using a microphone and solid state sound recorder to listen for turbulence on the lower surface of an HPA flying in various conditions.

R. Lean observed to the author that ground effect is predicted by inviscid theory and though there is extensive flight test data confirming its existence for heavily loaded (by HPA standards) aircraft it may not always be present for a very lightly loaded slow flying aircraft. He suggests using smoke to flow vis the trailing vortex sheet of some HPAs.

It should be added to this speculation that comparison of flight test data with the calculations performed here clearly show that ground effect must be present at least some of the time for HPAs.

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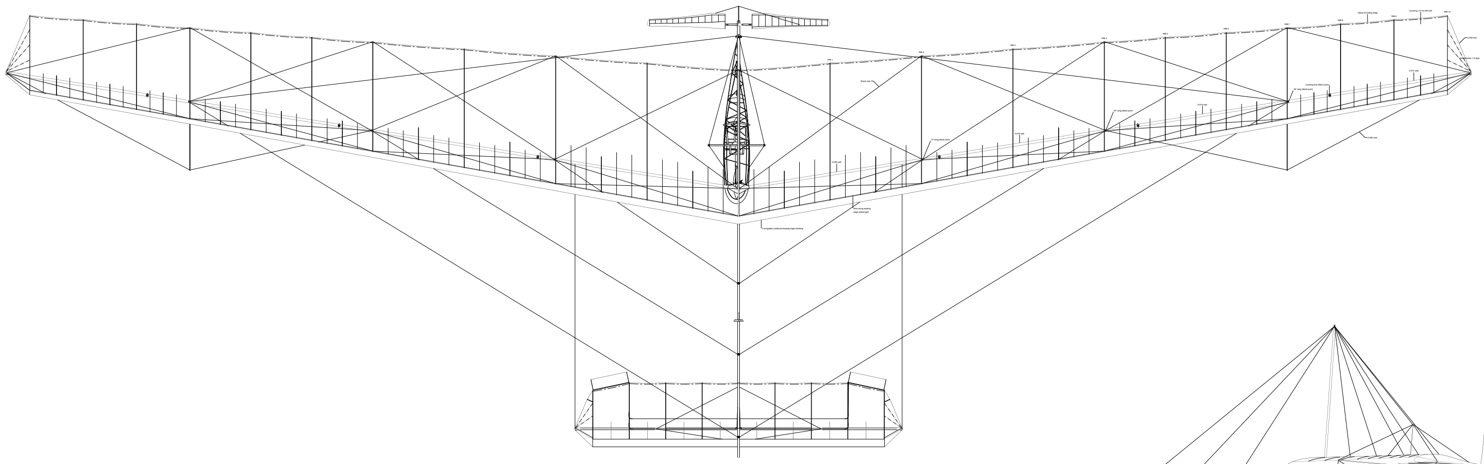
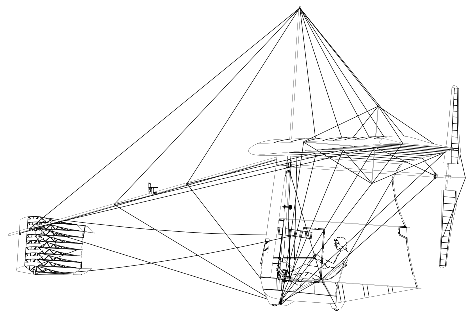
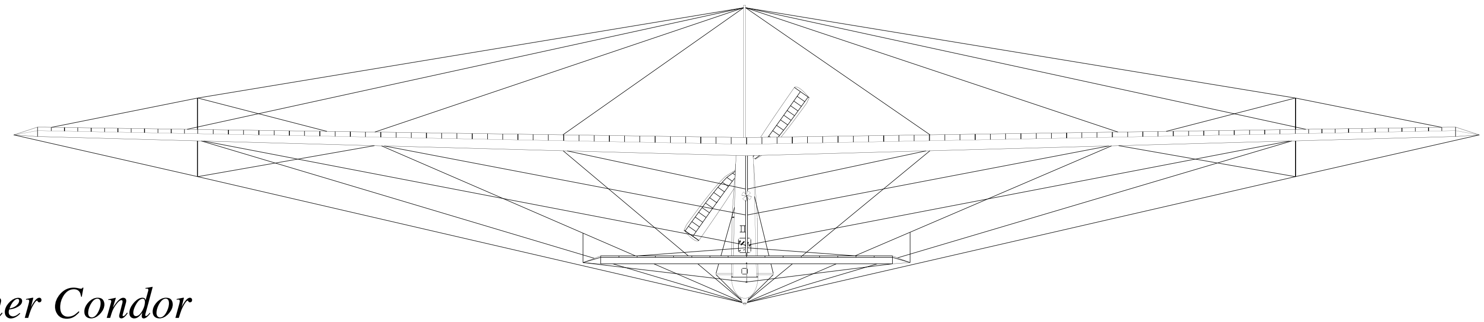
Gossamer Condor flown by Bryan Allan
Picture Don Monro from the RAeS archive

Gossamer Condor Crew

Bryan Allen
Bill Bueby
Jim Burke
Lin Burke
Sam Duran
Phil Esdale
Henry Jex
Jack Kyle
John Lake
Jack Lambie
Karen Lambie
Kirk Leonard
Peter Lissaman
Judy MacCready
Marshall MacCready
Parker MacCready
Paul MacCready
Tyler MacCready
Joe Mastropaolo
Paul McKibben
Greg Miller
Vern Oldershaw
Maude Oldershaw
Bill Richardson
Dave Saks







Gossamer Condor

On 23rd August, in ideal conditions with a windspeed of less than 2 knots, Bryan Allen made one of his typical 30ft take-off runs toward the north pylon on Shafter Airport runway. After a 500ft cruise it was all systems 'go' as Bryan cleared the Tee bar on the start line and observer Bill Richardson, a long experienced aviator who was appointed to authorise any claim, clicked his stopwatch. Bryan was soon into the first, right turn after 250 more feet and he made a 425ft diameter 180 degree sweep around the marker to head for the south pylon, 2,640ft away. It was a smooth cruise of almost three min-utes, then another sweeping left turn to re-trace his course back north-wards. As he neared the original take-off point, eager followers yelled encouragement and with one last effort Bryan took the Condor over the Tee bar to finish at precisely 6:22.5. He had traced an almost perfect figure eight, the flightpaths were a mere 9ft 7in. apart on the start/finish line
Jack Lambie

Kremer figure of eight prize 23rd August 1977 at Shafter Airport
Take off 07.30
Time to fly the course 6:22.5
Distance flown round course 1850
Airspeed 4.83 m/s
Total flight time 7:30
Total distance flown 2172 m

Aircraft data

Span 29.28 m
Wing area 66.3 square meters
Aircraft mass 31.8 kg
Pilot mass 62.27 kg
Gear ratio 1.19
62 teeth at cranks
52 teeth at shaft
Cadance 90 rpm
Propeller 107 rpm

