How Flies the Albatross

The Flight Mechanics of Dynamic Soaring

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This presentation accompanies the SAE technical paper of the same title, available at SAE.ORG

It is my pleasure to share with this interested audience recent discoveries explaining how the albatross uses its dynamic soaring technique to remain aloft without flapping its wings. This presentation will draw from several disciplines, primarily aerospace engineering, but also physics, mathematics, computer graphics, paleontology, photography, and even a little poetry, to observe what the albatross does, and how it does it, so that we may perhaps take greater interest in halting its slide toward extinction.

From ***The Rhyme of the Ancient Mariner*** *~ Part the First*

And a good south wind sprung up behind;
And the Albatross did follow,
And every day, for food or play,
Came to the mariners' hollo!

\- Samuel Taylor Coleridge

In "The Rhyme of the Ancient Mariner," the sailor shot the albatross with his crossbow, believing the albatross responsible for the ice-cold storm. This was unfortunate for both because, as the story goes, the albatross was also "the bird that made the wind to blow." Consequently, the ship drifted into the doldrums, and the crew perished from thirst. Today we are still shooting the albatross, in a manner of speaking. Our crossbows take the form of long-line fishing fleets, floating plastic at sea, and predators introduced to the remote islands where the albatross breeds. Many albatross species have lost half of their population within the last two human generations alone.

Observations

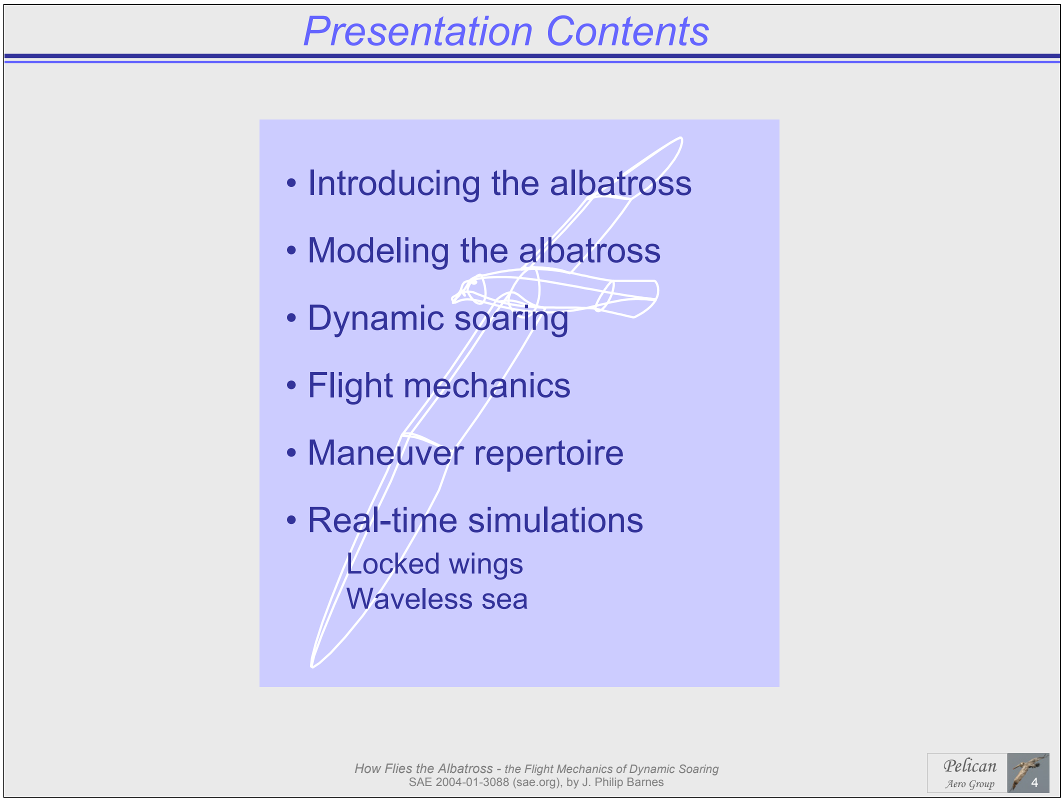
“The albatross can maintain this swooping soaring flight for hours on end without a single wing beat.” -- *David Attenborough*

Frans Lanting, *Forgotten Edens* National Geographic

“The albatross … manages to remain master of its own course, either being carried all the way around the globe or, on the contrary, making way against the strong winds without a beat of its wings.”

-- *Jacques Cousteau*

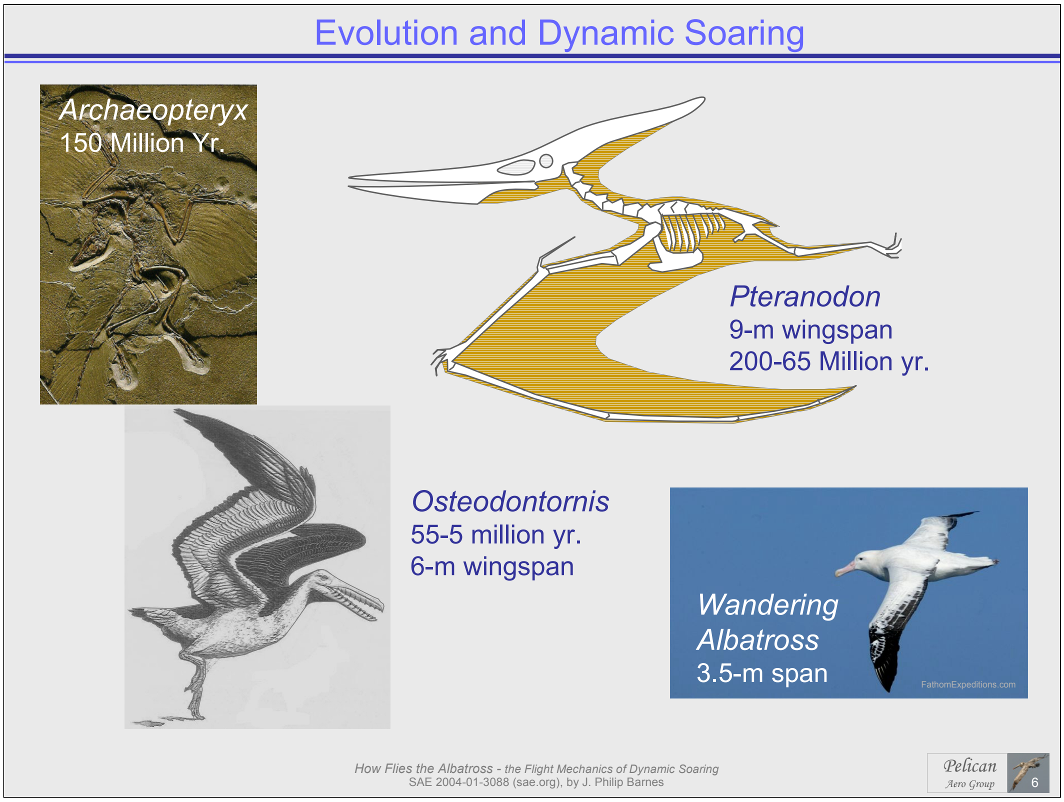
Let’s read these observations by two well-known naturalists…



Our presentation begins by introducing the albatross and its world. We will then model its geometry and aerodynamics, and explain the phenomenon of dynamic soaring. Next we will derive the flight mechanics and then suggest a repertoire of maneuvers. We will finish with real-time computer simulations which show the albatross soaring on locked wings over a waveless sea.

