High-Speed Dynamic Soaring

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Abstract

Dynamic soaring uses the gradient of wind velocity (wind shear) to gain energy for energy-neutral flight. Recently, pilots of radio-controlled gliders have exploited the wind shear associated with fast winds blowing over mountain ridges to achieve very fast speeds, reaching a record of 487 mph in January 2012. A relatively simple two-layer model of dynamic soaring was developed to investigate factors that enable such fast speeds. The optimum period and diameter of a glider circling across a thin wind-shear layer predict maximum glider airspeed to be around 10 times the wind speed of the upper layer (assuming a maximum lift/drag of around 30). The optimum circling period can be small ~1.2 seconds in fast dynamic soaring at 500 mph, which is difficult to fly in practice and results in very large load factors ~100 times gravity. Adding ballast increases the optimum circling period toward flyable circling periods of 2-3 seconds. However, adding ballast increases stall speed and the difficulty of landing without damage. The compressibility of air and the decreasing optimum circling period with fast speeds suggest that record glider speeds will probably not increase as fast as they have during the last few years and will probably level out below a speed of 600 mph.

1. Introduction

In April, 2011, I watched pilots of radio-controlled (RC) gliders at Weldon Hill California using dynamic soaring to achieve speeds up to 450 mph in wind gust speeds of 50-70 mph. One almost needs to see and hear these fast gliders to believe their amazing performance. These observations raised questions about how gliders could fly so fast and led me to try and understand the relevant dynamics. The motivation was the possibility that the technology of these gliders and the experience of the pilots could be used to help develop a fast robotic albatross UAV (unmanned aerial vehicle) for surveillance, search and rescue, and rapid scientific sampling of the marine boundary layer and ocean surface.

Dynamic Soaring

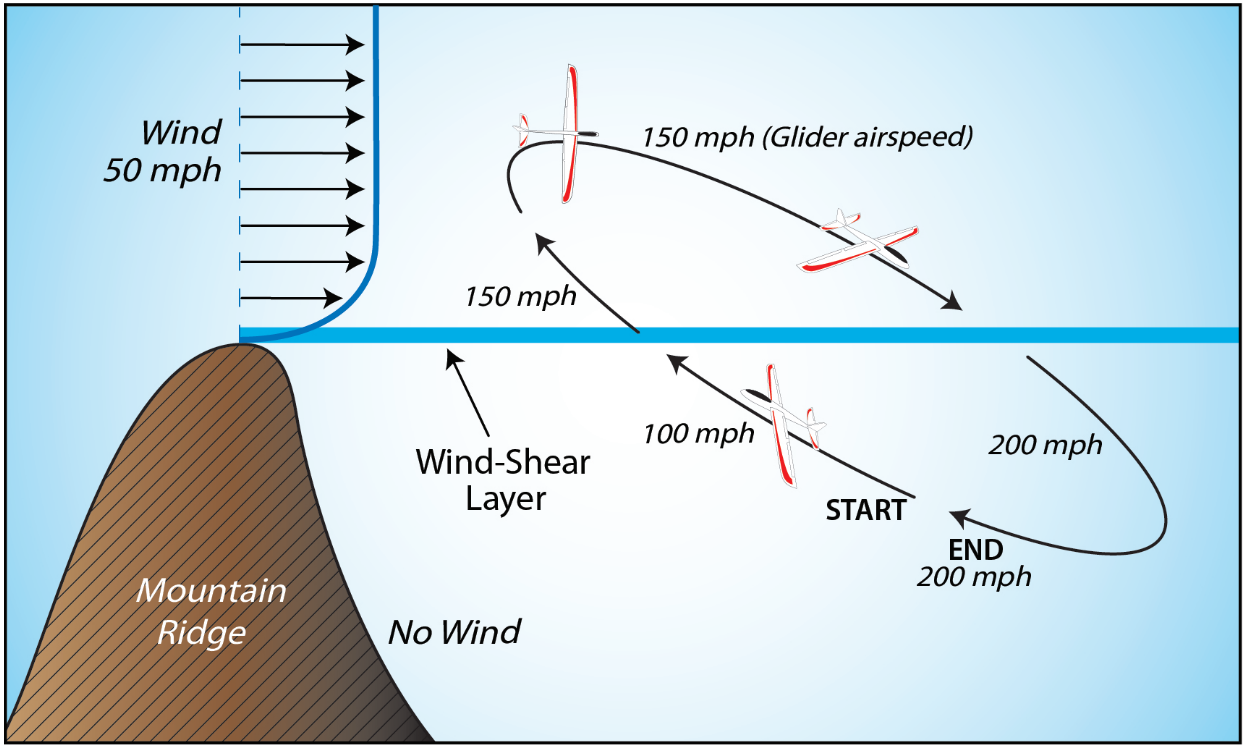

Figure 1. Idealized example of the increase of airspeed of a dragless glider soaring through a thin wind-shear layer in which the wind increases from zero below the layer to 50 mph above. This example shows how a glider could use dynamic soaring in the region downwind of a ridge crest as observed at Weldon. Starting in the lower layer with an assumed airspeed of 100 mph, a glider climbs upwind a short distance vertically across the wind-shear layer, which increases glider airspeed to 150 mph. The glider then turns and flies downwind with the same airspeed of 150 mph. During the turn, the glider's ground speed increases to 200 mph in the downwind direction and consists of the 150 mph airspeed plus (tail) wind speed of 50 mph. The glider descends downwind a short distance vertically across the wind-shear layer, which increases the glider's airspeed to 200 mph. The glider turns upwind flying with airspeed of 200 mph. Thus, one loop through the wind-shear layer increases the glider's airspeed from 100 mph to 200 mph (two times the 50 mph wind speed in the upper layer). The nearly-circular flight modeled in this paper is shown as an ellipse in this schematic figure.

Recently, I developed a fairly simple model of dynamic soaring to help understand how albatrosses use this technique to soar long distances without flapping their wings (Richardson, 2011). This present paper uses this model but concentrates on much faster glider airspeeds, which are more than ten times the typical wandering albatross airspeed of 35 mph. Specific questions explored are: 1) what are the key parameters of the flight that allow such high speeds to be achieved, 2) how can the flight be optimized for fast speeds, 3) what are the maximum airspeeds that can be achieved with realistic winds.

