Performance Testing of RNR's SBXC Using a Piccolo Autopilot

By Dan Edwards
17 September 2007
(Updated: 14 March 2008)
http://soaring.goosetechnologies.com

Figure 1: Dan Edwards' assembled RNR SBXC

Purpose:

Years ago I read an article by John Elias wherein he put a handheld GPS unit into an SBXC, did several flights, and created a sink polar for the aircraft. However, the reliability and repeatability of the data left me wanting to see more. Years passed by and I came across the means to update the testing originally done by Elias.

There are several performance parameters for gliders that are useful to know. The items I focused on are generating a sink polar, finding minimum sink speed, finding maximum L/D speed, and creating a speed to fly curve. Modelers using a system such as the Eagletree Glide can optimize their cross country soaring techniques by flying at the appropriate airspeed for the current flight conditions. Also, knowing the aircraft's sink polar will allow for a quick comparison of the SBXC to other gliders.

Introduction:

The lift over drag (L/D) ratio is an important parameter that describes gliding performance. It originally comes from the ratio of coefficient of lift over coefficient of drag (C_L/C_D); however, it can be shown to equivalently describe the distance dropped vertically for a distance flown horizontally. That is, for an L/D ratio of 25:1, the glider can travel 25 ft forward for every 1 ft dropped. The same ratio holds for speeds, since the per-time units cancel as shown in Equation 1.

$$\frac{L}{D} = \frac{dist_{horiz}}{dist_{vert}} = \frac{speed_{horiz}}{speed_{vert}} \qquad \text{(Eq. 1)}$$

To accurately measure airspeed and altitude, an air-data pitot-static probe is used that measure both total (pitot) and static pressures. Total pressure is the pressure of the freestream air that directly hits the tip of the probe due to forward velocity, whereas static pressure is the pressure measured parallel to the freestream and is independent of velocity. For more discussion about measuring airspeed, see *Anderson*. The advantage of using an air data probe is that the freestream air properties can be measured directly without being affected by the aircraft shape.

True airspeed is measured by a pitot-static probe pointed in the direction of travel. This true airspeed can be broken into its vector components as shown in Figure 1.

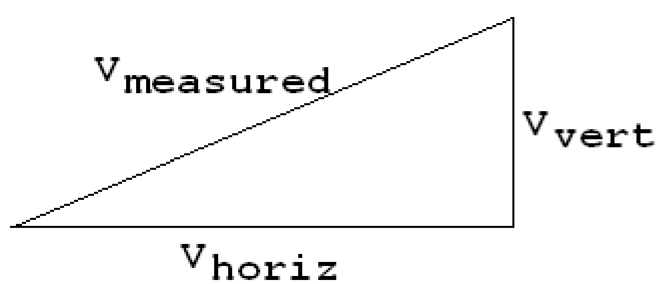

Figure 1: Measured airspeed component breakdown

From this geometrical relationship shown in Equation 2, the horizontal component can be found using the vertical and measured airspeeds.

$$V_{horiz} = \sqrt{V_{meas}^2 - V_{vert}^2} \qquad \text{(Eq. 2)}$$

Breaking the aircraft motion into vertical and horizontal speed components has another interesting relation. The sink polar is the result of plotting horizontal speed against the vertical speed (for a glider in calm air, vertical speed is negative as the aircraft descends). The trend in vertical speeds for several horizontal speeds becomes a curve, as shown in Figure 2.

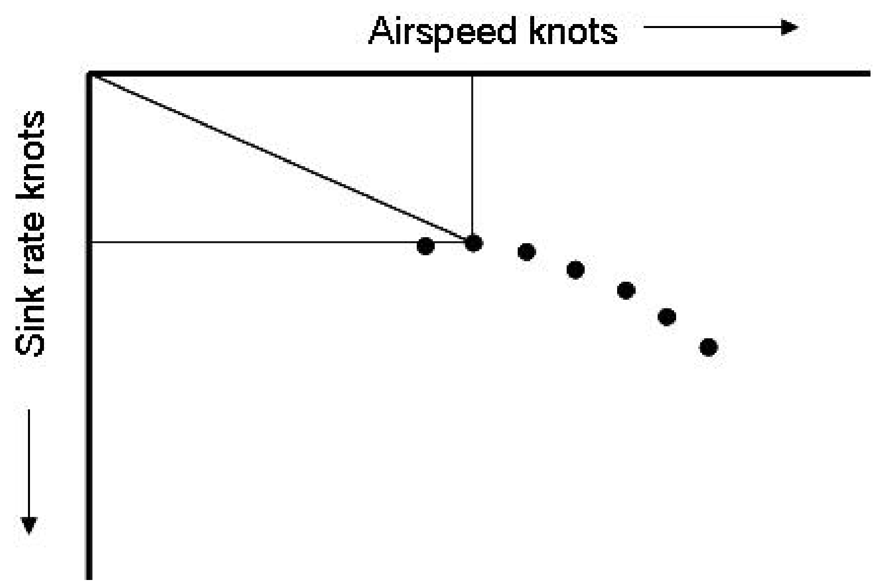

Figure 2: Construction of the Sink Polar (image from Wikipedia)

The curve shown in Figure 2 has a notable negative concavity. As the airspeed is increased, the sink rate increases. As the airspeed decreases, the sink rate increases. There is one particular location where the sink rate is at a minimum; this is known as the minimum sink speed. Different than minimum sink speed, speed for maximum L/D can be shown graphically as the line that runs through the origin and is just tangent to the sink polar. The point at which this line is tangent to the polar curve is the airspeed where the horizontal speed to vertical speed (recall this ratio is L/D) is maximized.