Why would we say “locked wings” and “waveless sea?” First, the albatross rests on its wings with a shoulder lock, skillfully varying wing planform and twist, all without flapping, as it conducts its dynamic soaring maneuvers. Also, waves are not required for dynamic soaring. Of course, the albatross takes advantage of wave lift when it is available. But the waves travel much slower than the wind, and as we shall see, the albatross can make net progress downwind faster than the wind itself. Indeed, whereas the waves progress downwind, we now already know that the albatross can progress overall upwind with dynamic soaring.

Introducing the albatross

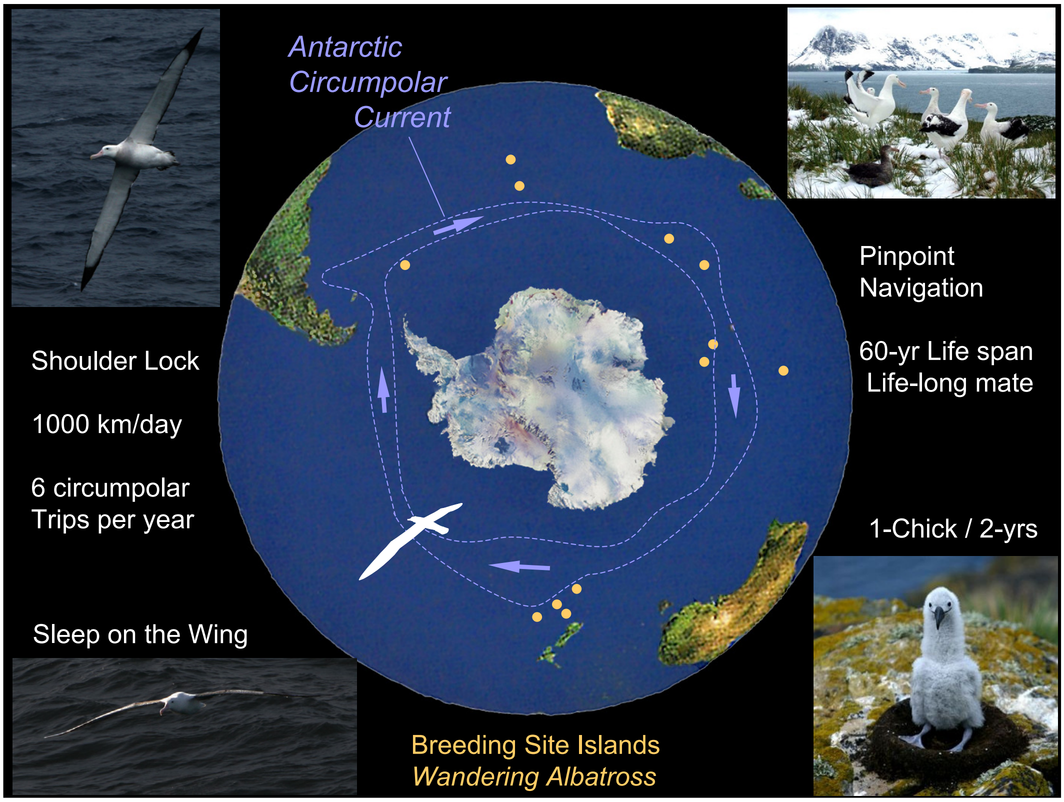


Let's do a little paleontology, starting with *Archaeopteryx*, the warm-blooded and feathered bird-dinosaur which lived 150 million years ago. Perhaps unable to sustain powered flight, *Archaeopteryx* may have used its feathered wings to help control its body temperature, and/or to enable a gliding attack upon its prey after climbing a tree, and/or to enhance its running speed by developing flapping thrust (1).

By around 100 million years ago, modern birds were well along their evolutionary path (2). An early albatross named *Osteodontornis* lived at least over the period between 55 and 5 million years ago. This enormous seabird had a wingspan up to 6-meters. We may be surprised to learn that *Osteodontornis* , and/or its ancestors, shared the ocean skies with the *Pteranodon* sea-going pterosaur. *Pteranodon* was no fleeting evolutionary experiment, having lived as a species for 135 million years. Warm-blooded and in other ways non-reptilian (3), *Pteranodon* perhaps originated the technique of dynamic soaring.

Today, the albatross carries forth the ancient skill of dynamic soaring. The Wandering albatross, the subject of our study herein, is one of 13 albatross species which grace our blue planet. It's 3.5-m wingspan is the largest of any living bird.

(1) Phillip Burgers & Luis Chiappe, "The Wing of Archaeopteryx as a Primary Thrust Generator," Nature, Vol. 399, 1999, p. 60
(2) Joel Carl Welty, "The Life of Birds," Alfred A. Knopf, 1962, p. 483
(3) Adrian Desmond, "The Hot-blooded Dinosaurs," Dial Press, 1976, p. 170-183



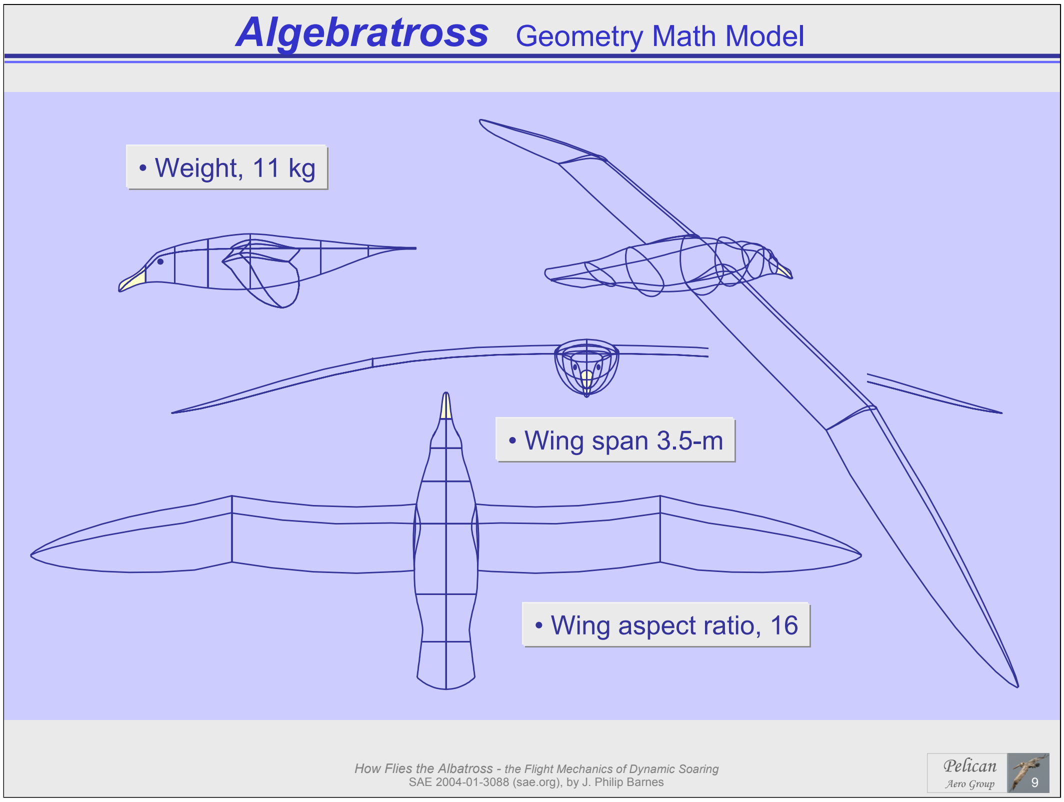
Here's a view of our spaceship Earth. The very thin line around the globe, a graphical artifact, closely represents the actual thickness of our atmosphere. In the center, we see Antarctica, a continent to which the albatross is intimately tied. The Antarctic land mass is depressed almost 1-km by the weight of 2-km of ice. This ice represents about 70% of the world's fresh water, and sea level would rise by 70-m were the ice to melt. Antarctica has numerous ice shelves (including Ross, Ronne, and Larson) and these extend out over the ocean, typically showing 50-m above water, while hiding 250-m below. These ice shelves are the source of tabular ice bergs which break away in lengths up to 300-km.