2. Observations of RC glider soaring

The RC dynamic soaring I observed at Weldon exploited the wind shear caused by fast wind blowing over a sharp-crested mountain ridge (see rcspeeds.com). The RC gliders flew in approximately circular loops lying roughly along a plane that tilted upward toward the wind direction and extended above the ridge crest. From the windy region above the ridge, the gliders descended headed in a downwind direction into the low-wind region below and downwind of the ridge crest. They then turned and climbed in an upwind direction back into the fast wind in the upper layer above the ridge crest. The gliders flew in fast steeply-banked loops with a loop period of around 3 seconds. The wings looked like they were nearly perpendicular to the plane all the way around a loop, implying very large accelerations. An accelerometer on one of the gliders recorded a maximum acceleration of 90 g, the accelerometer's upper limit (Chris Bosley, personal communication). At times the gliders were perturbed by turbulent wind gusts, and the pilots needed to quickly respond in order to prevent the gliders from crashing into the side of the ridge. High-speed crashes totally destroyed five gliders that day. Glider speeds up to 300-450 mph were measured with radar guns, usually after a glider had reached its lowest point on a loop and was climbing upwind again. This suggested that the recorded speeds are representative of typical speeds in the loop and could be somewhat slower than peak speeds. Wind speed gusts of 50-70 mph were measured on the ridge crest by holding a small anemometer overhead at a height 7 feet above ground level. Anecdotally, maximum glider speeds are around 10 times the wind speed, although this seems to be more realistic at lower speeds (< 350 mph) than at higher speeds (> 350 mph) (S. Lisenby, personal communication). However, there are generally very few wind velocity measurements with which to compare the glider speeds.

The gliders had ailerons and an elevator to control flight and a fixed fin in place of a moveable rudder. Flaps were used to reduce the stall speed when landing.

3. Inferences about the wind field

Wind velocity over a ridge crest generally increases with height from near zero velocity at the ground level. The largest vertical gradient of wind velocity (largest wind shear) is located in a thin boundary layer located within several feet of the ridge crest. Fast wind blowing over a sharp-crested ridge usually forms an area of weaker wind or a lee eddy just downwind of the ridge crest and below the level of the crest. Located above this region of weak wind is a thin wind-shear region, a wind-shear boundary layer that separates from the ridge crest, and

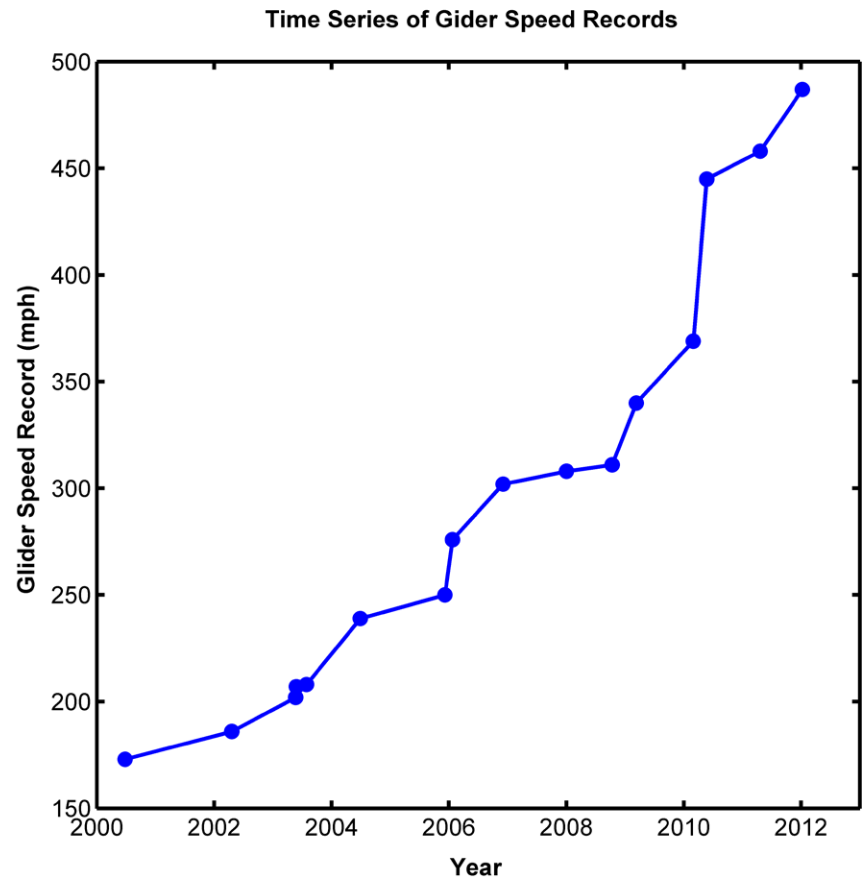

Figure 2. Time series of maximum recorded speeds of RC gliders using dynamic soaring as listed in the website rcspeeds.com. Each value represents an unofficial world record as measured by radar gun. The charted record holder is Spencer Lisenby who flew a Kinetic 100 (100 inch wing span) glider at a speed of 487 mph in January 2012. On 06 March 2012 Spencer flew the Kinetic 100 to a new record speed of 498 mph. <http://www.rcgroups.com/forums/showthread.php?t=1609281>

above that a layer of stronger wind and reduced wind shear. The wind-shear layer is inferred to extend nearly horizontally downwind of the ridge crest and gradually thicken with distance downwind. The glider loops crossed the wind-shear layer where it was thin just downwind of the ridge crest (see Figure 1).

4. Schematic illustration of dynamic soaring

The technique of dynamic soaring illustrated by the glider flight is to cross the wind-shear layer by climbing headed upwind, to then turn downwind, and to descend headed downwind (Figure 1). Each crossing of the wind shear layer increases the airspeed and kinetic energy of a glider. The rate of gain of airspeed and kinetic energy can be increased by increasing the frequency of the loops. Several things tend to limit a glider's airspeed including increased drag associated with both faster airspeeds and steeply-banked turns. When the gain of energy from crossing the wind-shear layer equals the loss due to drag, a glider reaches equilibrium in energy-neutral soaring.

Temporal wind gusts, in contrast to the structure gusts encountered by crossing the wind-shear layer, can be used to gain additional energy. A faster-than-average wind-speed gust contains greater-than-average wind shear, through which a glider could extract a greater-than-average amount of energy. The trick of soaring in gusts is to maximize time in the gusts and minimize time in the lulls.