Reichmann suggests the sink polar can be closely approximated by a 2nd order polynomial fit. This results in a sink polar equation shown in Equation 2.

$$vel_{vert} = a * vel_{horiz}^2 + b * vel_{horiz} + c \qquad \text{(Eq 2)}$$

The sink polar also can yield more information about the glider's performance through air that is not calm. If the aircraft flies through air sinking relative to the ground reference, then the aircraft sink rate is artificially higher for that time instant. For example, if the air is sinking at 5 ft/s, then the sink polar should be shifted down 5 ft/s; equivalently, the origin can be shifted up. Recalling that the max L/D is found by drawing a tangent from the origin to the sink polar, one can see the optimum L/D speed changes depending on the local air motion. By drawing the tangents for various air vertical-speeds and plotting the max L/D speeds, a curve is produced, shown in Figure 3.

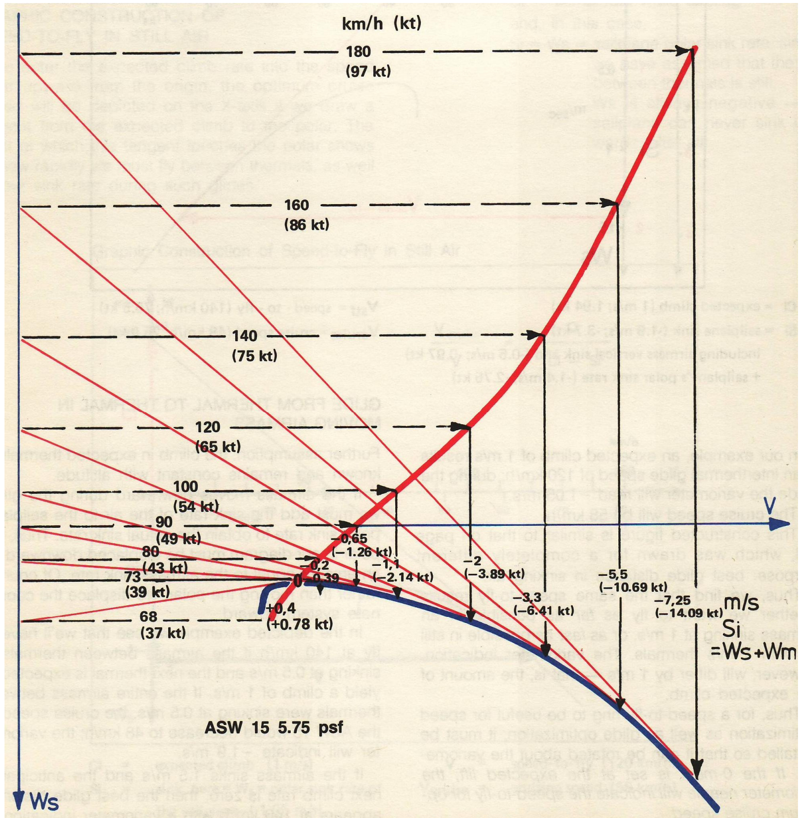

Figure 3: Locus of Speed-to-Fly points (Reichmann)

The resultant curve gives the optimum L/D airspeed to fly for a certain local airmass vertical movement. As is expected for high sink rates, the aircraft should fly a much higher airspeed than when flying in still air. Typically this method is not used for rising airmass (negative sink rates) because the difference in airspeeds between minimum sink and stall speed is very small.

Mathematically, the speed to fly for varying vertical airmass motion can be shown in Equation 3.

$$V_{stf} = \sqrt{\frac{c + airmass_{vert}}{a}} \qquad \text{(Eq. 3)}$$

Here, the *c* and *a* come from the approximated second order curve fit of the sink polar (Equation 2) and the $airmass_{vert}$ is measured.

Often model gliders carry lead ballast for allowing different performance for particular weather conditions. The resulting change in wing loading has a noticeable change in performance which is related to scaling the sink polar distance from the origin. The scaling factor is given in Equation 4.

$$\frac{weight_{ref}}{weight_{meas}} = scaling\_factor \qquad \text{(Eq 4)}$$

This factor proportionally scales both the horizontal and vertical velocities, as shown in Equations 5 and 6.

$$horiz\_vel_{ref} = \frac{horiz\_vel_{meas}}{scaling\_factor} \qquad \text{(Eq 5)}$$

$$vert\_vel_{ref} = \frac{vert\_vel_{meas}}{scaling\_factor} \qquad \text{(Eq 6)}$$

The sink polar shift for a heavier weight is shown in Figure 4. The blue line represents the original sink polar whereas the red line represents the same aircraft at a heavier-weight. The cyan lines show that the scaling is proportional to the distance from the origin.