Every southern winter, Antarctica is enveloped in darkness. During this time it doubles its apparent area by freezing and de-salinating the upper meter of the sea around it. This sea ice advances about 4-km/day. Throughout the year, the Antarctic Circumpolar Current, or ACC, sweeps around the continent. Here, in the roaring forties and furious fifties southern latitudes, the ACC is accompanied by strong and consistent east-bound wind, and on occasion, the largest waves on the planet. The northern and southern fronts of the ACC are marked by sharp changes in water temperature, salinity, and concentrations of phytoplankton and zooplankton. The ACC also represents a huge thermal engine exchanging heat between the northern and southern oceans.

Roughly speaking, the wandering albatross rides the wind above the ACC, although it may wander considerably farther north or south. Feeding primarily on squid, the albatross uses its dynamic soaring technique to travel perhaps 1000 km/day, circumnavigating the continent several times per year. It appears capable of sleeping on the wing.

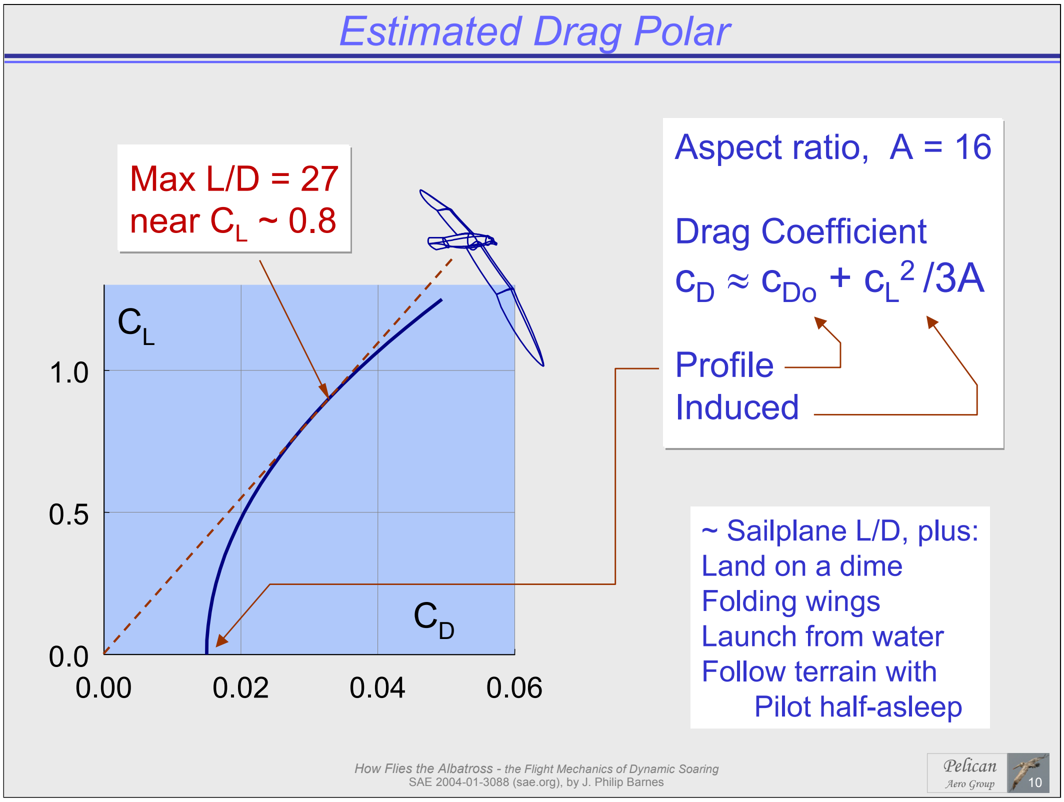
Every other year after about age ten, the albatross navigates with pinpoint accuracy to the island where it was hatched and, with good fortune, greets its life-long mate to raise a single chick. After an initial period of full-time supervision by one parent, the chick is left alone and fed every 5 days as each parent returns separately from a 10-day excursion. The young albatross, on its maiden flight from the nest or a nearby cliff, is capable of immediately implementing or quickly learning the technique of dynamic soaring on its own.

Modeling the albatross



Meet “Algebratross,” modeled with equations from beak to tail, and from wingtip to wingtip. Algebratross weighs 11 kg, or 24-lb. Its 3.5-m wing has an aspect ratio of 16.

As we shall see, high aspect ratio is essential to reduce drag during high-g turns associated with dynamic soaring.



Although we know very little about the wing twist and wing section under flight loads, we do know the body frontal area and wing aspect ratio, A. These are sufficient for a reasonable estimate of the drag polar, which anchored to a “zero lift drag,” adds a parabolic term representing the induced drag. The latter varies with the square of lift coefficient and inversely with the aspect ratio. The “3A” denominator is more accurate than the theoretical value of “pi A.”

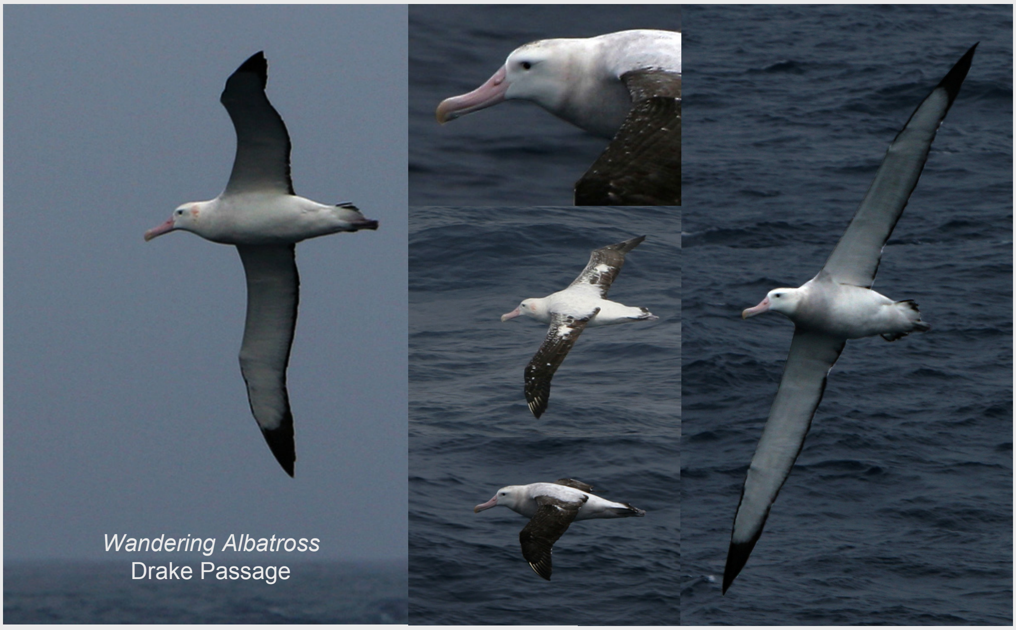
The slope of the line crossing through the origin and tangent to the polar yields a maximum L/D around 27, not much below that of a high-performance sailplane. This means the albatross sinks only one meter when gliding over a distance of 27 meters. As we shall see in our simulations, the albatross enjoys nearly constant, and near-optimal, L/D throughout its dynamic soaring maneuvers.