SCALE m

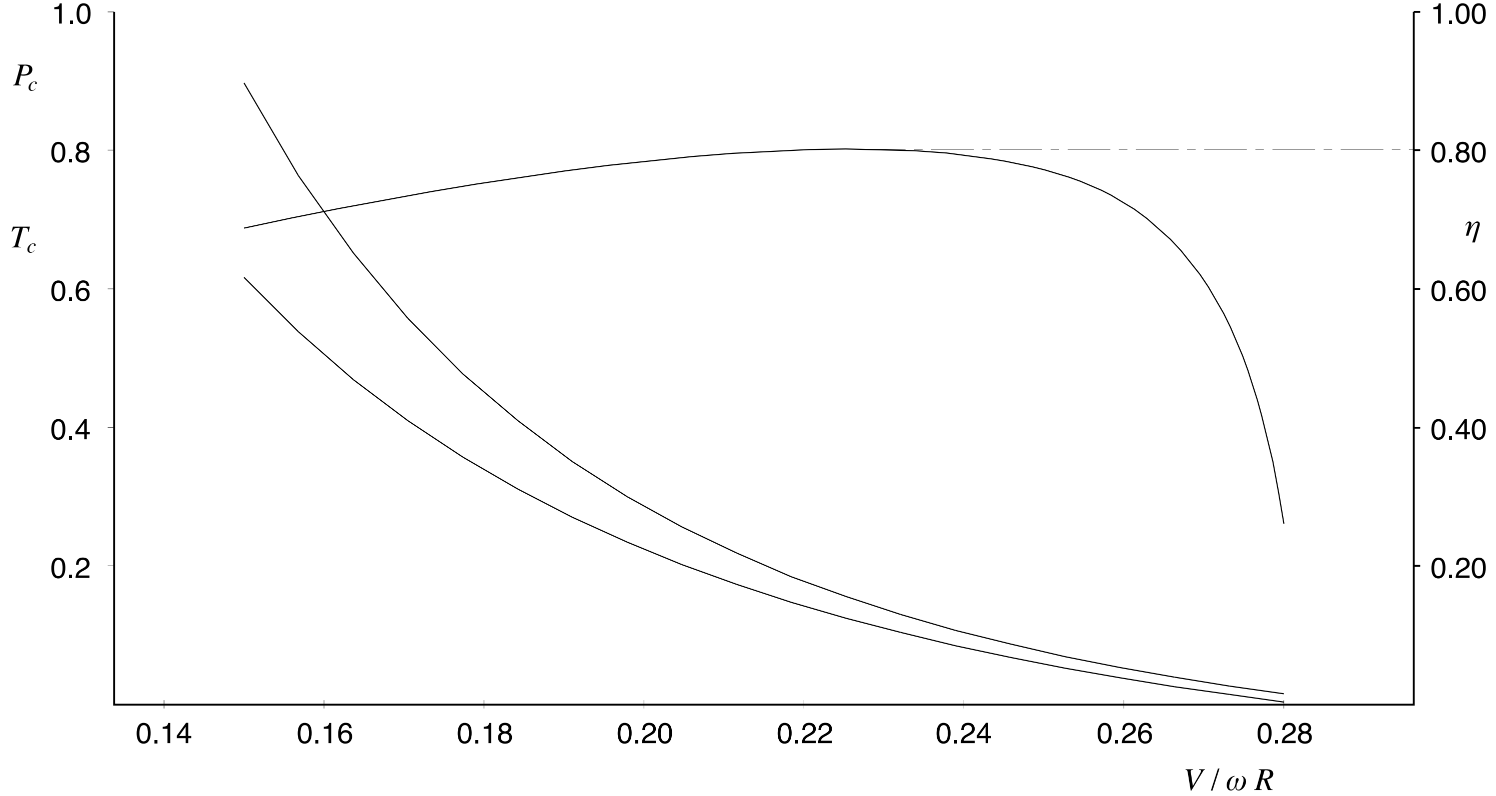
0 0.5 1.0 2.0 3.0 4.0 5.0 6.0 7.0 8.0 9.0 10.0

SCALE 1:32

Wire drag area								
Wire	No.	length	diameter	diameter	Wire Cd	angle	Cd corrected	Cda
	both sides	m	inch	mm			for wire angle	
inner lift	2	4.74	0.028	0.711	1.18	90	1.180	0.008
mid lift	2	7.90	0.022	0.559	1.18	90	1.180	0.010
outer lift	2	11.28	0.031	0.787	1.18	90	1.180	0.021
outer lift to diamon	2	11.28	0.031	0.787	1.18	90	1.180	0.021
warp	2	11.28	0.022	0.559	1.18	90	1.180	0.015
inner landing	2	6.70	0.028	0.711	1.18	90	1.180	0.011
mid landing	2	4.85	0.022	0.559	1.18	90	1.180	0.006
outer landing	2	8.34	0.022	0.559	1.18	90	1.180	0.011
mid drag wires	2	11.96	0.022	0.559	1.18	90	1.180	0.016
diamond landing	2	7.40	0.022	0.559	1.18	90	1.180	0.010
diamond lift	2	7.40	0.022	0.559	1.18	90	1.180	0.010
drag / bowsprit inn	2	4.38	0.022	0.559	1.18	55.9	0.670	0.003
drag / bowsprit mi	2	8.77	0.022	0.559	1.18	55.7	0.665	0.007
drag / bowsprit ou	2	12.74	0.022	0.559	1.18	58.6	0.734	0.010
drag diamond	2	5.31	0.022	0.559	1.18	70	0.979	0.006
prop shaft to 36’ a	2	11.28	0.022	0.559	1.18	90	1.180	0.015
prop shaft to seat	2	3	0.022	0.559	1.18	90	1.180	0.004
prop shaft to king	1	4.19	0.022	0.559	1.18	48.3	0.491	0.001
canard lift wire	1	6.8	0.022	0.559	1.18	90	1.180	0.004
king post / bowspr	1	4.13	0.022	0.559	1.18	61.5	0.801	0.002
king post / bowspr	1	5.82	0.022	0.559	1.18	47.9	0.482	0.002
king post / bowspr	1	6.88	0.022	0.559	1.18	43.3	0.381	0.001
bowsprit inner lift	1	2.37	0.022	0.559	1.18	47	0.462	0.001
bowsprit mid lift	1	3.90	0.022	0.559	1.18	21.2	0.056	0.000
bowsprit outer lift	1	4.80	0.022	0.559	1.18	13.2	0.014	0.000
drag diamond upp	2	3.20	0.022	0.559	1.18	29.2	0.137	0.000
drag diamond lowe	2	3.20	0.022	0.559	1.18	29.2	0.137	0.000
								0.196

Calculation of wire drag for Gossamer Condors using a spreadsheet

Gossamer Condor Propeller
Power 250 W
Airspeed 4.77 m/s
107 rpm
Blade twist at tip 17.8°
Advance ratio 0.2376



Calculation of Gossamer Condors propeller efficiency, using the drawings from Paul MacCready’s plans set and XROTOR