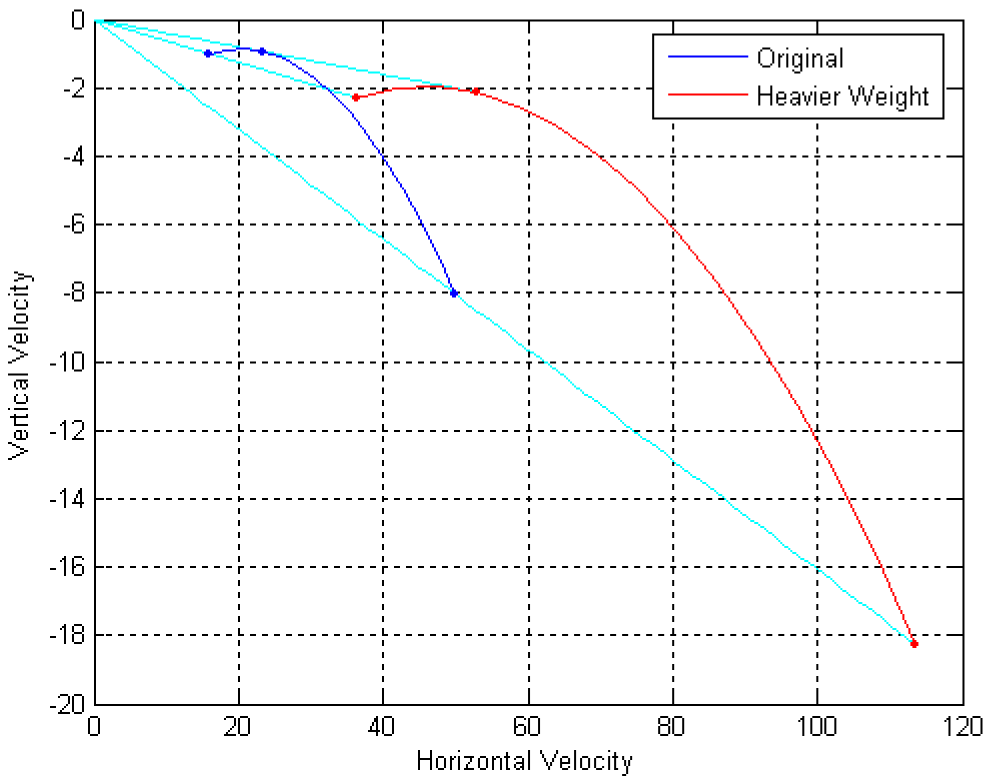

Figure 4: Sink Polar shift for weight change

It is interesting to note from Figure 4 that the shape of the curve does not change for a change in weight. That is, the maximum L/D is still the same, but the speed at which that maximum L/D is achieved has changed. Using this weight-scaling method can allow comparison of data taken on the same vehicle at different weights or be used to modify existing polars from a reference weight to actual flight weight.

Apparatus:

The SBXC is manufactured by RNR Products in Milpitas, California. The hollow molded wings are fiberglass and Rohacell foam with carbon fiber spar caps. The shear web is an end-grain balsa strip bonded in while joining the wing halves. Disassembling into four sections, the 14ft 4in wing is easily transportable in a small car. The full-flying horizontal stabilizer can be removed for transportation. However, the fuselage is still a large item. Dieter Meier has experimented cutting the aft fuselage apart for easier packing of the 6ft long fuselage, as shown in Figure 5. The main payload bay of the fuselage is rather spacious. Before servos and electronics, a two liter soda bottle fits with ease inside ahead of the wing.

Figure 5: Dieter Meier's SBXC fuselage modifications

Typical flight hardware includes six servos: one for the elevator, one for the rudder, two for the ailerons, and two for the flaps. In addition to a receiver and large capacity servo battery, many XC pilots install a variometer into the cavernous fuselage. Variometers with total-energy compensation typically need an air data probe called a TEK nozzle. The Skymelody offers a fuselage or v-tail mounted TEK nozzle, though homemade ones can be located in other areas.

The equipment used in this test is a stock SBXC airframe with four HS-422 servos, two HS-5125 aileron servos, a 9 channel JR N649 PCM receiver, a 3000mah NiMh battery, and a Skymelody variometer with the TEK nozzle tail-mount option.

An RxMux board from Reactive Technologies (see references) acts as an interface between the input source and the servos. The RxMux allows the pilot to manually control the aircraft servos or to allow a secondary source to control the aircraft servos. Here, the secondary input source is the autopilot.

To gather flight data, a Piccolo Plus autopilot from Cloud Cap Technologies has been installed just forward of the wing. The Piccolo includes a 4Hz GPS unit, air data system, and an inertial measurement unit. The sensor data is fused together with an Extended Kalman Filter for higher accuracy state estimation. The Piccolo can perform accurate airspeed hold maneuvers and can also be re-tasked to set new airspeeds, waypoints, or to tune the performance via a 900MHz serial link. With all these features combined, the data gathered here should greatly compliment the original sink polar from Elias.

All the measurement electronics are mounted inside the fuselage as shown in Figure 6. A standard TEK nozzle is mounted on the vertical tail, measuring 5 inches in length with the last 2 inches bent at approximately a 60deg down angle. A pitot-static probe is mounted 2 inches above the TEK nozzle on the tail. The probe is an 1/8 inch stainless steel tube aligned with the free-stream air flow that has both total and static ports to provide the two pressure measurements needed for airspeed and altitude. These items are assumed to have negligible drag effects compared to Elias' aircraft and are the only external changes to the stock airframe.