Although the albatross glides slightly steeper than a sailplane, only the albatross can land on a dime, fold its wings into a compact package, launch itself from the surface of the water, and closely follow the terrain with the pilot half asleep.

Dynamic Soaring

What's New Herein?

- "Wind-step" model yields Dynamic Soaring Rule
- Quantify dynamic soaring force & thrust vectors
- Derive Eqns. of Motion, coordinated maneuvers
- Quantify importance of high aspect ratio & L/D
- Math-modeled schedules of maneuver angles
- Maneuver repertoire, incl. upwind & hovering


Wandering Albatross
Drake Passage

Understanding Dynamic soaring

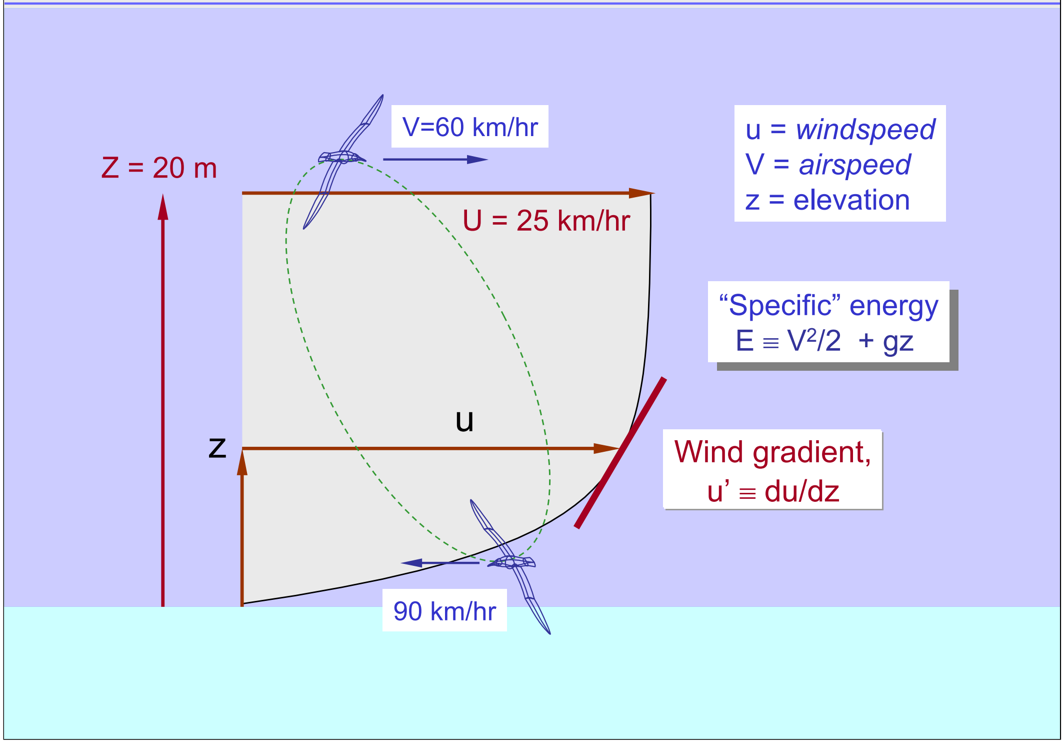
- Wind profile and wind gradient
- Zoom maneuver & total energy
- Moonroof & model airplane analogy
- Finite-step wind profile
- Maneuver Angles
- Equations of motion
- Simulations

We will first take a “qualitative” look at dynamic soaring. To aid our understanding of dynamic soaring, we will first study the wind profile out on the open sea. Next we will examine a circular zoom maneuver and define the total specific energy. Then the moonroof & model airplane analogy, together with a two-step wind profile model, will allow us to quickly grasp the essential principle of dynamic soaring.

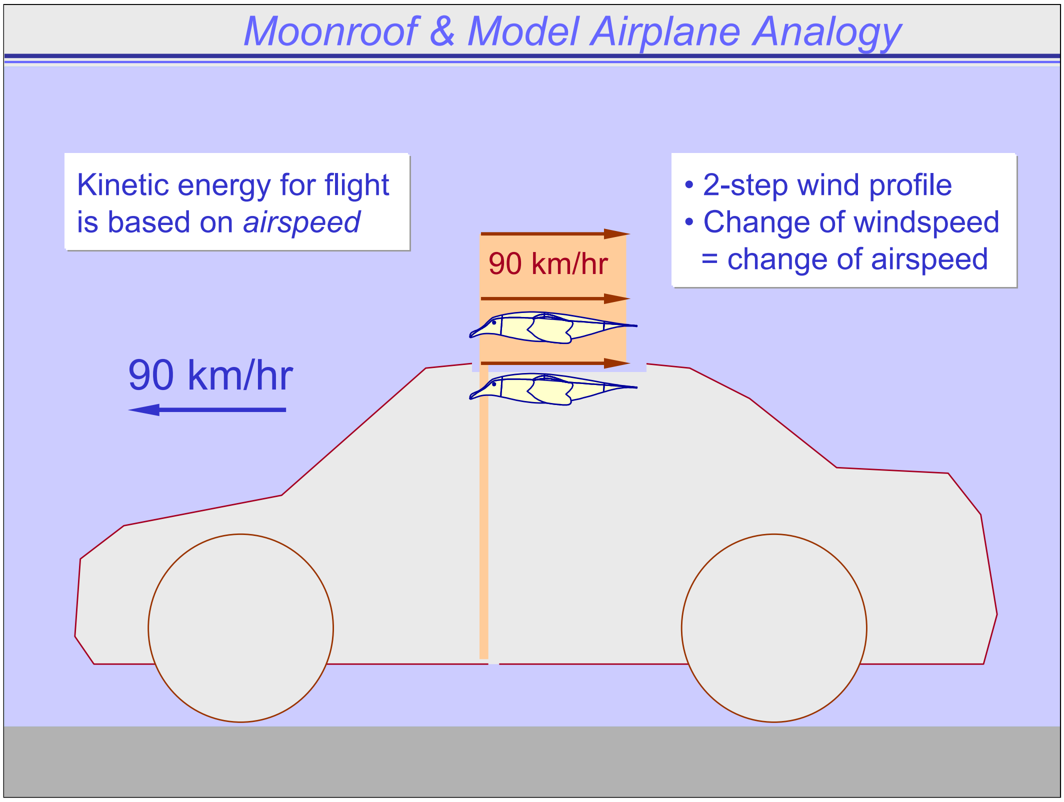
Next, taking strong advantage of physical principles outlined by Isaac Newton, and again modeling the wind profile as a series of finite-steps, we will derive and calculate dynamic soaring thrust. This will yield a “Dynamic Soaring Rule.” We will then relate the centripetal accelerations to the maneuver angles. These accelerations will then be used to derive the equations of motion for coordinated maneuvering.