5. Brief history of dynamic soaring

Interest in dynamic soaring began in the late 1800's as mariners watched albatrosses soaring over the ocean without flapping their wings. Observers tried to understand and model the birds' soaring techniques in order to adapt them for human flight. Two theories were suggested to explain how an albatross could extract energy from wind. The first theory, which has gained prominence, proposed that an albatross uses wind shear, the increase in wind velocity with height above the ocean surface, to gain energy (dynamic soaring). The second theory proposed that an albatross uses updrafts over waves to gain energy (wave-slope soaring). Albatrosses probably use both techniques, depending on the local wind and waves, but dynamic soaring is thought to provide most of the energy for sustained soaring. Albatrosses appear to exploit the thin wind-shear layer located above lee eddies, which are located downwind of ocean wave crests, as described by Pennycuick (2002).

The concept of dynamic soaring was first described by Lord Rayleigh in 1883, and the phrase "dynamic soaring" was used as early as 1908 by F. W. Lanchester. Over the years dynamic soaring has been discussed and modeled by many people, although only quite recently were the aerodynamics correctly developed (see Lissaman, 2005; Sachs, 2005). A problem for non-aerodynamicists is that the aerodynamic differential equations describing the accelerated twisting, turning, swooping flight of gliders in wind shear are very complex, which makes it difficult to understand the relevant dynamics. This note is an attempt to try to express the physics of dynamic soaring in a simpler framework and apply it to fast glider flight.

A little over a decade ago, pilots of RC gliders began using dynamic soaring and have been exploiting it to fly gliders downwind of mountain ridges much faster than had been previously possible. During the last 12 years, dynamic soaring speeds increased remarkably from around 170 mph in year 2000 up to 487 mph in 2012 with no sign of leveling off (Figure 2).

Speed gains have been achieved with the development of high performance airfoils, stronger airframes, better servos, and increased pilot experience. Along with these developments, pilots have flown gliders in progressively faster winds and larger wind shears. Along the way were many structural failures due to the large accelerations associated with fast highly-banked loops. Numerous crashes were caused by trying to fly fast gliders close to the ground near ridge crests. Maintaining control of gliders in quick loops and in wind turbulence is challenging and requires fast and accurate reflexes. In addition, large stall speeds of high-performance gliders make them tricky to fly at slow speeds and to safely land on top of a mountain ridge.

6. Model of dynamic soaring

The approach here uses the characteristics of observed glider loops to develop a simple model of dynamic soaring based on Rayleigh's (1883) concept of soaring across a sharp wind-shear layer and on the flight dynamic equations of motion (Lissaman, 2005). The modeled flight pattern is referred to as the Rayleigh cycle because he was first to describe the concept of dynamic soaring. The model provides a relatively easy way to understand the essential physics of dynamic soaring and provides predictions of soaring airspeeds, which agree well with more complex simulations of albatross flight (Lissaman, 2005; Sachs, 2005, Richardson, 2011). The Rayleigh cycle, which uses two horizontal homogenous wind layers, is the most efficient way for a glider in nearly-circular flight to gain energy from a wind profile and thus indicates the maximum amount of airspeed that can be achieved using dynamic soaring in energy-neutral flight.

When a glider soars in wind, the glider's airspeed (speed through the air) is different from its ground speed (speed relative to the ground). This should be kept in mind because airspeed, and not ground speed, is the quantity most relevant to flight. Aerodynamic forces on a glider depend on its airspeed not ground speed. Sufficient airspeed must be maintained to avoid a stall, which could be fatal at low altitude. The analysis of airspeed and ground speed leads to different conclusions about where kinetic energy is gained in dynamic soaring. An increase of glider airspeed comes from crossing the wind-shear layer. Most increase of ground speed occurs as a glider turns from a direction headed upwind to a direction downwind; during the turn wind does work on the glider and accelerates it in a downwind direction. Radar measurements of glider speed are relative to the ground and can be significantly different from glider airspeed.

Over time, gravity and drag relentlessly force a glider downward through the air. In balanced flight the glider's sinking speed through the air represents the glider's rate of energy loss. In order to continuously soar, a glider must extract sufficient energy from the atmosphere to counter the loss due to drag. For many years gliders exploited updrafts along ridges to gain energy from the wind and continuously soar, but recently gliders have used the vertical gradient of horizontal winds to gain energy; the exceptionally fast speeds achieved using wind gradients suggest that dynamic soaring is an effective way to gain energy.

The Rayleigh cycle of dynamic soaring as shown in Figure 1 was used to model a glider soaring in nearly-circular loops along a plane tilted upward into the wind similar to the glider observations at Weldon. The essential assumptions are that 1) the plane crosses the wind-shear layer at a small angle with respect to the horizon so that vertical motions can be ignored, 2) the average airspeed and average glide ratio can be used to represent flight in the circle, and most importantly, 3) conservation of energy in each layer requires a balance between the sudden increase of airspeed (kinetic energy) caused by crossing the shear layer and the gradual loss of airspeed due to drag over half a loop, resulting in energy-neutral flight. The motion during each half loop is somewhat similar to a landing flare when a glider maintains constant altitude and airspeed is slowly dissipated by drag. This study assumes that the lower layer has zero wind speed and that the increase of wind speed across the wind-shear layer is equal to the wind speed in the upper layer.

The glide polar for a particular glider is given by values of the glide ratio V/V_z, where V is the glider airspeed and V_z is

V (mph)	200		300		400		500		600	
V_c (mph)	45	55	45	55	45	55	45	55	45	55
t_{opt} (sec)	2.9	4.3	1.9	2.9	1.5	2.2	1.2	1.7	1.0	1.4
d_{opt} (feet)	270	400	270	400	270	400	270	400	270	400
W_{min} (mph)	20		30		40		50		60	
Bank angle (deg.)	87.1	85.7	88.7	88.1	89.3	88.9	89.5	89.3	89.7	89.5
Load factor	20	13	44	30	79	53	123	83	178	119

Table 1. Optimum loop period (t_{opt}) and diameter (d_{opt}) and the minimum wind speed (W_{min}) required for different glider airspeeds in energy-neutral dynamic soaring. V is the average airspeed (speed through the air) of a glider circling in a Rayleigh cycle. V_c is the assumed cruise airspeed (45 mph) of the glider corresponding to the airspeed of maximum lift/drag, which was assumed to equal 31.4 in this example. Cruise airspeed increases to 55 mph by adding ballast of around 50% of the original glider weight. The optimum loop period t_{opt} corresponds to the minimum wind speed W_{min} in the upper layer required for dynamic soaring at the listed glider airspeeds (Eq. 6). Optimum loop diameter d_{opt} corresponds to the optimum loop period (Eq. 9). Bank angle is for balanced circular flight. Load factor is equal to $1/\cos\varphi$ and is the total acceleration of the glider, including gravity plus centripetal acceleration, normalized by gravity.