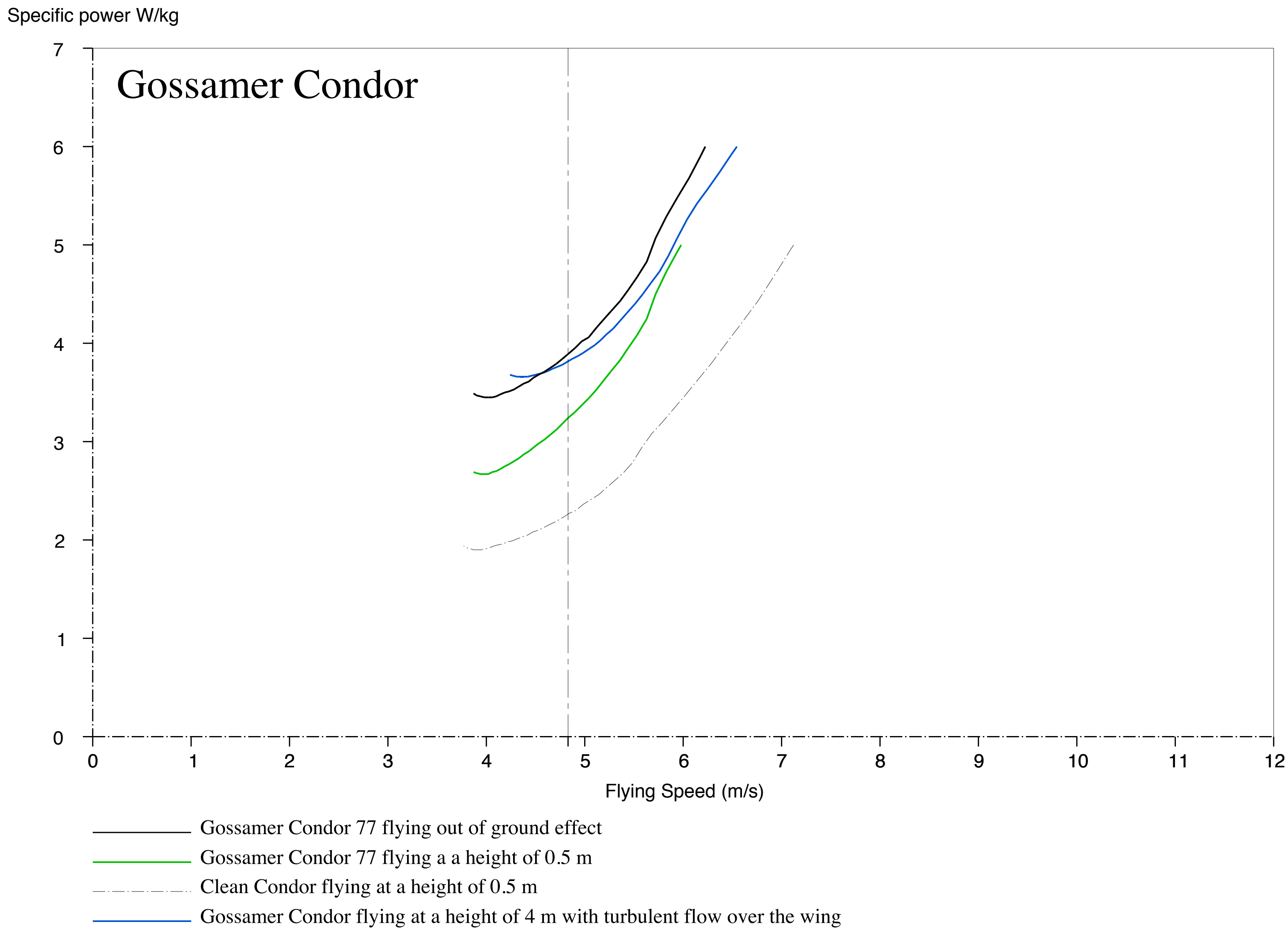
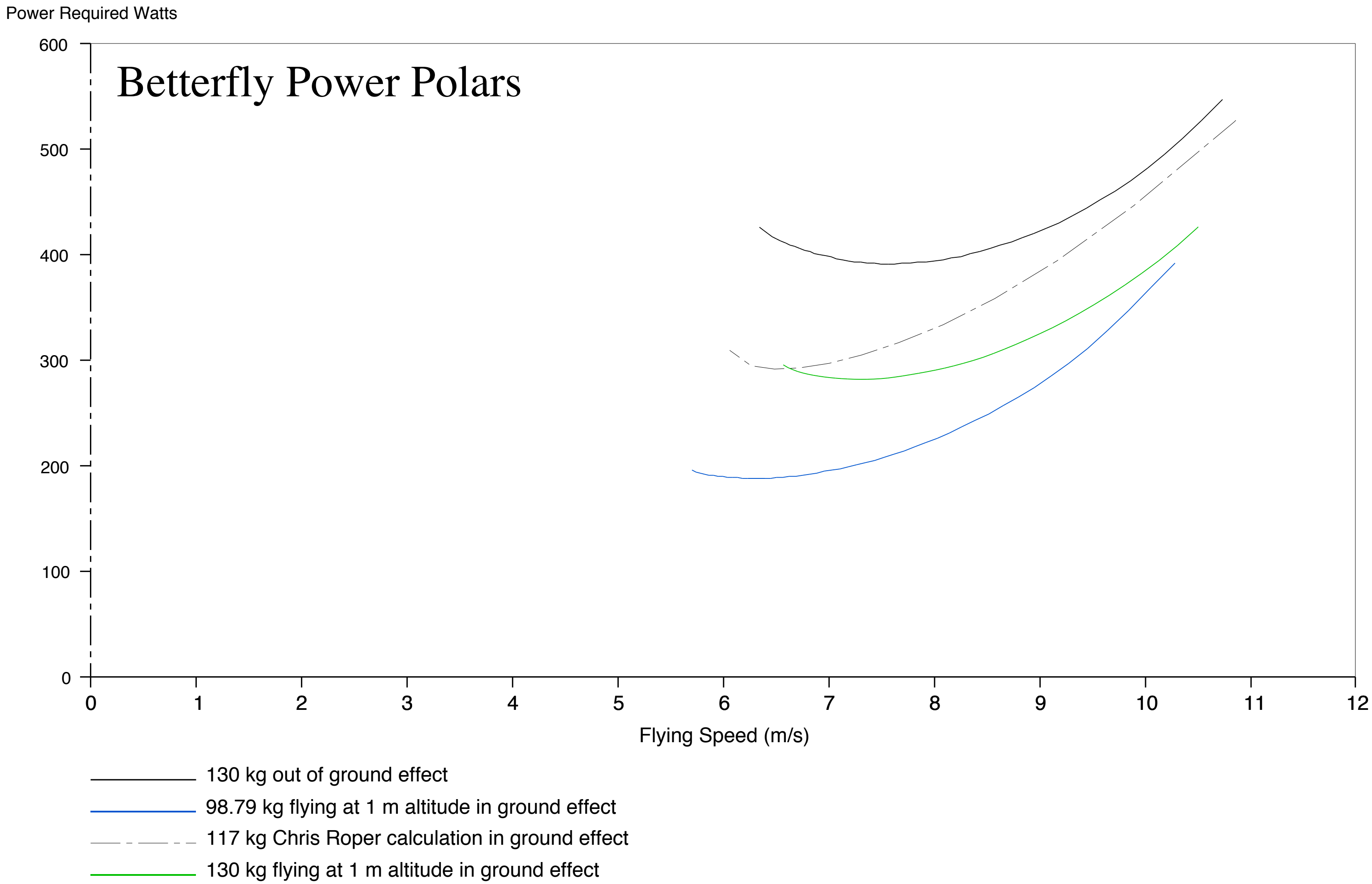


Figure 1. Calculated power polars for Gossamer Condor for several assumptions.

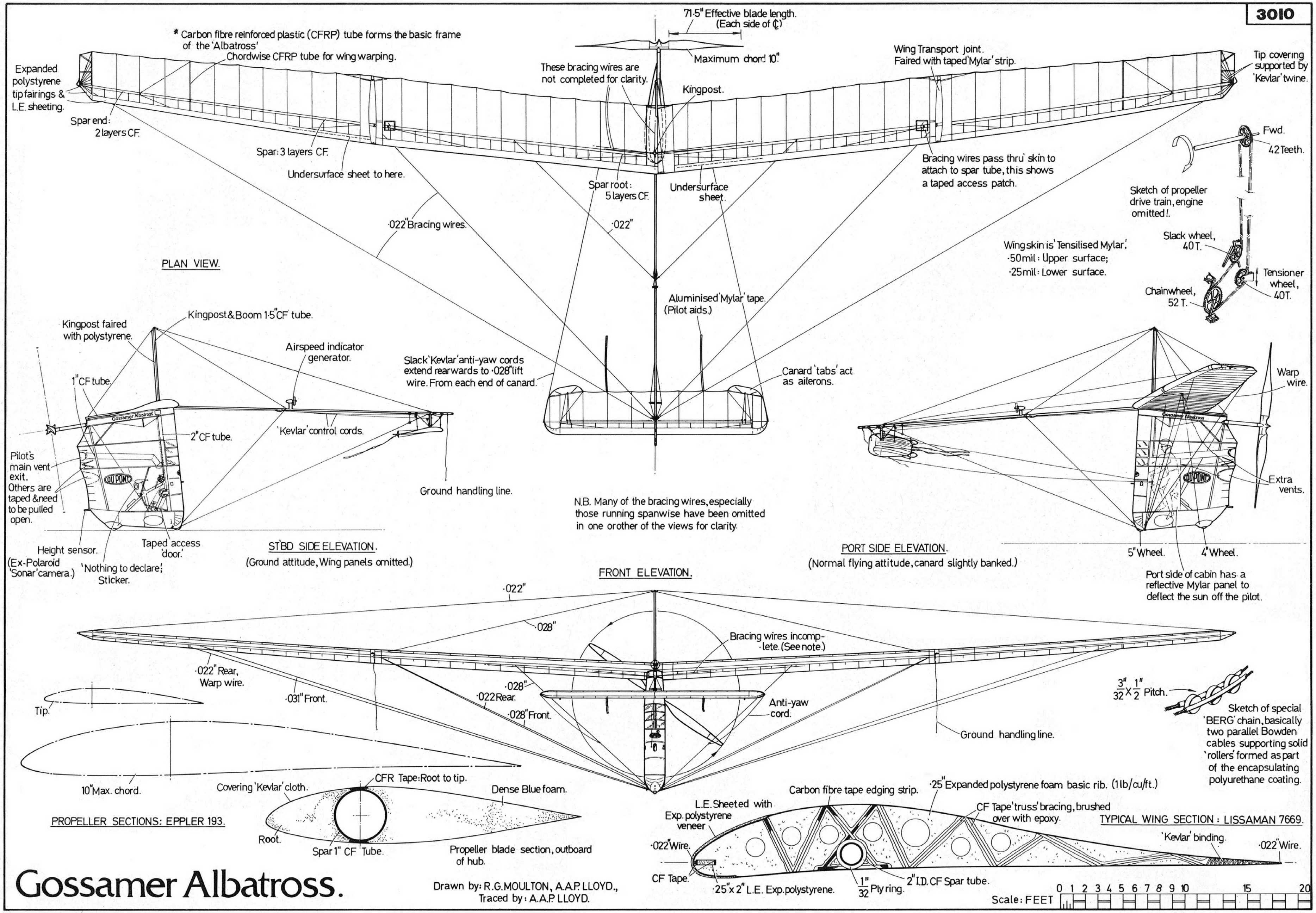
Betterfly at Sywell
Photo Ian Johnson

Betterfly takes off at Sywell
Photo R. Young

Betterfly being test flown by Bill Brooks at Kemble



Calculated power polars for Betterly for several assumptions.