We will then find ourselves at a crossroads where we will need computer simulations to assess whether dynamic soaring thrust is sufficient to overcome drag to the extent that energy is preserved for each zoom maneuver cycle.

Wind Profile and Gradient



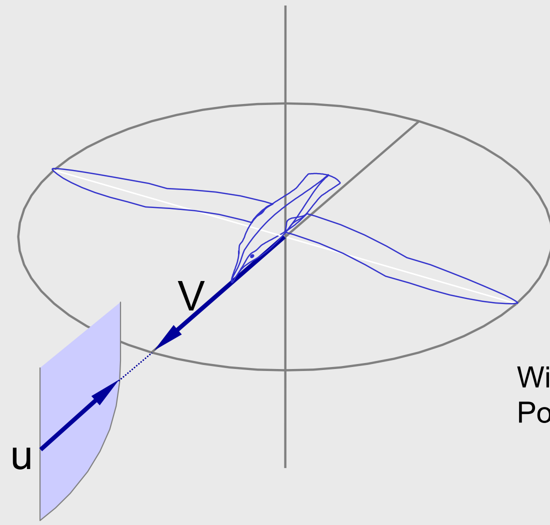
Out on the open ocean, the boundary layer, or wind profile, is about 20-m high. A typical windspeed at the top of the profile is 25 km/hr. We'll designate the windspeed as (u) and elevation as (z). The gradient at any elevation is then du/dz, which we will call "u-prime." The albatross conducts repeated zoom maneuvers within the wind profile, constantly exchanging kinetic and potential energy. Here, the albatross constantly loses energy to drag, but as we shall show, periodically regains energy due to vertical motion in the wind gradient. We'll designate the airspeed as (V), and this is typically about 90 km/hr near the water and 60 km/hr at the top of the zoom.



Let’s say we are driving our car with the moonroof open. Even though there is no one else on the road, we are respecting the speed limit of 90 km/hr. Just beneath the moonroof we hold a model airplane in hand. Although the model at this point is traveling at 90 km/hr it has no airspeed, and thus no usable kinetic energy, relative to the air in the car. Were we to let go of the model it would fall to the floor of the car. If, however, we were to raise the model just above the moonroof, it would suddenly gain 90 km/hr of airspeed and the corresponding amount of kinetic energy. Once released, the model would convert its newfound kinetic energy into potential energy by climbing way up in the sky.

Therefore, kinetic energy for flight must be based on airspeed, not groundspeed. More interestingly, we have in effect applied a simple two-step finite model of the wind profile, and this reveals the essence of dynamic soaring: climbing against the wind profile converts the increase of windspeed to an increase of airspeed, thus providing an energy gain.

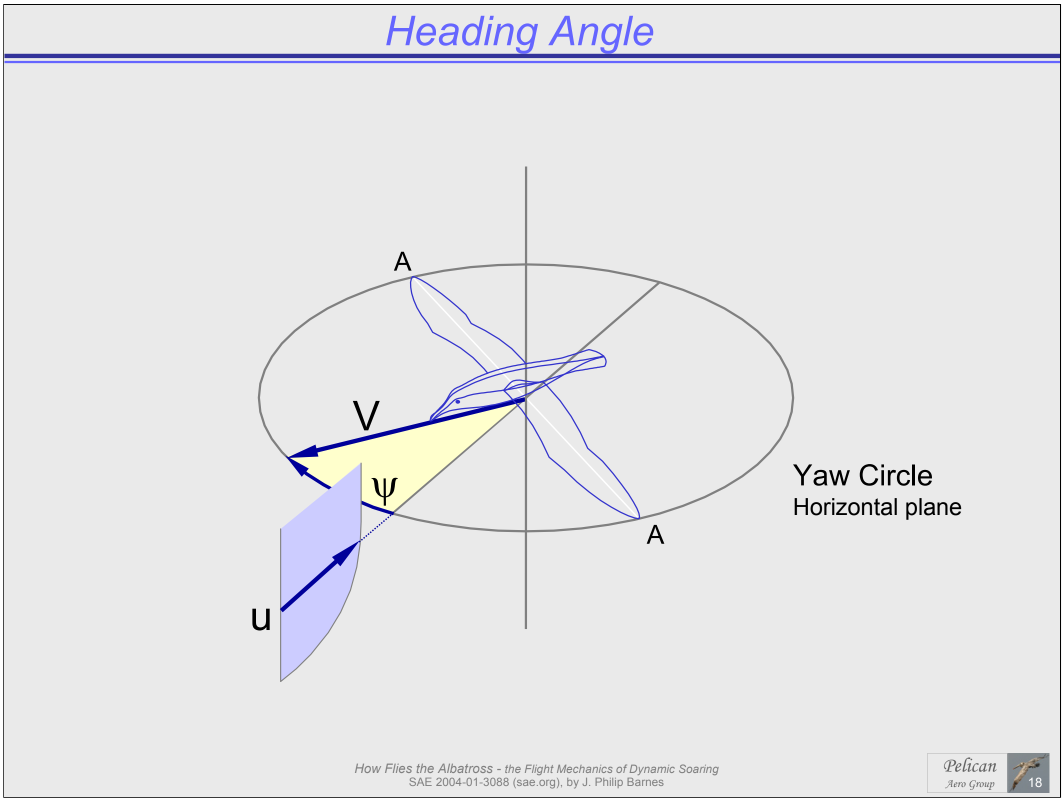
Maneuver Angles ~ Initial Orientation



Wings level
Point upwind

We are now almost ready to quantify the forces associated with dynamic soaring. However, we must first review the maneuver angles. These will affect the quantity and direction of dynamic soaring forces.

Before maneuvering, the albatross points directly upwind with body level and wings level. At this point, the heading, pitch, and roll angles are all zero.

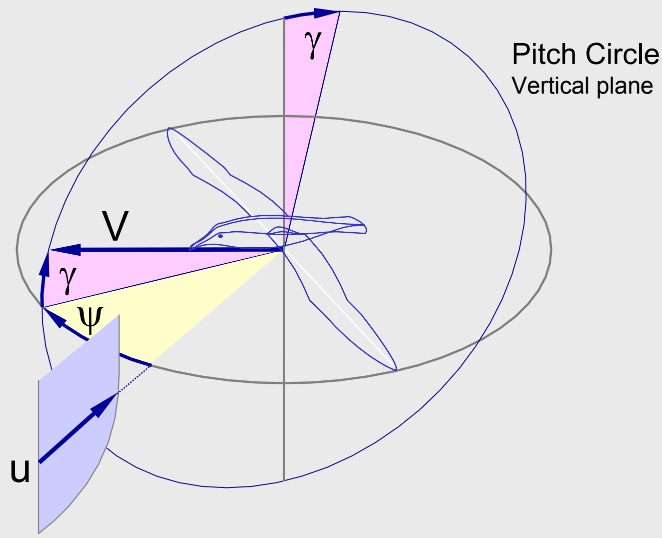


Next the albatross yaws off the wind to the heading angle (psi).