V (mph)	500					600	
t (sec)	1.0	1.5	2.0	2.5	3.0	2.0	3.0
d (feet)	230	350	470	580	700	560	840
W_{min} (mph)	51 (58)	52 (51)	58 (53)	66 (53)	78 (58)	77 (63)	103 (77)
V/W_{min}	9.9 (8.7)	9.6 (9.9)	8.7 (9.9)	7.6 (9.4)	6.7 (8.6)	7.8 (9.5)	5.8 (7.8)
Bank angle (deg.)	89.6	89.4	89.2	89.0	88.0	89.3	89.0
Load factor	143	95	72	57	48	86	57

Table 2. Minimum wind speed (W_{min}) required to fly at 500 mph (and 600 mph) using different loop periods (t) and the associated loop diameters (d) in energy-neutral dynamic soaring. The maximum L/D is assumed to equal 31.4 at a cruise airspeed V_c of 45 mph (no ballast). V is the average airspeed of a glider circling in a Rayleigh cycle, t is an assumed loop period, and d is the corresponding loop diameter. W_{min} is the minimum wind speed in the upper layer required for dynamic soaring at the listed glider airspeed. Values in parentheses are for a cruise airspeed V_c of 55 mph (added ballast). V/W_{min} is the ratio of glider airspeed to wind speed and, when multiplied by the wind speed, indicates the maximum airspeed. Values in parentheses are for a cruise speed of 55 mph (added ballast). Bank angle is for balanced circular flight. Load factor is equal to $1/\cos\varphi$ and represents the total acceleration acting on the glider, normalized by gravity.

the glider's sinking speed through the air. The glide ratio is closely equal to lift/drag (*L/D*) for *L/D* values >> 1 typical of glider flight. Values of V/V_z for circular flight were modeled using a quadratic drag law, in which the drag coefficient is proportional to the lift coefficient squared, and the aerodynamic equations of motion for balanced circular flight (Lissaman, 2005; Torenbeek and Wittenberg, 2009). The equation for a glide polar can be specified by using a glider's maximum *L/D* value and the associated cruise speed V_c. In balanced circular flight the horizontal component of lift balances the centripetal acceleration and the vertical component of lift balances gravity. A more complete discussion of glide polar model and derivation of relevant equations are given in the appendix. Equation numbers below refer to the equations derived in the appendix.

For a given wind speed in the upper layer, the maximum possible glider airspeed coincides with an optimum loop period (t_{opt}) and the associated optimum loop diameter (d_{opt}). For fast glider speeds, > 150 mph, t_{opt} is given by

$$t_{opt} = \frac{2\pi V_c^2}{gV}. \qquad (6)$$

V_c is the glider cruise speed, V is the glider airspeed, and g is gravity. Equation 6 indicates that t_{opt} is inversely proportional to glider airspeed. The optimum loop period decreases with increasing glider airspeed because drag increases with airspeed, which requires more frequent shear-layer crossings to achieve a balance and energy-neutral flight.

The optimum loop diameter d_{opt} is given by

$$d_{opt} = 2V_c^2/g. \qquad (9)$$

Equation 9 reveals that the optimum loop diameter is independent of glider airspeed but is proportional to cruise airspeed squared.

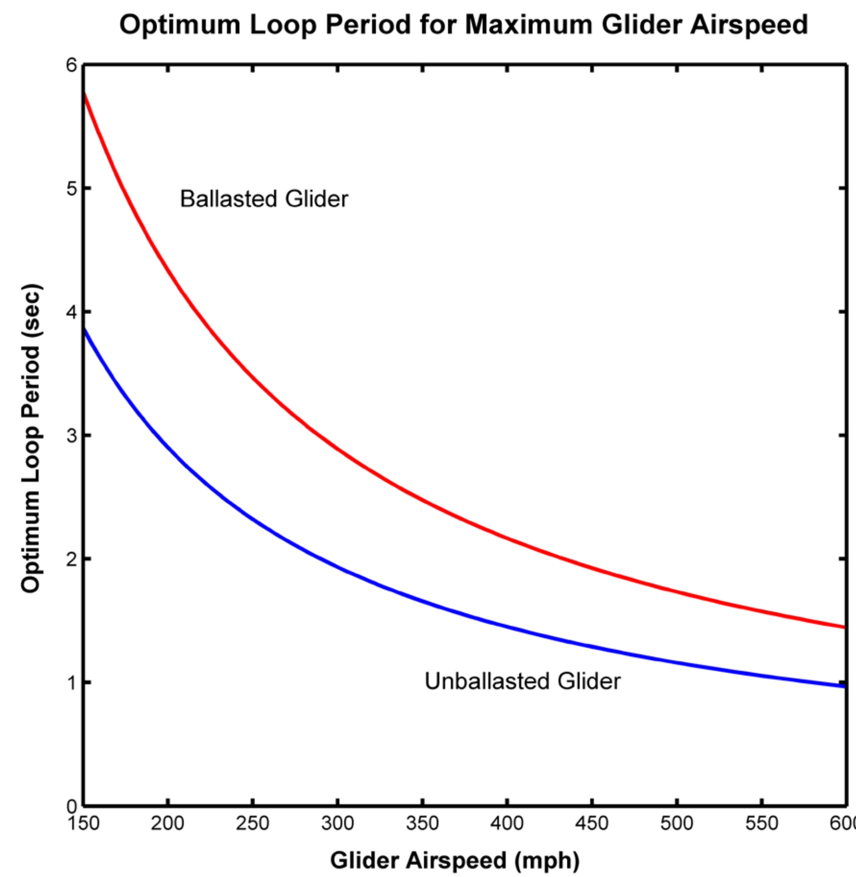

Figure 3. Optimum loop period t_{opt} required to achieve the maximum glider airspeed in a Rayleigh cycle plotted as a function of glider airspeed. Curves are shown for the unballasted (V_c = 45 mph) and ballasted (V_c = 55 mph) gliders. Ballast is around 50% of the unballasted glider weight.