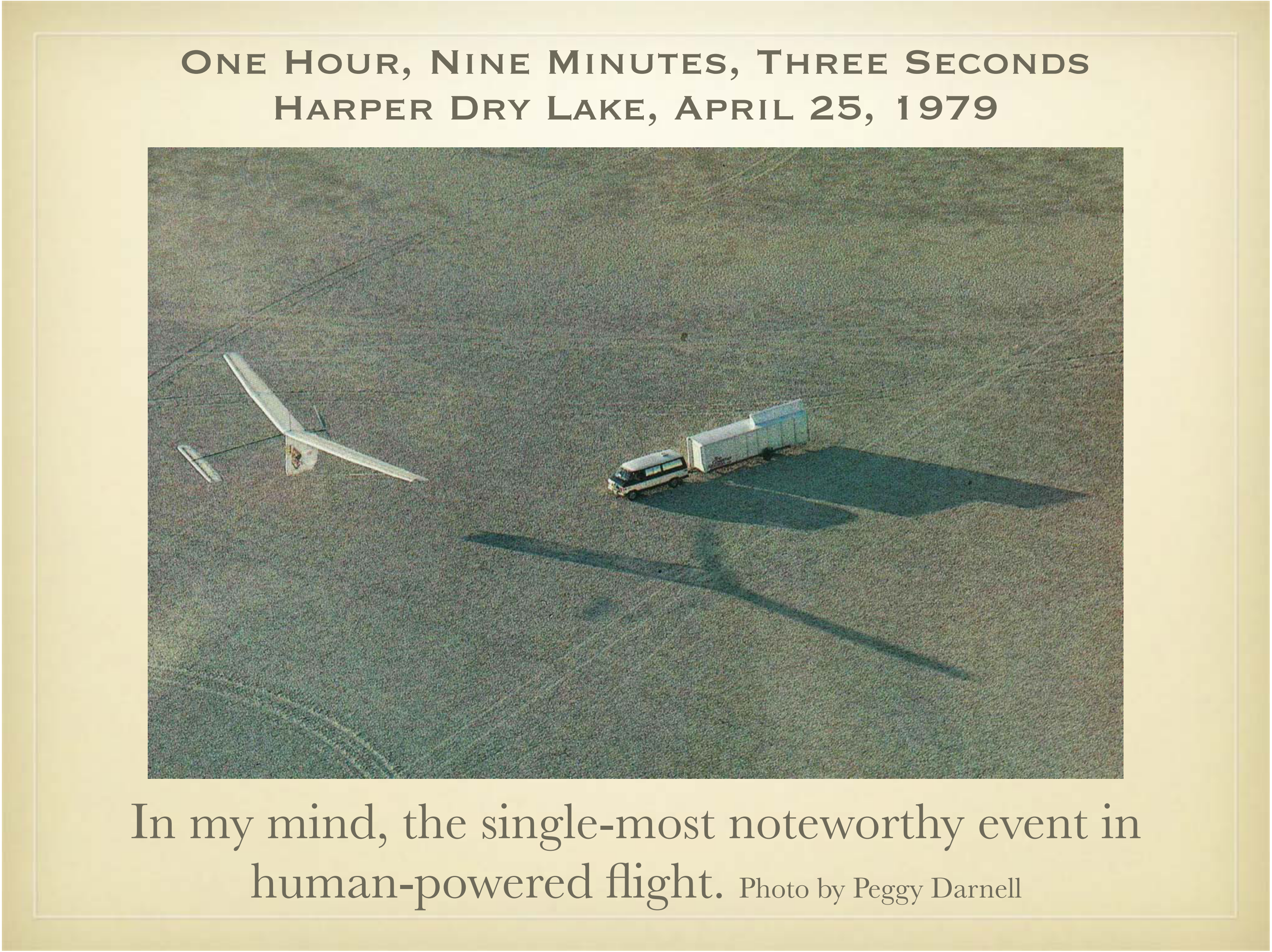
Gossamer Albatross plan. Drawing by A.A.P. Lloyd. From measurements taken at RAF Manston.

"Quick & Dirty" shows its limitations

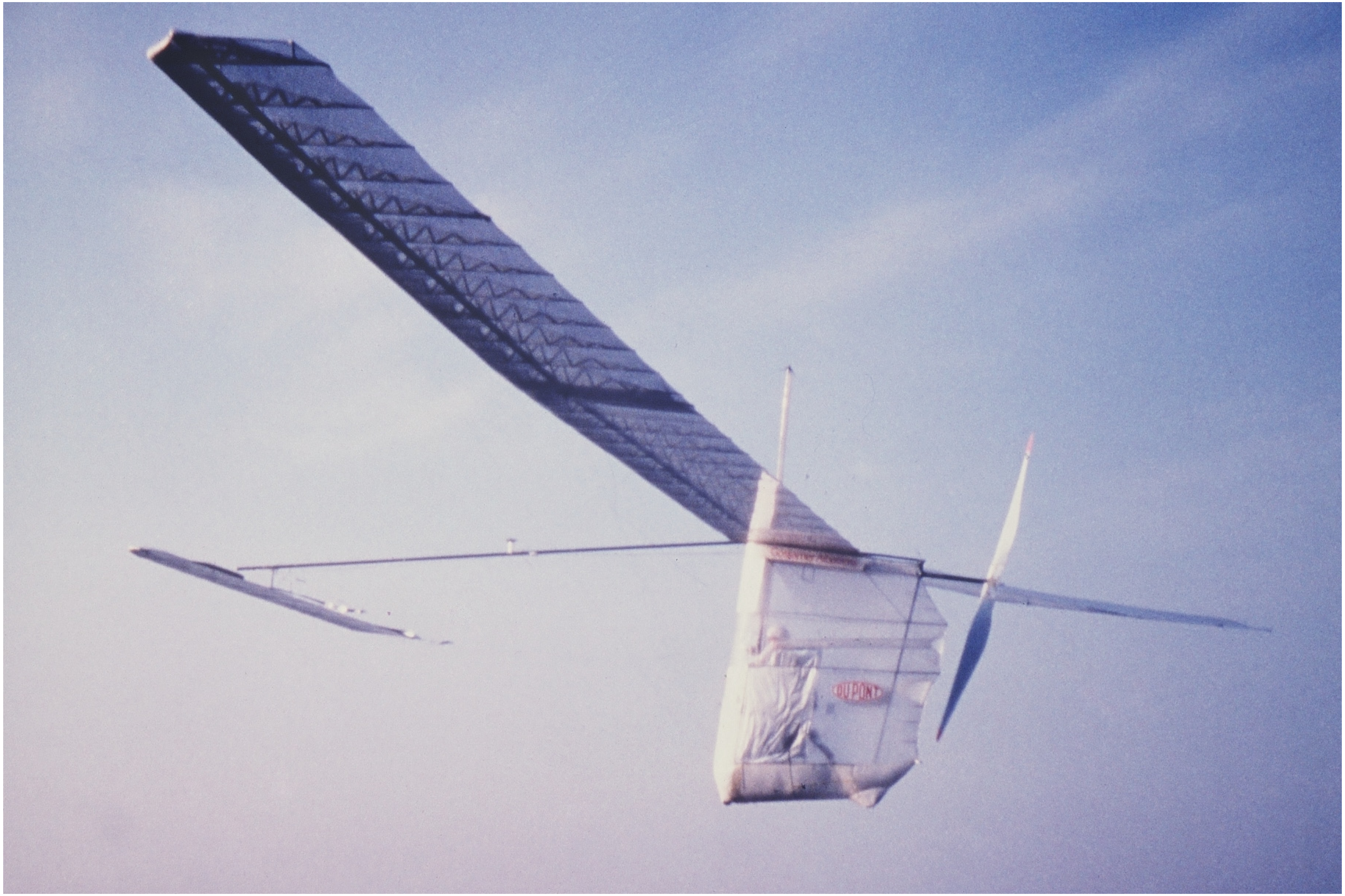
Loss of control, 1978 @ Shafter. due to control-system failure; I still have scars. Substantial structural damage from this and *five* other crashes, plus modifications made for transportability, led to this craft (GA #1) gaining **fifteen pounds** from its original fifty-five pounds