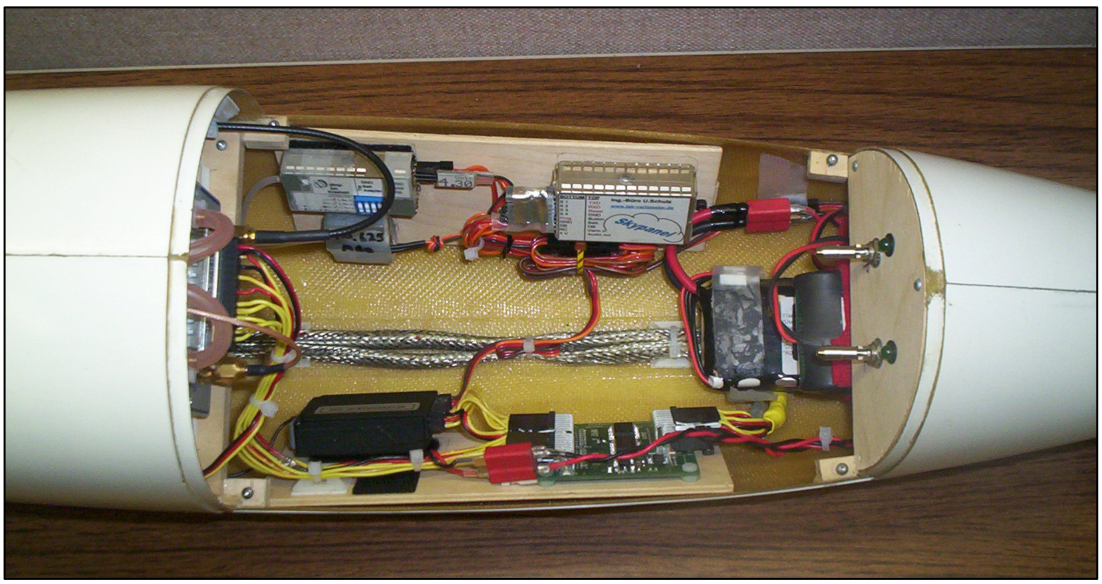

Figure 6: System Setup. Boxes CW from bottom right are:
RxMux, RC Receiver, Piccolo autopilot, Skymelody system, and batteries.

As with any UAV, safety is a primary concern. One critical safety feature of the system used is that it can be configured for redundant RF links. Also, if the autopilot communication link is lost, then an auto-return function in the Piccolo flies the aircraft to a pre-determined orbit waypoint in a safe area. Additionally, the pilot always has a manual override capability of the autopilot. All operations are carried out within visual range where the manual pilot has see-and-avoid capability equivalent to any other model aircraft.

Testing Procedure

Since the air data system measures aircraft speed relative to the oncoming free-stream (as opposed to using pure GPS ground-speed), testing could be done on days with wind. Wind was assumed to hold constant for the short duration of the data gathering for a data point. All testing was done on dead-air days and verified by listening to the Skymelody.

The vehicle weight was recorded before each flight, including a CG check and thorough range test. CG is 27.75" aft of the nose by the manufacturer's suggestion. Flying weight is 11.15 lb.

The Piccolo has been configured to record all flight parameters at 20Hz. For this testing, only the aircraft airspeed and altitude are used. The test procedure for gathering sink polar data points is as follows:

1. The glider is launched with a winch to approximately 600ft altitude.
2. The pilot "engages" the autopilot.
3. The Piccolo is commanded to assume a straight flight path across the field holding a specified airspeed (altitude hold is turned off because this vehicle does not have a motor).
4. The run is conducted for approximately 20 seconds.
5. If the Skymelody detects lift during the run, the run is scrubbed and repeated.
6. After a day of testing, the data log is downloaded from the Piccolo Operator Interface.

Results

Including the original runs from Elias minus the runs with flap camber (so all runs represent the same aircraft configuration), the data collected is shown in Table 1. The Sink Rate shown is determined by the derivative of altitude, computed by Equation 7.

$$V_{vert} = \frac{\Delta altitude}{\Delta time} \qquad \text{(Eq 7)}$$

Air Speed shown is the horizontal components of airspeed from Equation 2. All sink rate and air speed collected are time averages of a minimum 10 seconds of data while the aircraft was in steady-state flight. Elias' data is taken verbatim.