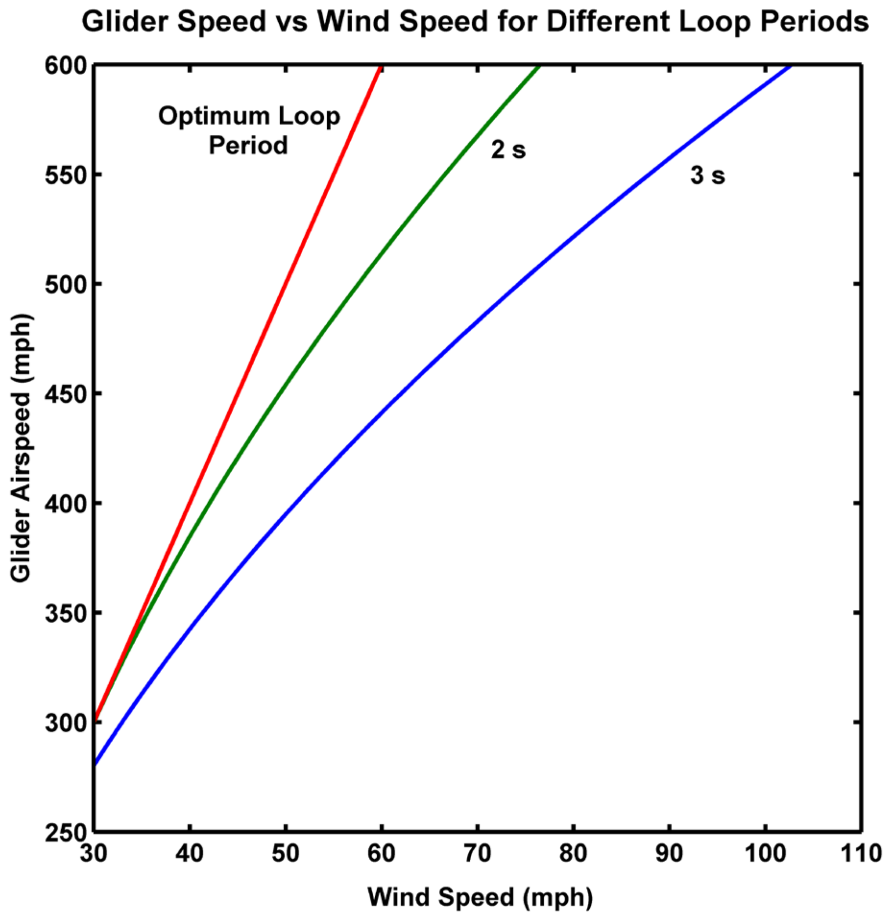

Figure 4. Maximum glider airspeed as a function of wind speed using a Rayleigh cycle and the unballasted glider (V_c = 45 mph). Curves are shown for the (variable) optimum loop period (see Figure 3) as well as for constant loop periods of 2 s and 3 s.

t_{opt} was used to calculate the maximum glider airspeed V_{max} for a given wind speed W

$$V_{max} = \frac{(V/V_z)_{max}}{\pi}(W). \quad (8)$$

Equation 8 indicates that for fast flight (> 150 mph) the maximum average airspeed in a Rayleigh cycle is proportional to the wind speed W in the upper layer. For a high-performance RC glider like the Kinetic 100, $(V/V_z)_{max}$ is around 30 (S. Lisenby, personal communication), and the maximum possible (average) dynamic soaring airspeed is around 10 times the wind speed of the upper layer. Consider a glider with a maximum L/D of around 30 soaring with an optimum loop period and with an upper-layer wind speed of 50 mph. Equation 8 predicts that the maximum possible average glider airspeed would be around 500 mph (10 times the 50 mph wind speed). A glider flying in a loop would increase its airspeed by 50 mph on crossing the wind-shear layer from 475 mph just before the crossing to 525 mph just afterward. Between shear-layer crossings airspeed would gradually decrease back to 475 mph due to drag. At these fast speeds the variation of airspeed due to vertical motions in a loop is much smaller than that due to crossing the shear layer.

The total acceleration of a glider includes centripetal acceleration and gravity and is given by the load factor, which equals $1/\cos\varphi$, where φ is the bank angle (Eq. 3). For fast dynamic soaring, the load factor is approximately equal to $2\pi V/gt$.

7. Results

The main results are the derivation of equations for the optimum loop period (Eq. 6), the optimum diameter (Eq. 9), and the maximum glider airspeed V_{max} (Eq. 8), which predicts that maximum glider speed equals around 10 times the wind speed for fast flight and $(L/D)_{max}$ around 30. It is helpful to explore these results by using values for a typical glider, so the values of the flight characteristics of a glider dynamic soaring at different airspeeds were calculated. The examples assume a high-performance glider $(L/D)_{max}$ value of 31.4 at a cruise speed V_c of 45 mph, similar to a Kinetic 100, the present world speed record holder (see dskinetic.com). The 31.4 $(L/D)_{max}$ value was chosen so that V_{max} = 10.0 W. Adding ballast was assumed to maintain the same $(L/D)_{max}$ and to increase cruise speed V_c to 55 mph. V_c is proportional to the square root of glider weight, and (approximately) a 50% increase of glider weight increases V_c from 45 mph to 55 mph.

Figure 3 shows that, as glider speeds increase from 150 mph to 600 mph, the optimum loop period t_{opt} for the unballasted (V_c = 45 mph) glider decreases from 3.8 s to 1.0 s (t_{opt} is inversely proportional to V). Over this speed range the optimum loop diameter is 270 feet (Table 1). Small loop periods of around 2 s, or smaller, are difficult to fly in efficient dynamic soaring and stressful for the glider. More typical flyable minimum loop periods are between 2-3 s with 3 s being easier to fly and more common than 2 s, which is rare (Spencer Lisenby and Chris Bosley, personal communications). Thus, to fly at 500 mph, say, it is necessary to use flyable loop periods ~ 2-3 s, which are larger than the optimum loop period of 1.2 s and correspond to larger loop diameters of 470-700 feet (Table 2). The downside of these flyable loop periods is that the minimum wind speed required for a glider to reach an airspeed of 500 mph increases over the minimum wind speed required at the optimum period and diameter (as predicted by Eq. 7) (Figure 4). For example, the minimum wind speed W_{min} required for dynamic soaring at 500 mph (Eq. 4) increases from 50 mph for a 1.2 s loop (at t_{opt}) (Table 1) up to 78 mph for a 3 s loop (Table 2).