This motion takes place within a horizontal yaw circle.

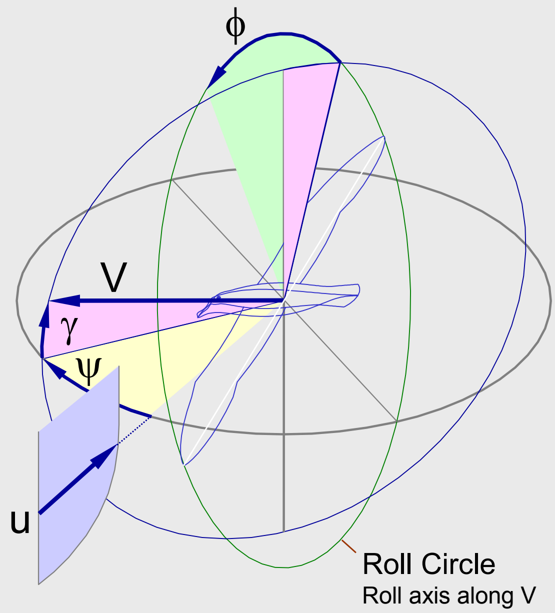
After the yaw, the wingtips form a pitch axis A-A

Flight Path Angle



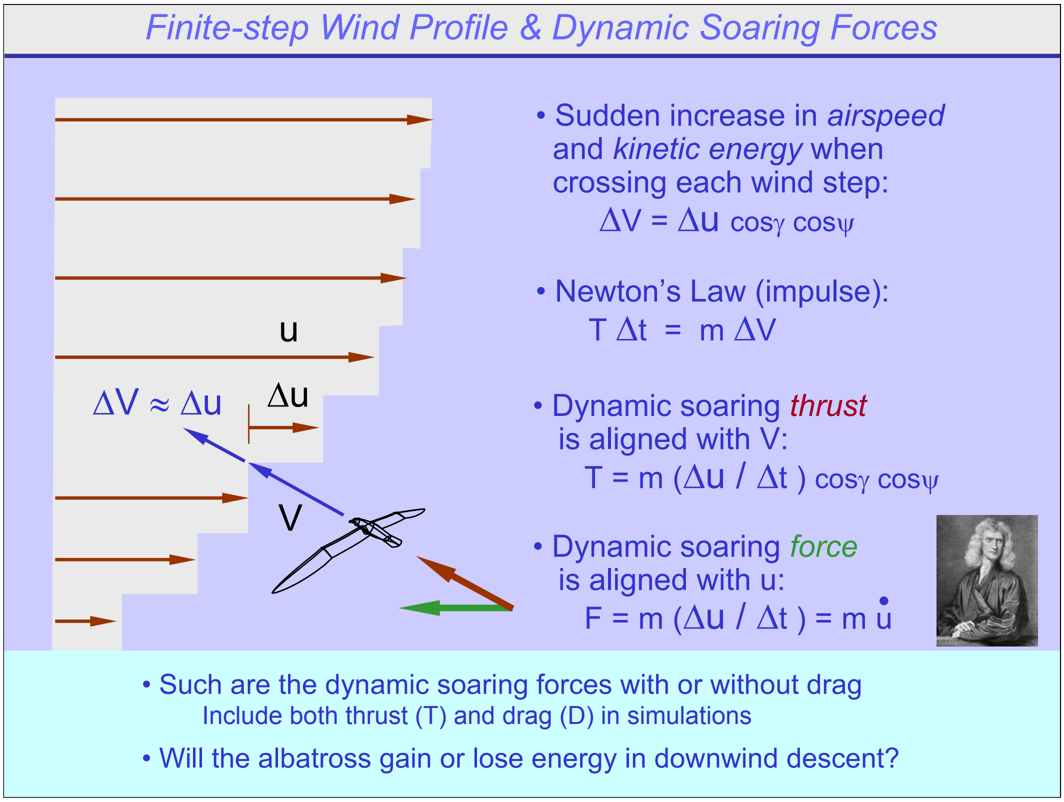
The albatross and airspeed vector together pitch up to the flight path angle, gamma. This motion takes place within a vertical pitch circle.

Roll Angle



Finally, the albatross rolls about the airspeed vector by the angle (phi).

The wingtips sweep out a roll circle which is tilted at the angle (gamma).

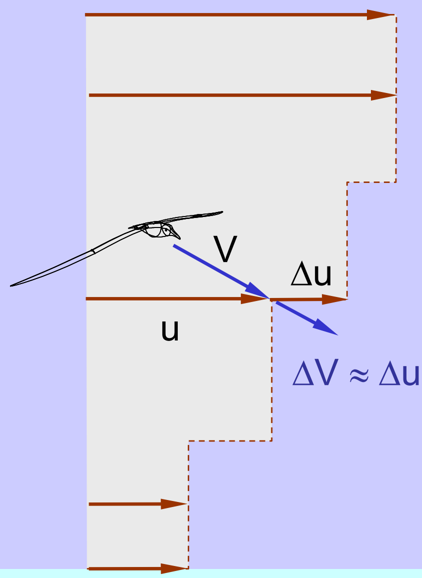


Let's now derive the dynamic soaring forces associated with climbing upwind through a finite step in the wind profile. First, immediately before and immediately after crossing the wind step, the albatross has the same absolute velocity seen by a stationary observer on the ground. However, the airspeed has suddenly increased by an amount (delta-V) which equates roughly to the change in windspeed (delta-u). More precisely, the delta-V depends on the climb and heading angles, gamma and psi.

Second, Newton's law states that the impulse equates to the change of momentum. Combining and re-arranging these two equations obtains the dynamic soaring *thrust*. This vector is aligned with the airspeed. We then deduce from this the dynamic soaring *force,* a vector which lies in a horizontal plane, pointing directly upwind, and having a value proportional to the mass of the bird and the apparent rate of change of windspeed, "u-dot." Notice the similarity to Newton's famous law: force = mass times acceleration. Of course, the wind is not accelerating, but vertical motion in the wind profile gives rise to an *apparent* acceleration of the wind.

These forces arise from crossing the wind profile steps, and thus will have the values shown, with or without the presence of drag. In our simulations, however, we will of course include the effects of both thrust and drag. The next question to arise is this: Does the albatross gain or lose energy upon downwind descent?