Table 1: Raw Data and Computed Parameters from Flight Testing

	Run #	Air Speed (kt)	Sink Rate (ft/s)	Horiz Speed (kt), 11 lb scaled	Sink Rate (ft/s), 11 lb scaled	L/D
Elias (11 lb)	1	25.2	-1.64	-	-	26.0
	2	18.2	-1.21	-	-	25.5
	3	22.6	-1.36	-	-	28.0
	4	18.8	-1.24	-	-	25.5
	5	22.2	-1.77	-	-	21.2
	6	28.9	-2.51	-	-	19.5
	7	33.0	-3.72	-	-	15.0
	8	21.7	-1.50	-	-	24.5
Edwards (11.15 lb)	9	24.0	-2.11	23.7	-2.1	19.2
	10	31.0	-2.53	30.6	-2.5	20.7
	11	20.5	-1.69	20.2	-1.7	20.5
	12	18.0	-1.43	17.8	-1.4	21.2
	13	24.5	-2.36	24.2	-2.3	17.5
	14	26.5	-2.45	26.2	-2.4	18.3
	15	28.3	-2.70	28.0	-2.7	17.7
	16	24.5	-2.03	24.2	-2.0	20.4
	17	24.8	-2.03	24.4	-2.0	20.6
	18	28.0	-1.94	27.6	-1.9	24.4
	19	30.0	-3.38	29.7	-3.3	15.0
	20	44.3	-10.63	44.1	-10.5	7.1
	21	39.8	-8.61	39.5	-8.5	7.9
	22	35.0	-5.91	34.7	-5.8	10.0
	23	30.0	-2.11	29.6	-2.1	24.0
	24	23.8	-1.86	23.5	-1.8	21.6

By a 2nd order polynomial fit (as recommended by Reichmann, see References), an approximated sink polar equation can be determined and is shown in Equation 8.

$$V_{vert} = -0.0095 * V_{hoiz}^{2} + 0.3782 * V_{horiz} - 4.6072 \quad \text{(Eq. 8)}$$

The experimentally measured data points and the curve fit approximation are shown in Figure 7.

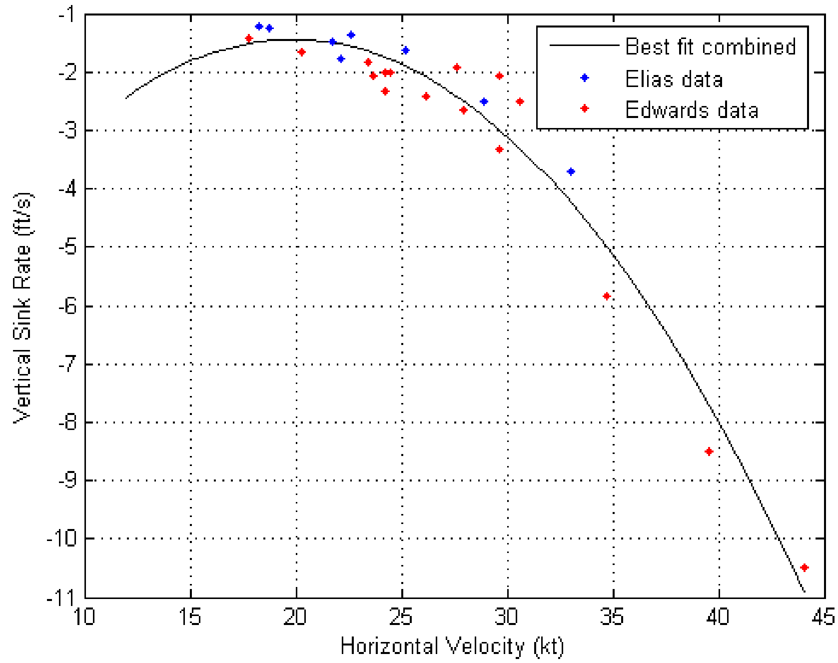

Figure 7: SBXC Sink Polar

The experimentally determined L/D points and the L/D curve using the approximated sink polar are shown in Figure 8. Note that the L/D curve is the derivative of the sink polar.

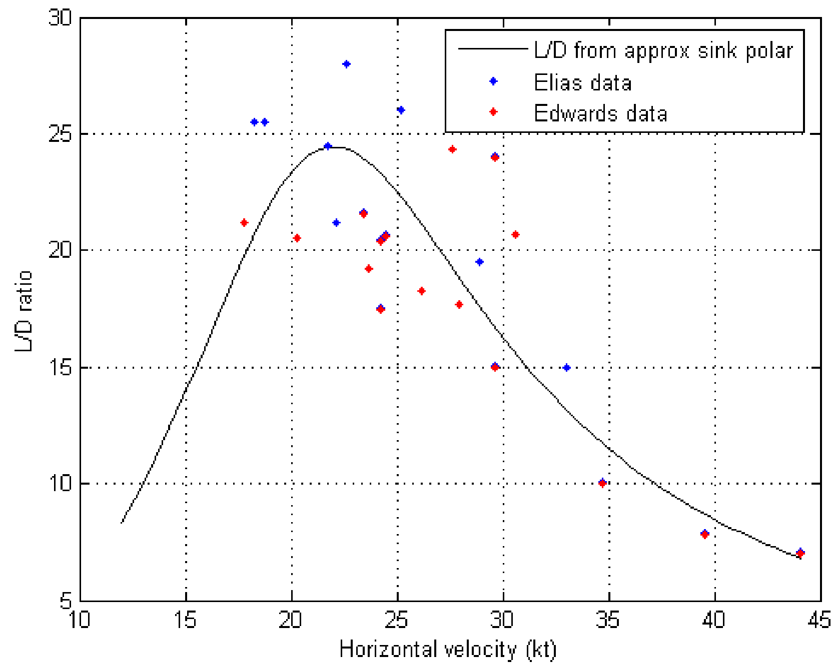

Figure 8: SBXC L/D performance curve at 11 lb

From the approximated sink polar in Equation 8, the speed-to-fly curve was constructed for various airmass sink speeds and shown in Table 2. The resultant L/D over the ground is also noted for comparison.