Therefore, a major difficulty in trying to fly at glider airspeeds of 500 mph (or faster) is that by using flyable loop periods of 2-3 s the minimum required wind speed increases substantially over that at the optimum loop period and diameter (Figure 4). In

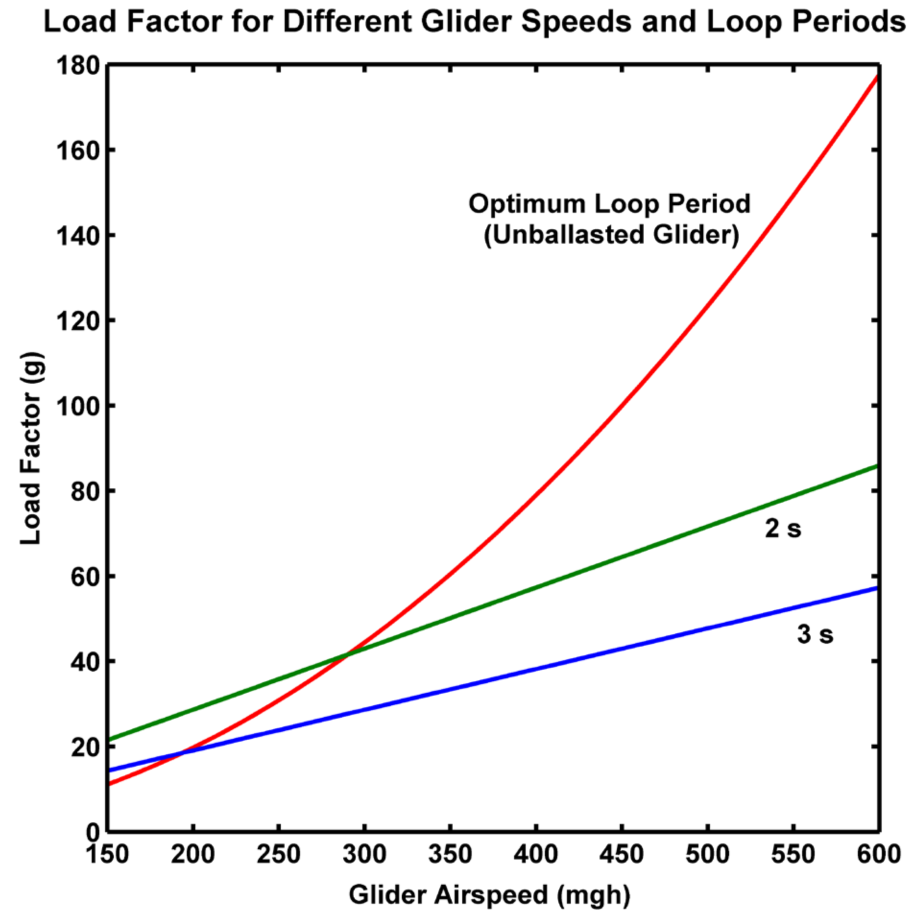

Figure 5. Load factor plotted as a function of glider airspeed and different loop periods for the unballasted glider (V_c = 45 mph). Load factor is equal to the total acceleration of the glider in terms of the acceleration of gravity (g).

other words, the glider's maximum airspeed for a wind speed of 50 mph (say) decreases from values predicted by $V_{max} = 10\ W$ (Eq. 8), which is based on the optimum period. In order to take advantage of $V_{max} = 10\ W$ one needs to fly close to the optimum period, and this becomes increasingly difficult at fast airspeeds of 500 mph (Table 1). This suggests that it will be difficult to continue to achieve such fast speed gains as seen in the last few years.

The effects of flying with and without added ballast are shown in Tables 1 and 2 and Figure 3. At a glider airspeed of 500 mph, adding ballast increases the optimum loop period from 1.2 s to 1.7 s (optimum loop period is proportional to glider weight), which is still difficult to fly but closer to flyable loop periods. A benefit is that at a flyable loop period of 3 s the minimum required wind speed decreases to 58 mph (ballasted glider) from 78 mph (unballasted glider) (Table 2). A main benefit of adding ballast is to increase the optimum loop period and to reduce the minimum wind speed required to fly at 500 mph from that obtained without ballast, assuming a flyable 3 s loop period. Table 1 and Figure 3 show that the optimum loop period of the ballasted glider falls below 3 s near an airspeed of 300 mph, indicating that at airspeeds greater than 300 mph V_{max} will be below values predicted by Eq. 8. This is in accord with the anecdotal evidence of $V_{max} = 10\ W$ being more realistic at glider speeds below 350 mph.

Another way to interpret the effect of ballast is to compare maximum glider airspeeds achievable with a wind speed of 50 mph (say). At the optimum loop period (1.2 s) and optimum diameter (270 feet) an unballasted glider could reach 500 mph (Table 1). With a loop period of 3 s, maximum airspeed of the unballasted glider would be 370 mph (loop diameter 520 feet) and that of the ballasted glider 450 mph (loop diameter 630 feet) (Eq. 4). Thus, adding ballast increases the maximum glider airspeed over that possible without ballast (for t = 3 s and wind speeds > 30 mph).

Figure 5 shows the load factor (total acceleration) of an unballasted glider at airspeeds of 150 mph to 600 mph. At a glider airspeed of 500 mph and optimum loop period of 1.2 s, the load factor is 123 g. Increasing the loop period to 2 s at 500 mph reduces the load factor to 72 g, and increasing the loop period to 3 s reduces the load factor to 48 g. Table 1 also shows that the ballasted glider has a smaller load factor ~ 83 g than the unballasted glider ~ 123 g due to the larger optimum loop periods of the ballasted glider. (Load factors are similar for ballasted and unballasted gliders when using the same constant loop period). Therefore, adding ballast and increasing V_c from 45 mph to 55 mph reduces the load factor, and that seems beneficial. However, for a given glider airspeed, the lift force on a glider's wings is the same for both the unballasted and ballasted glider. This is because lift force equals the glider weight times the load factor, and the glider weight is larger with ballast.

Values of load factor in the tables are for average airspeeds in a loop. When a glider crosses the wind-shear layer, the airspeed suddenly increases ~ 5% over the average airspeed and that can cause a ~ 10% jump in load factor and lift force over average values given in the tables.