Energy Gain, Descending Downwind



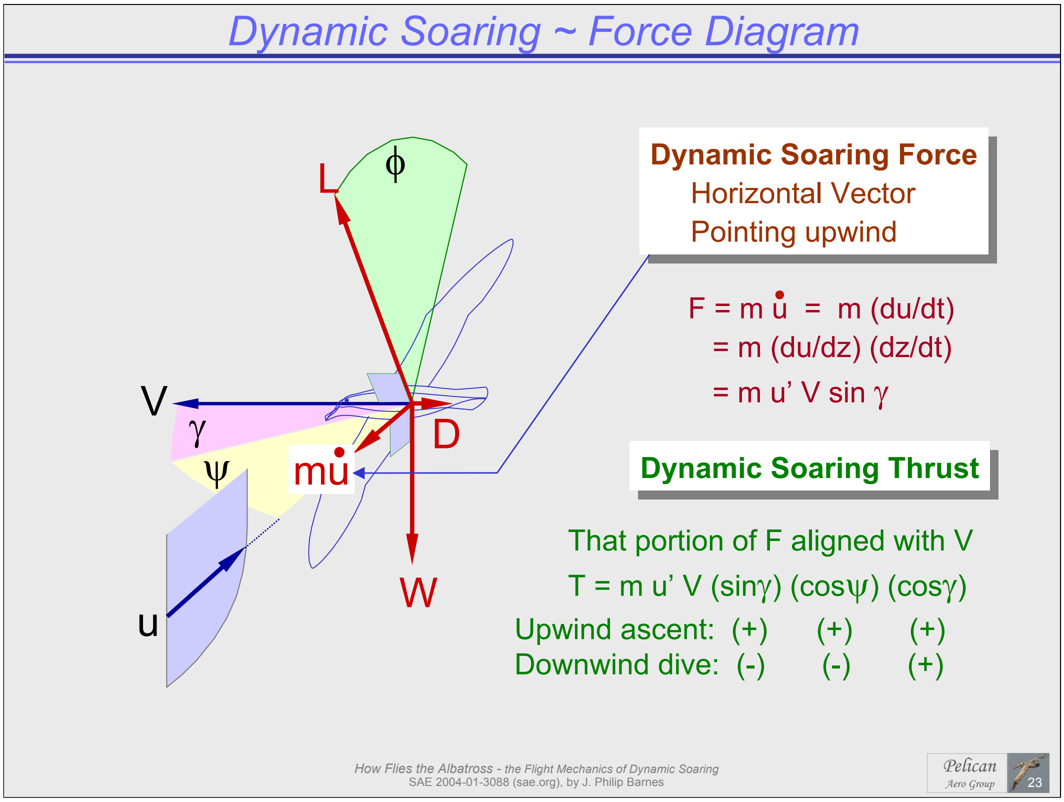
The albatross encounters decreasing tailwind upon downwind descent through each wind profile "step"

Same result as upwind ascent:
Airspeed, V increases by ~ Δu
Kinetic energy (K.E.) increases

Dynamic Soaring Rule (DSR):
Climb when pointed upwind &
Dive when pointed downwind

Can the dynamic soaring forces offset the energy lost to drag?

1. Construct force diagram
2. Derive Eqs. of motion
3. Simulate; follow the DSR



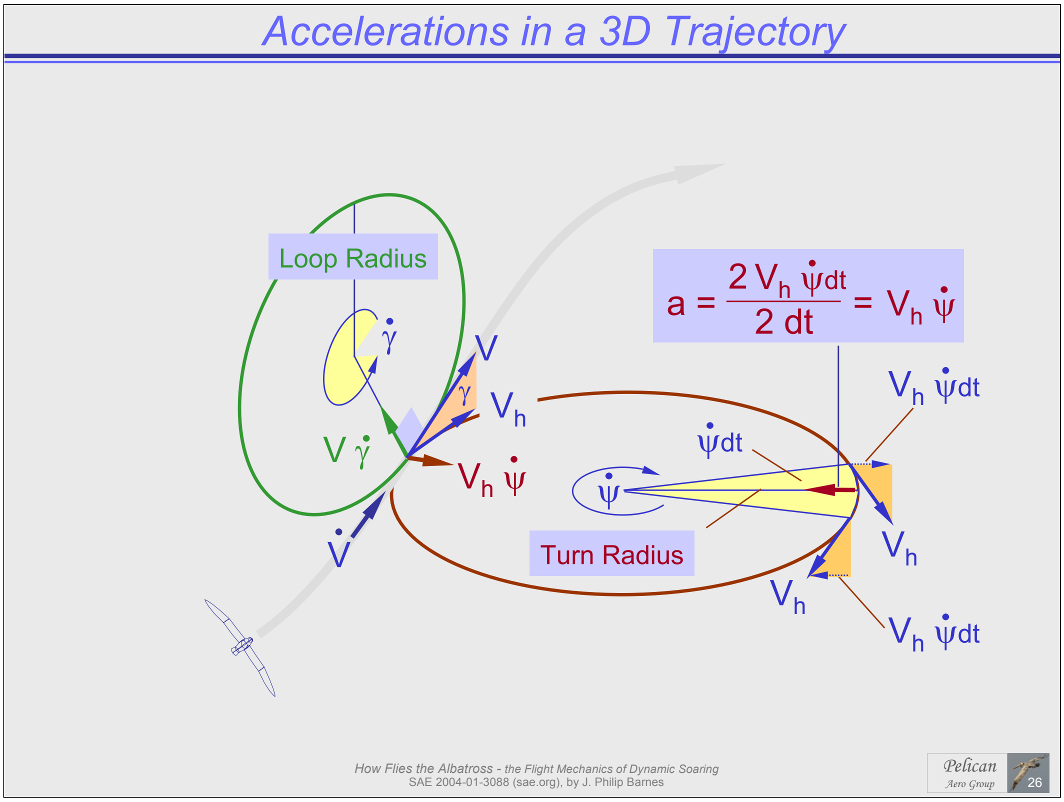
Now that the albatross has maneuvered into position, we show all the forces, including lift, weight, drag, and in particular, the dynamic soaring force. As the albatross maneuvers, this vector of magnitude m du/dt remains steadfastly level and pointed upwind. Components of the dynamic soaring vector will yield thrust, side force, and a slight increase or decrease of lift.

If at any time the albatross were to fly at constant elevation, udot would be zero, and as expected, there would be no dynamic soaring force.

During descent in any direction, udot is negative. Thus, if the albatross were to descend downwind, the dynamic soaring force vector which points upwind with a negative value would in effect point downwind with a positive value. Thus, the albatross extracts thrust from the wind during both upwind ascent and downwind descent.

Flight Mechanics

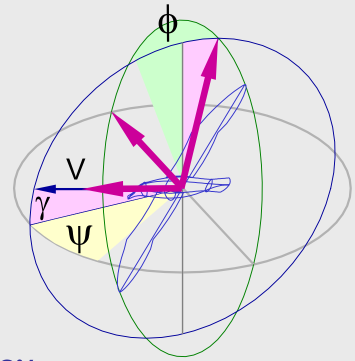

Black-Browed Albatross
Cape Horn



We will apply Newton's Law in three orthogonal directions to evaluate the flight path of the albatross, imagining ourselves to ride in a soap bubble which floats horizontally in the current wind layer. This reduces the problem to trajectory analysis in still air, where the albatross has an airspeed V. First, at any point along the way, the airspeed vector V will be directed along the path and will be inclined at the flight path angle gamma. Let's now designate the horizontal projection of the airspeed vector as Vh. That will be V cos gamma.Taking a view perpendicular to the plane determined by the vectors V and Vh, we can fit a local loop radius to the flight path. Here we imagine the albatross to temporarily leave its flight path and travel as if it were riding a roller coaster loop. Such motion has an angular rate gamma dot. The centripetal acceleration toward the center of the loop is given by the product (V)(gamma dot).