Table 2: Computed Speed-to-Fly values and Resultant Performance

Airmass Motion (ft/s)	Speed-to-Fly (kt)	Resultant L/D
0.0	22.0	24.4
1.7	24.3	23.3
3.4	26.3	20.9
5.1	28.3	18.5
6.8	30.1	16.2
8.4	31.8	14.4
10.1	33.4	12.8
11.8	34.9	11.6
13.5	36.4	10.5
15.2	37.8	9.6
16.9	39.2	8.9
18.6	40.5	8.2

The speed-to-fly points are shown in Figure 9.

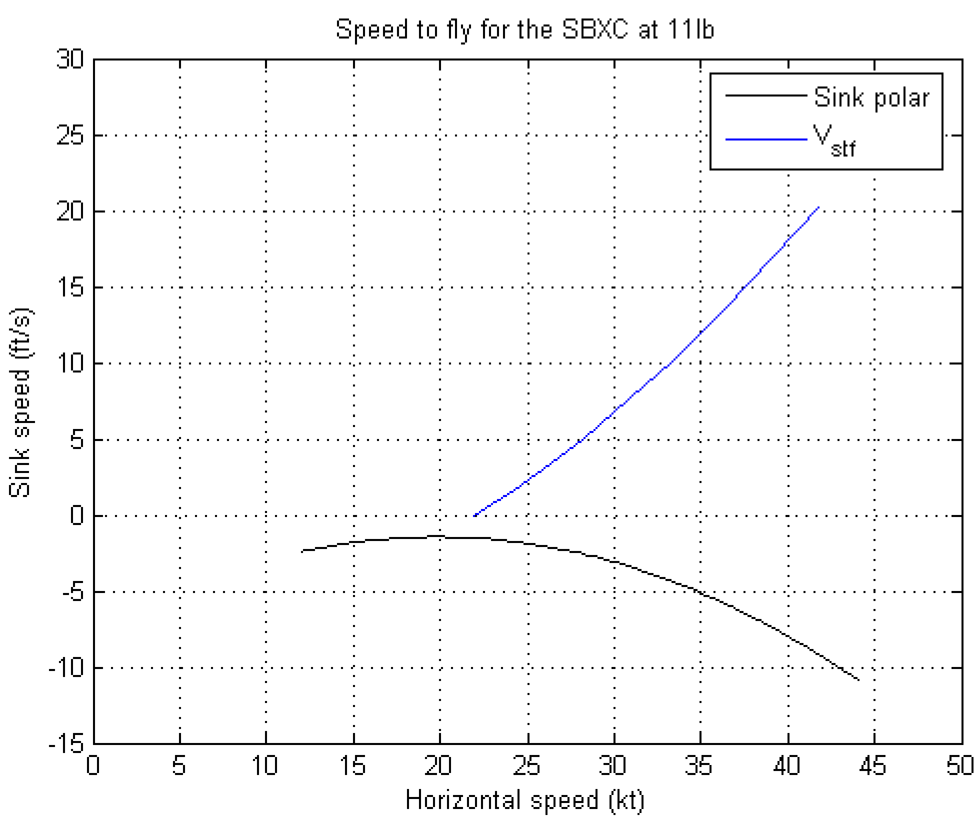

Figure 9: SBXC (11 lb) Speed to Fly

Discussion:

The data collected corresponds quite well with Elias' data. Two points from Elias' data are tossed due to having flap deflections, which would require a separate sink polar. Elias' one high-speed point was dropped because it did not fit the trend from the updated data and was not well-supported in the original data set.

The Elias data shows slightly lower sink rates than the majority of the new data. This could be from any drag-reduction modifications Elias did beyond the stock airframe. Alternately, the drag on this experiment's aircraft could be greater due to using pull-pull cables for the rudder instead of an enclosed pushrod setup as on Elias' aircraft.

The sink polar approximation on the combined data set visually has an acceptable fit to the experimental data. There is a bit of deviation in measured sink rate around 27 knots, where most of the testing was performed. There are very few data points at the higher speeds, in the range of 35 to 50 knots. The slowest data points were around 18 knots, which is just slightly above stall. It is planned to gather more data at the higher speeds and at the near-stall speeds to further confirm the approximation is good.

Given that a second order polynomial fit should be a good fit to a sink polar, the assumption can be made that this approximated sink polar is a good estimate with the data given. However, it will not be applicable close to or below stall speeds. Stall speed for the SBXC was tested to be approximately 17 knots (scaled for 11lb).

From the sink polar approximation, the minimum sink speed is -1.45 ft/s at 20.1 knots. Elias' original estimate was a minimum sink speed of approximately -1 ft/s at slightly above 20 knots.

The L/D experimental points show considerable deviation from the approximated curve. This is likely due to the L/D ratio being sensitive to deviations in sink rate. The approximated sink polar suggests the maximum L/D is 24.4 at 22.0 knots. The maximum L/D Elias recorded (excluding flap deflection points) was 28 at 22.6 knots.