Don Monroe photo

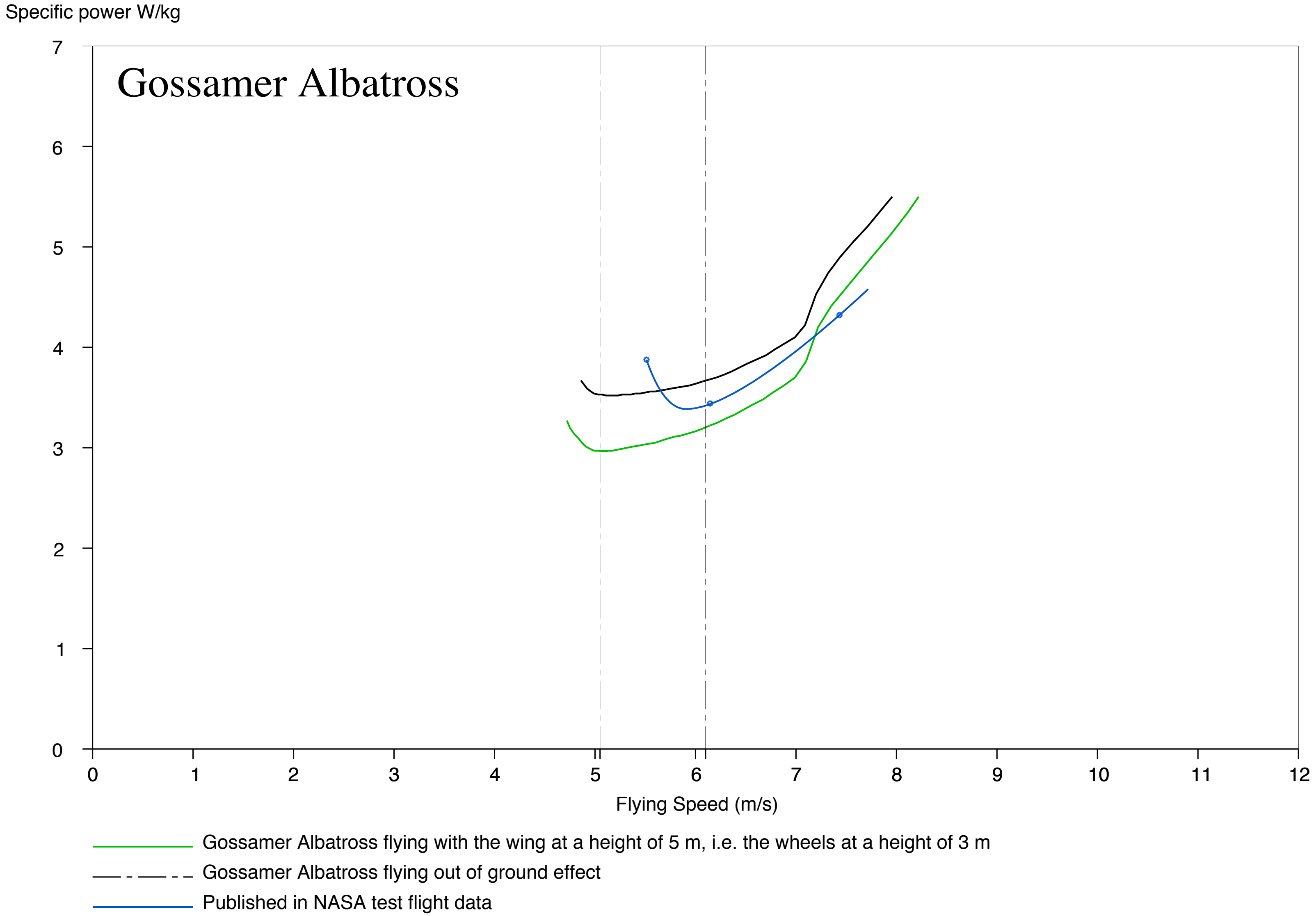
Slide from a talk given by Bryan Allan at Aerovironment's 40th Anniversary. [17]



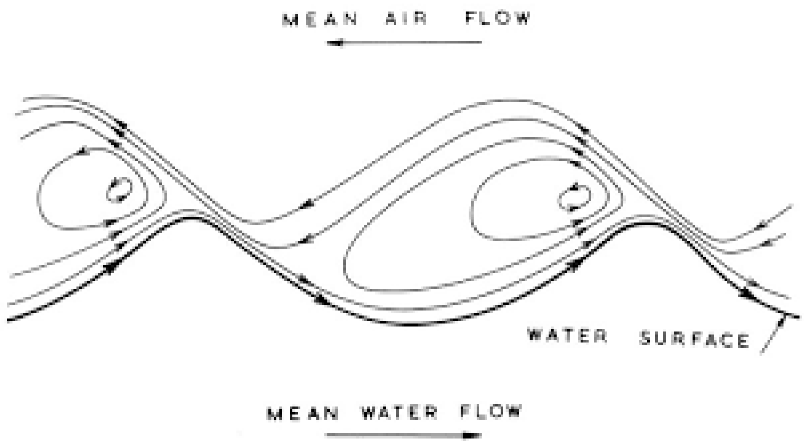
Slide from a talk given by Bryan Allan at Aerovironment’s 40th Anniversary. [17]



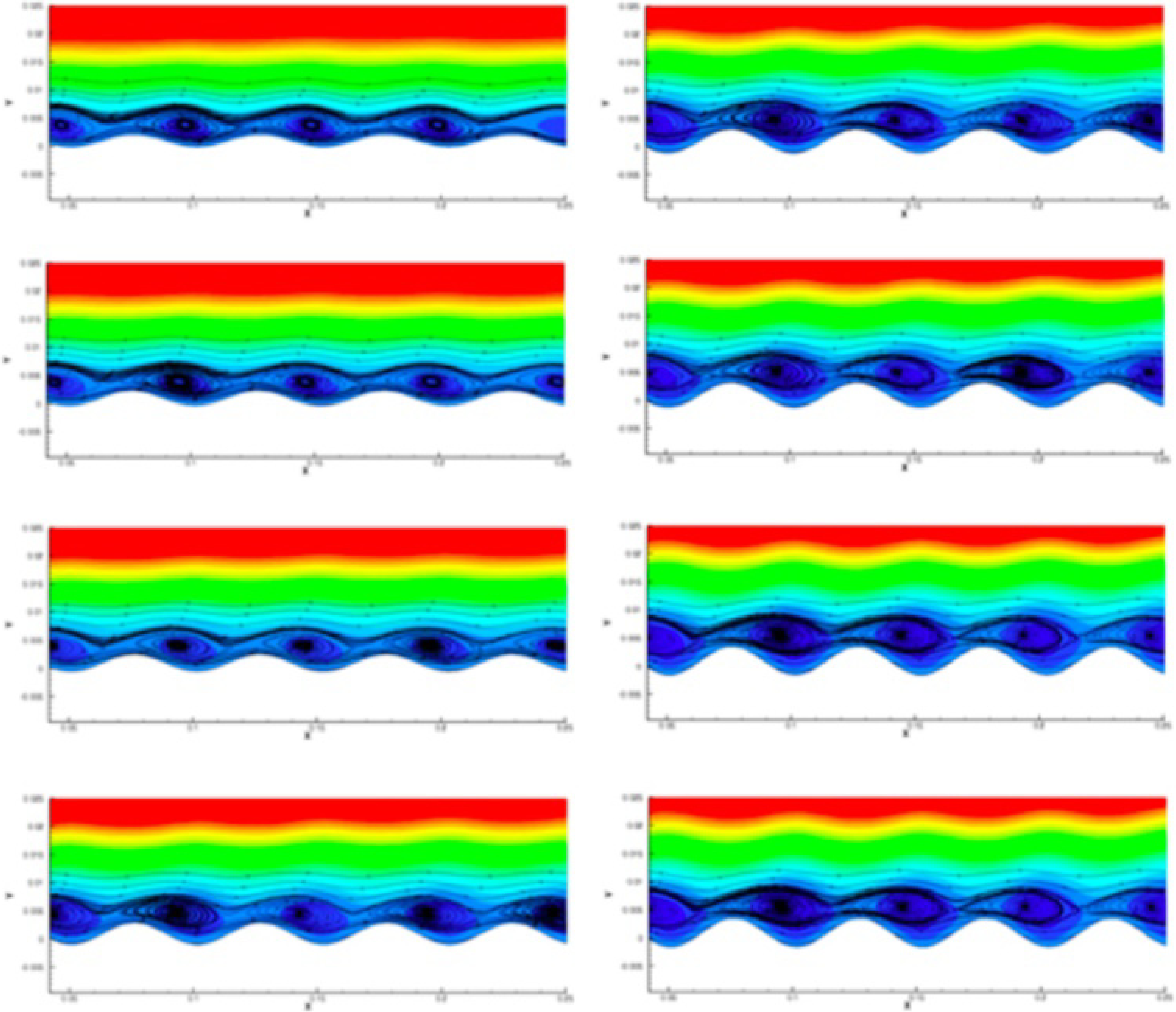
Gossamer Albatross in flight on its way to France
Photo Ron Moulton



Gossamer Albatross power polars for several assumptions.