8. Speed limits for dynamic soaring

At a critical aircraft speed of (roughly) Mach 0.7 ~ 540 mph (or greater) the flow of air past the aircraft can increase locally and reach, in places, the speed of sound, Mach 1 ~ 770 mph (see Torenbeek and Wittenberg, 2009). The aircraft speed at which this occurs depends on the wing shape, the angle of attack, and the particular configuration of the aircraft. Some modifications that have led to a higher critical speed are a supercritical airfoil, swept wings, and a smooth variation from nose to tail of an aircraft's cross-sectional area and a small maximum area (area rule). At the critical speed, shock waves begin to form due to the compressibility of air, and the aerodynamics of incompressible flow is no longer valid. The lift coefficient drops, drag coefficient increases, and lift/drag decreases enormously. The linear relationship V_{max} = 10 W fails, since maximum lift/drag (Eq. 8) decreases, even when flying at the optimum loop period and diameter for incompressible flow. This suggests that an increasingly large wind speed would be required to obtain a particular glider airspeed, larger than predicted by V_{max} = 10 W.

At an airspeed of 600 mph, the optimum loop period of the Rayleigh cycle is 1.0 s for the unballasted glider and 1.4 s for the ballasted glider, and the wind speeds required to fly with loop periods of 2-3 s increase substantially over 60 mph (Table 1). The minimum required wind speed of an unballasted glider is 103 mph for a loop period of t = 3 s (Table 2). Adding ballast decreases the minimum required wind speed to 77 mph for t = 3 s (Figure 3). Thus, adding ballast could help gliders reach 600 mph, assuming that loops could be flown with periods of 2-3 s and that wind speeds of 77 mph are available and flyable. Of course, reaching 600 mph using these wind speeds is based on a glider flying a nearly-circular loop in a two-layer Rayleigh cycle, which gives the maximum amount of energy possible from wind shear. In practice, somewhat less energy would be gained than from a Rayleigh cycle, and thus a larger wind speed would be needed to achieve the airspeeds predicted using the Rayleigh cycle. For example, flying a nearly-circular loop through a linear wind shear would result in around 80% of the maximum glider airspeed achievable in the two-layer case, assuming a similar increase of wind velocity over the heights flown. Additional limits to speed are the structural strength of the glider, which is subjected to very large accelerations and lift forces, and the glider's ability to control flutter at high speeds.

In summary, although record glider speeds have increased rapidly during the last few years up to 487 mph (Figure 2), and the shape of the curve in Figure 2 looks like it could continue upwards to much higher glider speeds, the limits mentioned above—the decreasing optimum loop period at higher speeds, the effects of the compressibility of air, and the larger wind speeds required to reach a particular glider airspeed--suggest that maximum speeds in dynamic soaring will tend to level out near between 500 and 600 mph. Further modifications of gliders for high-speed flight might help increase maximum speeds somewhat, but these modifications would probably make it difficult to fly at slower speeds and land safely. The addition of an autopilot might possibly help to fly a glider at small loop periods.

9. Conclusions about how to soar at 500 mph

The following conclusions about how to soar at 500 mph were derived from the analysis of the Rayleigh cycle model of dynamic soaring:

1) Fly a high-performance and strong glider with a large maximum L/D and large associated cruise airspeed (V_c). A larger maximum L/D results in a larger glider airspeed for a given wind speed (Eq. 8). A larger cruise speed results in a larger optimum loop period (t_{opt}), closer to flyable airspeeds of 2-3 s (Eq. 6).

2) Fly in fast wind ~ 50-70 mph (or more) and large wind shear (Table 2).

3) Fly as close to the optimum loop period (Eq. 6) and optimum loop diameter (Eq. 9) as possible because that increases the maximum glider airspeed to be around 10 times the wind speed (V_{max} = 10 W) and results in the fastest airspeed for a given wind speed (Eq. 8). However, fast flight at optimum loop periods results in large accelerations and large lift forces and requires very strong gliders. Flyable loop periods (~ 2-3 s) are significantly larger than the optimum loop period ~ 1.2 s of an unballasted glider at 500 mph and increase the minimum required wind speed to reach 500 mph (Table 1).

4) Add ballast to increase the cruise airspeed V_c because that increases the optimum loop period toward flyable loop periods and tends to reduce the minimum wind speed and

shear required for flight at 500 mph (Tables 1 and 2). However, increasing V_c leads to higher stall speeds and difficulties in safely landing a glider on a ridge crest. For this reason, S. Lisenby, (personal communication) limits ballast to around 25% of the weight of his unballasted Kinetic 100 glider.

5) Fly at high altitudes and warm temperatures where air density is lower, which has effects similar to adding ballast. Warm temperatures tend to keep the critical airspeed high.

To further investigate the dynamic soaring of gliders, it would be helpful to add instruments to measure at high resolution, positions, orientations, velocities and accelerations over the ground and through the air, as well as information about the structure of the wind interacting with ridges. It would be useful to continuously monitor glider airspeeds and groundspeeds in order to more accurately document maximum airspeeds. With this information one might be able to refine glider performance and achieve faster airspeeds. Numerical modeling could be used to further investigate high-speed dynamic soaring in more realistic conditions (wind interacting with a ridge) and help refine high-performance glider design.

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Chris Bosley and Spencer Lisenby helped with my visit to Weldon to see fast dynamic soaring and explained and discussed glider dynamic soaring techniques. Don Herzog flew us down to Bakersfield in his “high-performance” Trinidad airplane at 200 mph (much slower than the RC gliders) and joined in the trip up to Weldon. Paul Oberlander drafted Figure 2. Steve Morris and Pritam Sukumar read an earlier version of this paper and provided helpful comments about how to improve it.