The speed to fly curve shows the trend that was expected: speed up in sinking air. The L/D gets progressively worse as the air is sinking faster. For example, the maximum L/D in calm air is 24.4, but in air sinking 5.1 ft/s the maximum L/D is only 18.5 at 28.3 knots.

Conclusions

The experimental flight test data collected here corresponds well with the data from Elias, with minor differences between the two. The method to scale the presented sink rate data for varying SBXC weights is presented and helped in creating a fair comparison of Elias' results to the new data gathered. A mathematical representation of the sink polar is also given to support future projects in need of this information.

At a reference weight of 11lb, the new experimental performance parameters are:

Minimum sink:		
20.1 knots	-1.45 ft/s sink	23.5 L/D ratio

Maximum L/D:		
22.0 knots	-1.53 ft/s sink	24.4 L/D ratio

Approximate Sink Polar
$V_{vert} = -0.0095 * V_{hoiz}^2 + 0.3782 * V_{horiz} - 4.6072$
Valid for: *17 knot* < V_{horiz} < *48 knot*

Planned future work includes filling in more data points near stall and in the high speed regimes, creating a sink polar with various flap deflections to determine absolute minimum sink speed and maximum L/D for the SBXC, and flights at differing weights to confirm the weight scaling factor method.

Special Thanks

I would like to thank Michael Allen for being more of an inspiration to me than he realizes. Many thanks to Adam Propst and Chris Bovais for piloting while my nose was buried in a laptop, among all the other helpful things you have done. Thanks to Brady Baggs and the Down East Soaring Society gurus for encouraging and offering their support. Thanks also to the Autosoar project sponsors: NASA Dryden, Dean Gradwell of xcsoaring.com, Jim Gray of Jim D Gray & Associates Inc., Tri-M Systems, and Phytec America.

Corrections & Edits

- Fixed bug in weight scaling (was dividing by weight factor, needed to multiply)
- Fixed unit error in Appendix B (was displaying knots, not ft/s)
- Misc. grammar corrections
- New image of the inside of the fuselage showing the Piccolo connected
- Updated weight value: 11.15lb
- Better quality scanned image from Reichmann

References:

Ellias, J., “Performance Testing of RNR’s SBXC Using GPS,” Camarillo, California, http://www.xcsoaring.com/articles/john_ellias_1/sbxc_performance_test.pdf

Reichmann, H., “Cross Country Soaring,” Soaring Society of America, Inc., 1993, ISBN 1-883813-01-8.

Anderson, John. Introduction to Flight. McGraw Hill Higher Education; 5th International edition (June 2004)

“Polar Curve (aviation)”. Wikipedia. July 25, 2007 http://en.wikipedia.org/wiki/Polar_curve_%28aviation%29

Francis, Jay. “REACTIVETECHNOLOGIES.COM”. Merrimack, New Hampshire. http://www.reactivetechnologies.com

Appendix A: Smoothing Filter

For this experiment, the raw data from the altitude and airspeed pressure transducers was noisy and needed smoothing. A smoothing function was written that averaged a certain number of points forward and backward in time. This type of filter has zero phase change. Figure 3 shows the performance of the filter when used on a snippet of altitude data.