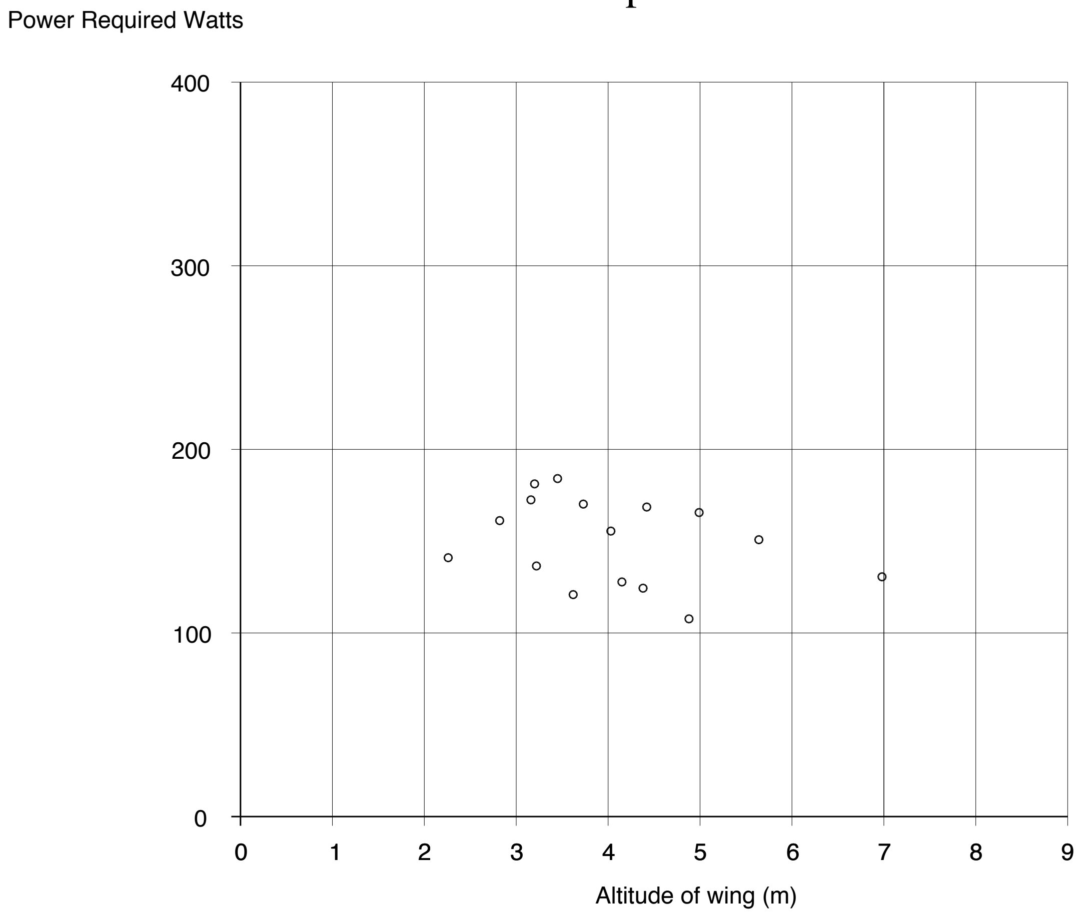
Structure of airflow over water waves.



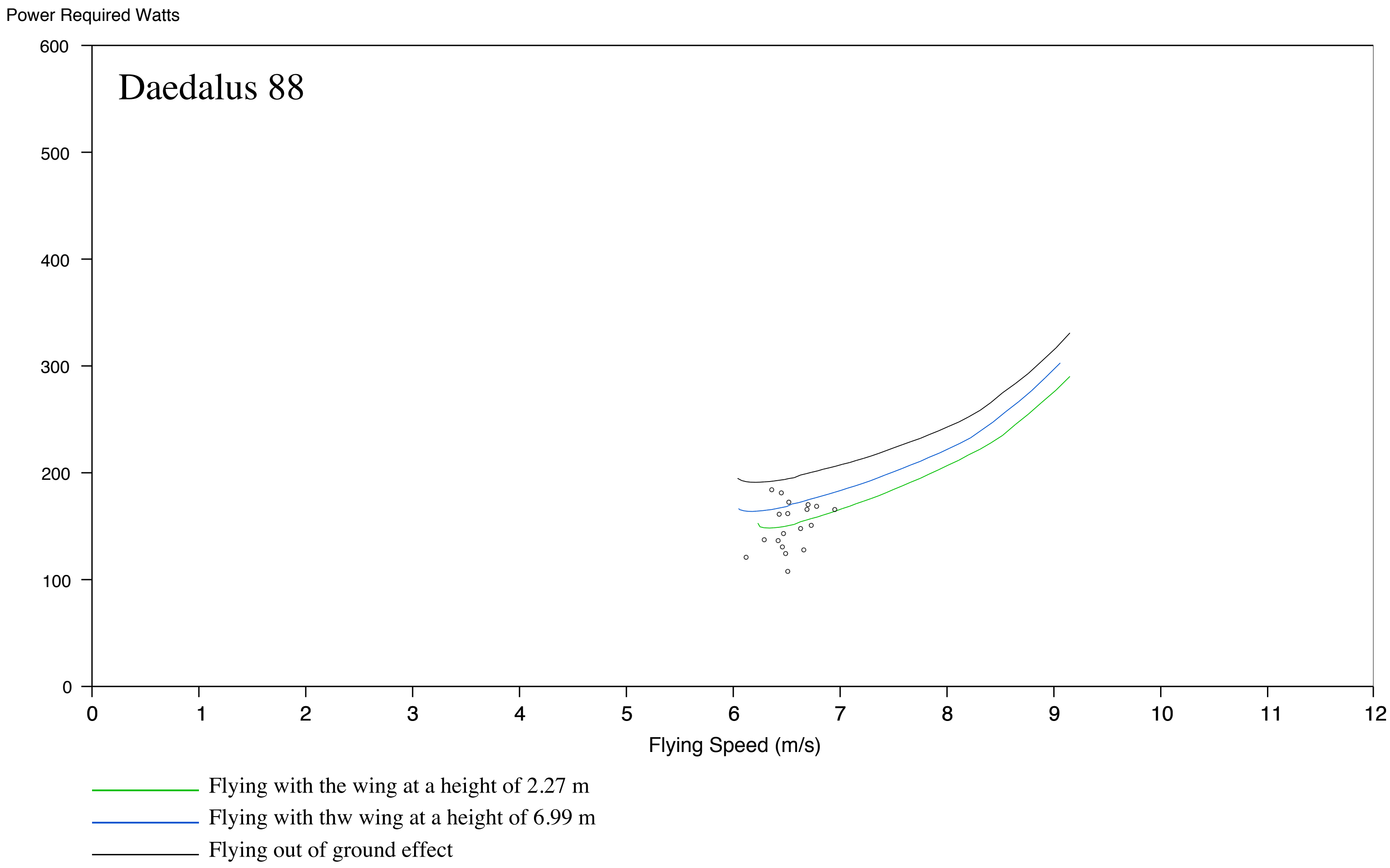
Structure of airflow over water waves, showing smoother air flow as altitude increases.
Remember that though the wind may be light there may also be a less visable long wave swell running that the wind must flow over.

Daedalus in flight on its way to Satorini
Photo J McIntyre

Daedalus 88 power verses altitude

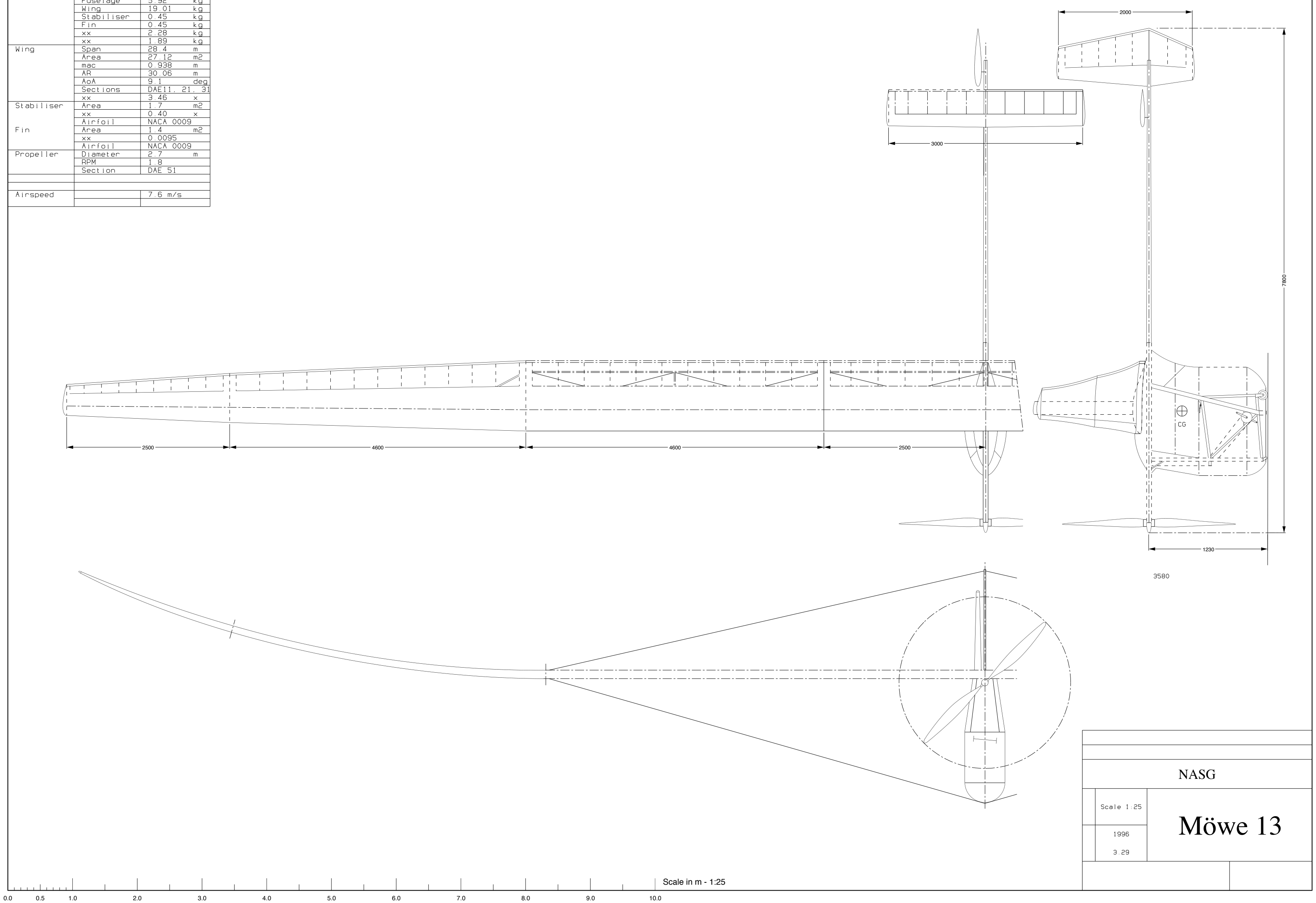


NASA flight test data marked as circles
Altitudes correspond to those given in the report
1 m/s added to reported ASI readings to compensate for calibration error
Flight test results for the Daedalus and Light Eagle human powered aircraft
R. Bryan Sullivan and Siegfried H. Zerweckh