Appendix

Modeled Rayleigh cycle

In the modeled Rayleigh cycle the loss of potential energy over a half loop (t/2) is given by $mg(t/2)V_z$, where m is mass, g is gravity, t is the period of a loop, and V_z is the glider’s sinking speed through the air due to drag. Conservation of energy for energy-neutral soaring requires that this energy loss must be balanced by the sudden gain in kinetic energy (airspeed) from crossing the wind-shear layer, which is given by $m(V_2^2 - V_1^2)/2$, where V_1 is the airspeed before crossing the wind-shear layer, and V_2 is the airspeed after crossing the layer. In this latter term, $V_2^2 - V_1^2 = (V_2 - V_1)(V_2 + V_1)$. $V_2 + V_1$ is assumed to equal twice the average airspeed (2V) in the nearly-circular flight, and $V_2 - V_1$ is the increase of airspeed ΔV of a glider crossing the wind-shear layer, which is assumed to equal the vertical increase of wind speed (ΔW) across the layer and also the wind speed W of the upper layer, assuming zero wind speed in the lower layer. Conservation of energy and the approximations given above indicate that

$$\Delta V = \frac{gt}{2\,(V/V_z)}, \qquad (1)$$

where V/V_z is the glide ratio averaged over a half loop and over ΔV. Values of V/V_z define the glide polar for a particular glider and indicate values of its sinking speed V_z through the air as a function of airspeed V. The glide ratio is closely equal to lift/drag (L/D) for L/D values >> 1 typical of glider flight. Lift $L = Cl(\rho/2)V^2S$, drag $D = Cd(\rho/2)V^2S$, Cl is the lift coefficient, Cd the drag coefficient, ρ the density of air, and S the characteristic area of the wings.

The decrease in airspeed at the assumed nearly-constant height during a half loop was obtained by balancing the rate of change of airspeed (kinetic energy) with dissipation due to drag. This balance indicates that $dV/dt = g/(V/V_z)$. Since V/V_z is nearly constant in the relevant glider airspeed range ΔV centered on a particular average airspeed, airspeed decreases nearly linearly in time. (The variation of V/V_z is around 10% of the average V/V_z in an energy-neutral loop.) Therefore, the total decrease of airspeed ΔV in a half loop (t/2) is equal to $gt/2(V/V_z)$ as derived above (Eq. 1).

Values of V/V_z for circular flight were modeled using a quadratic drag law, in which the drag coefficient is proportional to the lift coefficient squared, and the aerodynamic equations of motion for balanced circular flight (Lissaman, 2005; Torenbeek and Wittenberg, 2009). In balanced circular flight the horizontal component of lift balances the centripetal acceleration and the vertical component of lift balances gravity. Specifically, V/V_z was modeled by

$$V/V_z = \frac{2\,(V/V_z)_{\max}}{(V/V_c)^2 + (V_c/V\cos\varphi)^2}, \tag{2}$$

where $(V/V_z)_{max}$ is the maximum glide ratio at V_c the associated cruise airspeed (airspeed of minimum drag) of a representative glider in straight flight, φ is the bank angle, and $\cos\varphi$ is given by

$$\cos\varphi = \sqrt{\frac{1}{(2\pi V/gt)^2 + 1}}. \tag{3}$$

Combining Equations (2) and (3) with (1) indicates that

$$\Delta V = \frac{gt}{4\,(V/V_z)_{\max}}\left[(V/V_c)^2 + (V_c/V)^2 + (2\pi V_c/gt)^2\right]. \tag{4}$$

The $(2\pi V_c/gt)^2$ term is due to the centripetal acceleration and bank angle. Equation 4 indicates that for a particular glider in energy-neutral soaring, the glider airspeed (ΔV) gained by crossing the wind-shear layer (and the gradual loss in a half loop) is a function of both the loop period t and the average airspeed V.

A minimum ΔV (and also minimum ΔW and minimum W) for a given glider airspeed occurs at an "optimum" loop period t_{opt} coinciding with minimum energy loss in a loop (minimum $V_z t$). The optimum loop period (t_{opt}) was obtained by setting the derivative $d(\Delta V)/dt$ of (Eq. 4) equal to zero and solving for t.

$$t_{\text{opt}} = \frac{2\pi V_c/g}{\sqrt{(V/V_c)^2 + (V_c/V)^2}}. \tag{5}$$

At fast glider speeds >150 mph and for V_c ~ 50 mph, $(V/V_c)^2 >> (V_c/V)^2$ and $(V_c/V)^2$ can be neglected. This simplifies Eq. 5 to

$$t_{\text{opt}} = \frac{2\pi V_c^2}{gV}. \tag{6}$$

Equation 6 indicates that t_{opt} decreases with increasingly large V. Substituting Eq. 6 into Eq. 4 provides an expression for minimum ΔV (and minimum ΔW and minimum W) for a given V. The minimum wind speed W_{min} needed for a given glider airspeed V in energy neutral dynamic soaring is

$$W_{\min} = \frac{\pi V}{(V/V_z)_{\max}}. \tag{7}$$

This equation can be rearranged to provide the maximum glider airspeed V_{max} for a given wind speed W

$$V_{\max} = \frac{(V/V_z)_{\max}}{\pi}(W). \tag{8}$$

Equation 8 indicates that for fast flight (> 150 mph) the maximum average airspeed in a Rayleigh cycle is proportional to wind speed. It is important to note that this linear relation depends on flying with an optimum loop period. Other loop periods result in a smaller maximum airspeed for a given wind speed.

The diameter of a loop is given by $d = Vt/\pi$. Substituting into this equation the expression for optimum loop period t_{opt} in fast flight (Eq. 6) gives the optimum loop diameter d_{opt}

$$d_{opt} = 2V_c^2/g. \quad (9)$$

Equation 9 reveals that the optimum loop diameter is proportional to cruise airspeed but is independent of glider airspeed squared.

The total acceleration of a glider includes centripetal acceleration and gravity and is given by the load factor, which equals $1/\cos\varphi$ (see Eq. 3). For fast dynamic soaring $(2\pi V/gt)^2 >> 1$, and the load factor is approximately equal to $2\pi V/gt$.

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Calling all F3J pilots

We are planning the pre-contest for the World Championships in August.

The pre-contest will be held on Friday 3 August and Saturday 4 August 2012. The contest will be limited to 150 pilots including anyone of the international competitors that would like to enter. Additional information will be sent to interested parties along with the bulletin for the event.

This pre-contest event will include as many qualifying rounds as we are able to fit in and three fly-off rounds as per normal F3J regulations.

This is a great opportunity to compete against international pilots and remember, not all of them are WC pilots.

The preliminary World Champs schedule is as follows:

Friday 3 August	Pre-contest day 1
Saturday 4 August	Pre-contest day 2
Sunday 5 August	Model processing and opening ceremony
Monday 6 August through	World Champs rounds
Thursday 9 August	World Champs rounds
Friday 10 August	WC final fly-off rounds
Saturday 11 August	Tour and banquet

Kind regards, Michelle Goodrum