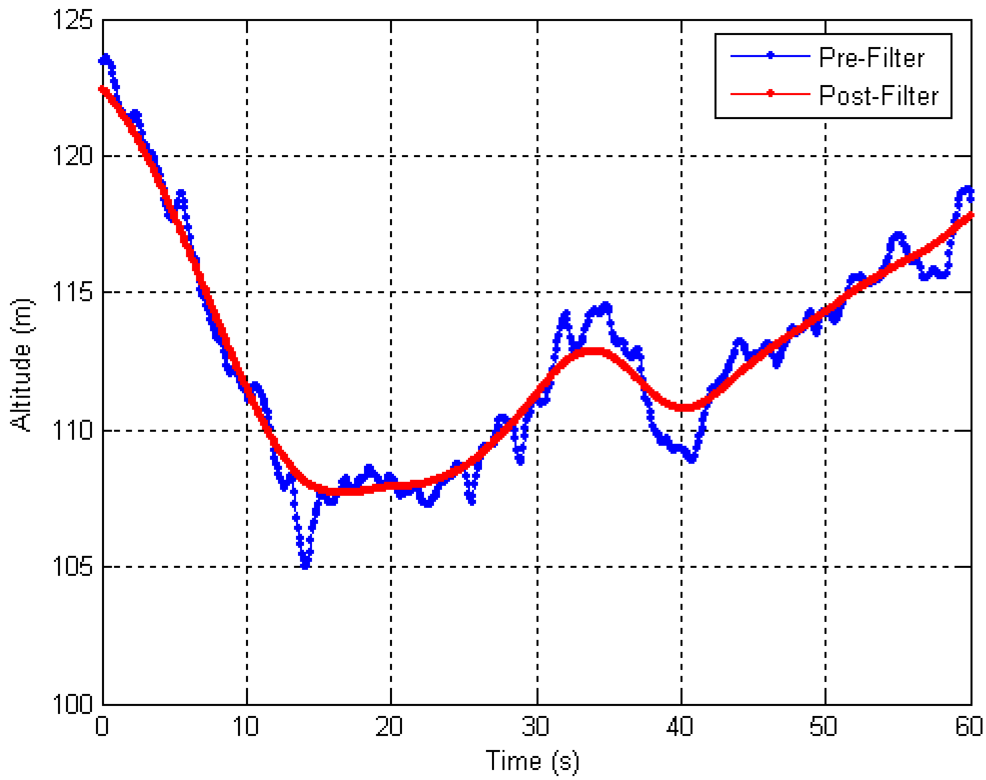

Figure 3: Smoothing Function Performance

Appendix B: Approximated Sink Rate and L/D data

Velocity (kt)	Sink Rate (ft/s)	L/D Ratio		Velocity (kt)	Sink Rate (ft/s)	L/D Ratio
12.0	-2.4	8.3		28.2	-2.6	18.5
12.3	-2.4	8.8		28.5	-2.7	18.1
12.6	-2.3	9.4		28.9	-2.8	17.7
13.0	-2.2	9.9		29.2	-2.8	17.3
13.3	-2.1	10.5		29.5	-2.9	16.9
13.6	-2.1	11.1		29.8	-3.1	16.5
13.9	-2.0	11.7		30.2	-3.2	16.1
14.3	-1.9	12.4		30.5	-3.3	15.8
14.6	-1.9	13.1		30.8	-3.4	15.4
14.9	-1.8	13.7		31.1	-3.5	15.0
15.2	-1.8	14.4		31.5	-3.6	14.7
15.6	-1.7	15.1		31.8	-3.7	14.4
15.9	-1.7	15.8		32.1	-3.9	14.0
16.2	-1.7	16.5		32.4	-4.0	13.7
16.5	-1.6	17.2		32.7	-4.1	13.4
16.9	-1.6	17.9		33.1	-4.3	13.1
17.2	-1.6	18.6		33.4	-4.4	12.8
17.5	-1.5	19.3		33.7	-4.5	12.5
17.8	-1.5	19.9		34.0	-4.7	12.3
18.2	-1.5	20.6		34.4	-4.8	12.0
18.5	-1.5	21.2		34.7	-5.0	11.7
18.8	-1.5	21.7		35.0	-5.2	11.5
19.1	-1.5	22.2		35.3	-5.3	11.2
19.5	-1.4	22.7		35.7	-5.5	11.0
19.8	-1.4	23.1		36.0	-5.6	10.8
20.1	-1.4	23.5		36.3	-5.8	10.5
20.4	-1.5	23.8		36.6	-6.0	10.3
20.8	-1.5	24.0		37.0	-6.2	10.1
21.1	-1.5	24.2		37.3	-6.3	9.9
21.4	-1.5	24.3		37.6	-6.5	9.7
21.7	-1.5	24.4		37.9	-6.7	9.5
22.0	-1.5	24.4		38.3	-6.9	9.4
22.4	-1.5	24.4		38.6	-7.1	9.2
22.7	-1.6	24.3		38.9	-7.3	9.0
23.0	-1.6	24.2		39.2	-7.5	8.8
23.3	-1.6	24.0		39.6	-7.7	8.7
23.7	-1.7	23.8		39.9	-7.9	8.5
24.0	-1.7	23.5		40.2	-8.1	8.4
24.3	-1.8	23.2		40.5	-8.3	8.2
24.6	-1.8	22.9		40.9	-8.5	8.1
25.0	-1.9	22.6		41.2	-8.8	7.9
25.3	-1.9	22.2		41.5	-9.0	7.8
25.6	-2.0	21.8		41.8	-9.2	7.7
25.9	-2.0	21.4		42.1	-9.5	7.5
26.3	-2.1	21.0		42.5	-9.7	7.4
26.6	-2.2	20.6		42.8	-9.9	7.3
26.9	-2.2	20.2		43.1	-10.2	7.2
27.2	-2.3	19.8		43.4	-10.4	7.0
27.6	-2.4	19.4		43.8	-10.7	6.9

Appendix C: Discussion of Elias' Data Collection

Elias used a barometric altimeter inside the aircraft, which creates inaccuracies if the aircraft is not vented properly. The pressure inside the aircraft can be affected by any open seal, hatch, or air vent. For example, a hole directly in the nose would create a ram pressure inside the fuselage, raising the pressure that the altimeter is measuring.

The vertical speed was not measured directly both in Elias' and this experiment.. Instead, altitude measurements were differentiated over time to create an estimate for the vertical velocity. Since the differential altitude is of primary concern, Elias' assumption that the fuselage pressure is the same as the static pressure is reasonable. So long as the fuselage was vented enough that changes in altitude created a proportional change in altitude as measured by the internal static pressure, Elias' estimate of vertical speed is acceptable.

In Elias' experiment, a GPS was used to estimate the horizontal velocity. This is only partially accurate since GPS does not measure airspeed, rather it measures ground speed. That is, between GPS location fixes, the GPS engine will subtract the current location from the previous location to get the effective speed between fixes. Most current GPS engines provide this ground track speed estimate only in two dimensions: this speed estimate is purely the horizontal motion. However, since the speed estimate is based on location rather than airspeed, the measurement for horizontal speed will have errors if the air is not completely calm. Also, this speed estimate is created at 1Hz which is the update rate of most GPS receivers. Thus, if Elias' aircraft was not in true steady state for longer than 1 second, then the speed estimate would miss the smaller motions of the aircraft.