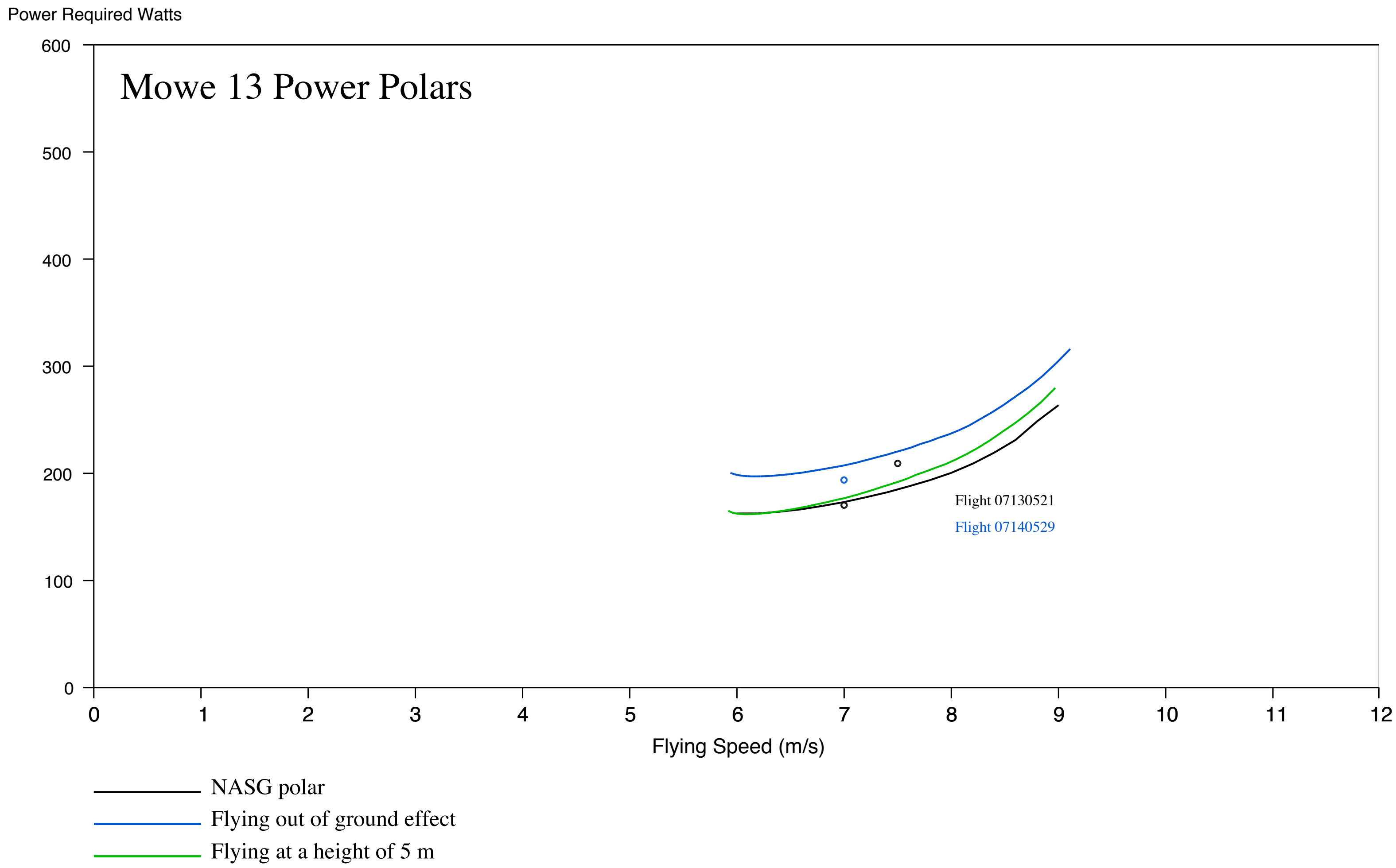


Daedalus power polars with flight test data shown as circles.

Weights	Flying	94 kg
	Aircraft	30 kg
	Fuselage	5.92 kg
	Wing	19.01 kg
	Stabiliser	0.45 kg
	Fin	0.45 kg
	xx	2.28 kg
	xx	1.89 kg
Wing	Span	28.4 m
	Area	27.12 m2
	mac	0.938 m
	AR	30.06 m
	AoA	9.1 deg
	Sections	DAE11, 21, 31
	xx	3.46 x
Stabiliser	Area	1.7 m2
	xx	0.40 x
	Airfoil	NACA 0009
Fin	Area	1.4 m2
	xx	0.0095
	Airfoil	NACA 0009
Propeller	Diameter	2.7 m
	RPM	1.8
	Section	DAE 51
Airspeed		7.6 m/s

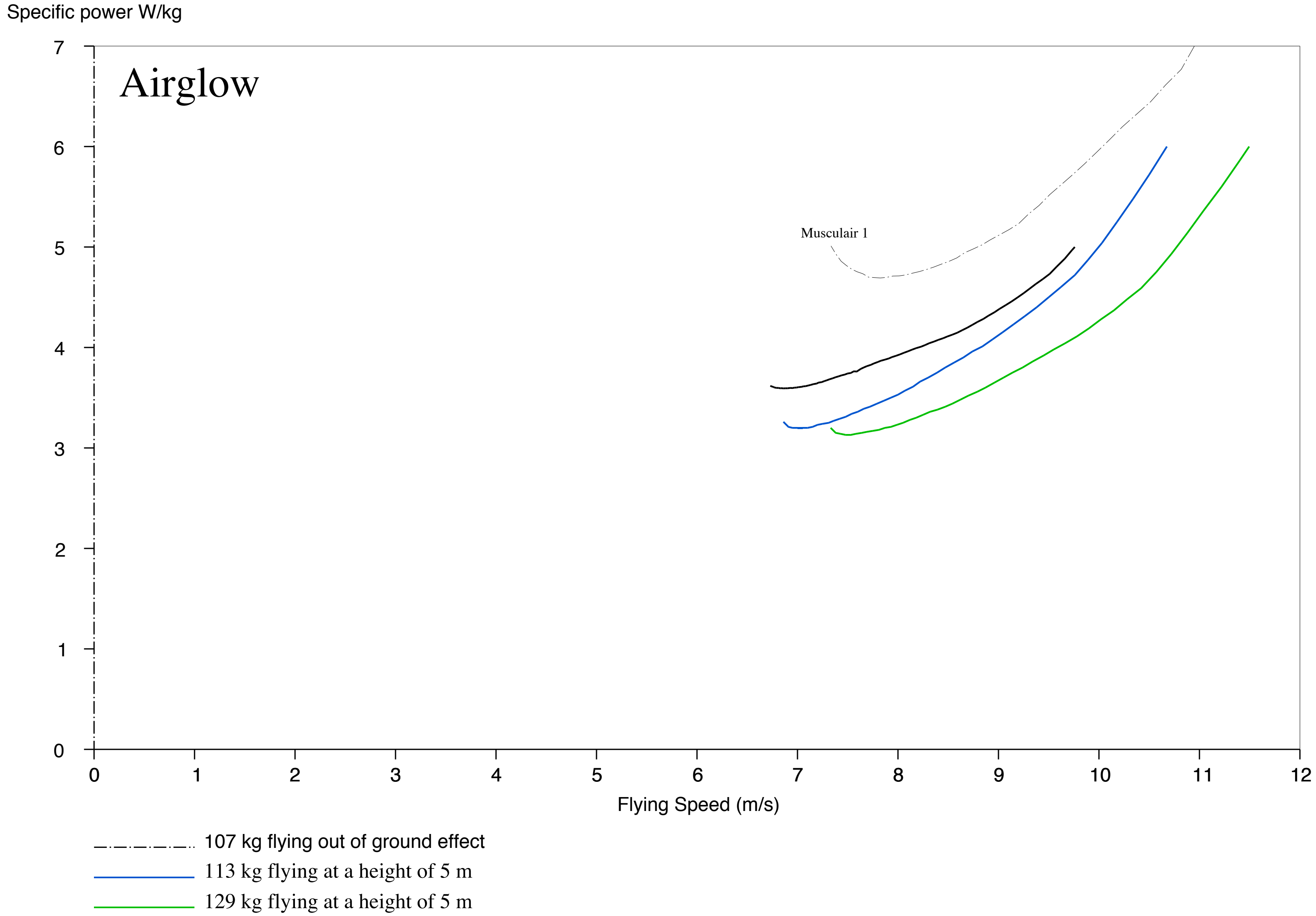


Plan for the NASG Mowe 13

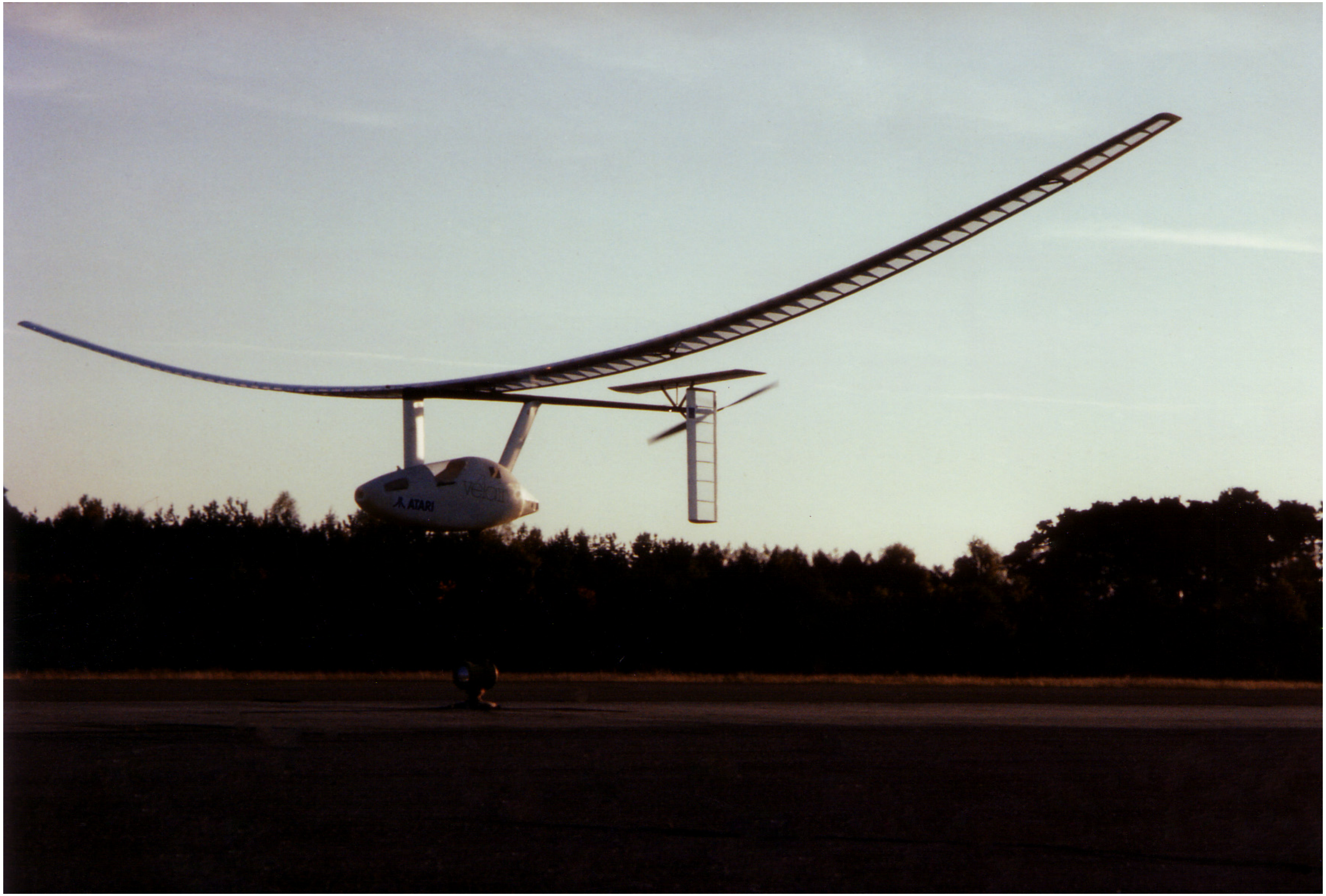


Power polars for NASG Mowe 13 with flight test data plotted as circles

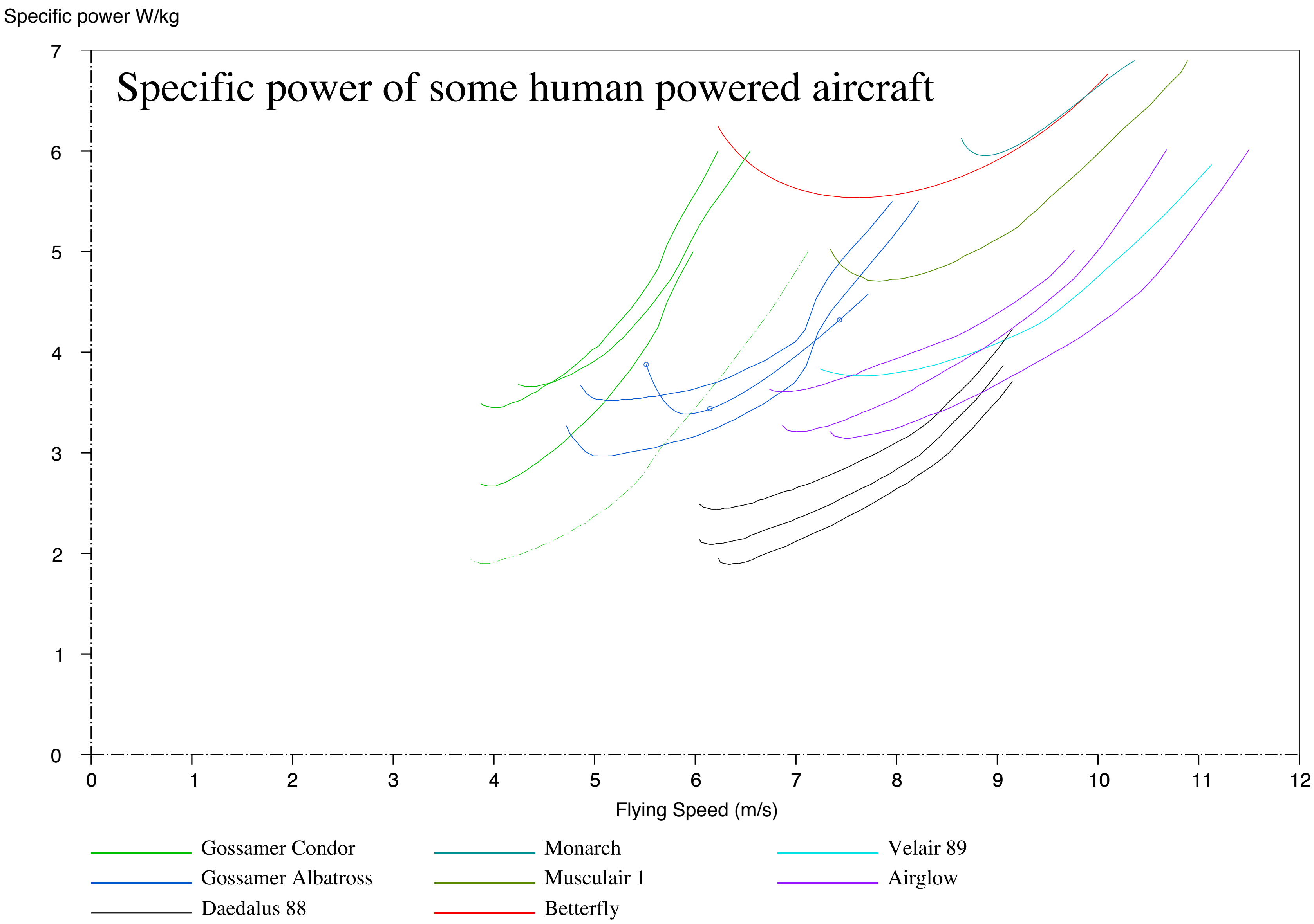
Airglow flying at Lasham.
Photo Fred To.



Power polars for Airglow for several assumptions.



Velair 89 flying



Power polars for several aircraft comparead.