This result may not be obvious to all, so let's take a minute to understand it by studying the motion in the horizontal turning circle. Now looking down on the trajectory, we can fit a local turn radius. Here the albatross can be imagined to travel in a circle at the fixed velocity Vh, sweeping out the heading angle psi at the rate psi dot. A short time (dt) before the albatross sweeps out a small angle psi dot dt, the velocity has a component (Vh psidot dt) parallel to the turn radius and directed away from the center. A short time afterwards, that component points toward the center. The centripetal acceleration is therefore given by Vh psidot, and this is the same at all points along the circle. Finally, we have the tangential acceleration (Vdot), and this will be determined in part by dynamic soaring thrust in relation to drag.

Equations of Motion ~ Apply Newton's Laws



- Sum forces along the flight path
  - $\Rightarrow$ tangential acceleration, $\dot{V}$
- Forces in *vertical* plane normal to V
  - $\Rightarrow$ centripetal acceleration, $V\dot{\gamma}$
- Forces in *horizontal* plane normal to $V\cos\gamma$
  - $\Rightarrow$ centripetal acceleration, $V\cos\gamma\,\dot{\psi}$
- Non-dimensionalize the equations using:
  - Tangential load factor, $n_t \equiv (1/g)\,\dot{V} + \sin\gamma$
  - Normal load factor, $n_n \equiv L / W$
  - Lift-to-Drag ratio, L / D

Now let's apply Newton's Law in three orthogonal directions to obtain the equations of motion. First we sum the forces aligned with the airspeed vector to obtain the acceleration dV/dt, tangential to the flight path.

Next we take all forces in a vertical plane normal to the airspeed vector to obtain the centripetal acceleration V gamma dot.

Likewise, but with a subtle difference, we project the airspeed onto the horizontal plane, obtaining V cos gamma. Then, summing all forces in a horizontal plane normal to this will yield the centripetal acceleration which is proportional to the turn rate.

Finally, we non-dimensionalize the equations in terms of the tangential and normal load factors, and the all-important lift-to-drag ratio, L/D.

Equations of Motion for Dynamic Soaring

1. $u' \equiv du/dz = (U/Z)\, a\, e^{-a\, z/Z}$

2. $$n_t \equiv \dot{V}/g + \sin\gamma = \overbrace{(u'V/g)\sin\gamma\cos\gamma\cos\psi}^{\text{Thrust group}} - \overbrace{n_n(D/L)}^{\text{Drag group}}$$

3. $$n_n \equiv \frac{L}{W} = \frac{(V/g)\dot{\gamma} + \cos\gamma + (u'V/g)\sin^2\gamma\cos\psi}{\cos\phi}$$

4. $$\dot{\psi} = \tan\phi\,(g/V + \dot{\gamma}/\cos\gamma) + u'\tan\gamma\,\{\sin\gamma\,\tan\phi\cos\psi - \sin\psi\}$$

5. $C_L = n_n W / (\tfrac{1}{2}\rho V^2 S)$

6. $D/L \approx (C_{Do}/C_L) + C_L/(3A)$

7. $\dot{x} = u - V\cos\gamma\cos\psi$ downwind
$\dot{y} = V\cos\gamma\sin\psi$ crosswind
$\dot{z} = V\sin\gamma$ vertical

1: Wind gradient
2: Tangential load factor
3: Normal load factor
4: Turn rate
5: Lift coefficient
6: Drag-to-lift ratio
7: Trajectory

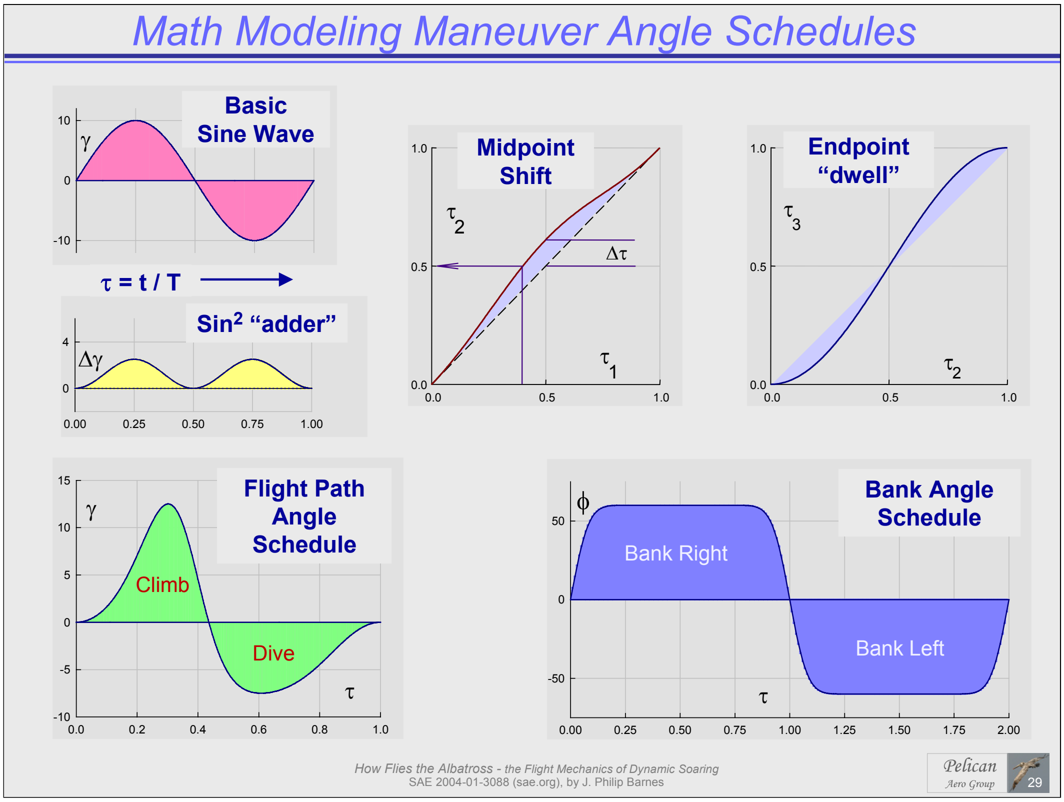
We are now ready to summarize the equations which describe dynamic soaring. Not looking at them too closely, let's just say that they represent the wind gradient, tangential load factor, normal load factor, turn rate, lift coefficient, drag-to-lift ratio, and trajectory. The computer cycles through these several times, every fraction of a second, to track the orientation and trajectory of the albatross.

Note in equation 7 that the downwind velocity "xdot" is given by the local windspeed "u," less the upwind component of the airspeed.

Equation 2 could be designated the "Dynamic Soaring Equation" since it relates the tangential load factor (Nt) to the balance between dynamic soaring thrust and aerodynamic drag. Positive Nt represents increasing energy.

First, note that the dynamic soaring thrust is proportional to both airspeed (V) and wind gradient (u'). Thus, to enhance the dynamic soaring thrust and allow upwind penetration, nature has endowed the albatross with a high airspeed in relation to the windspeed.

Second, note that the drag penalty is increased by the g-load factor (Nn), but is decreased with high L/D. Thus, to minimize energy loss during high-g turns, nature has endowed the albatross with a high aspect ratio wing.



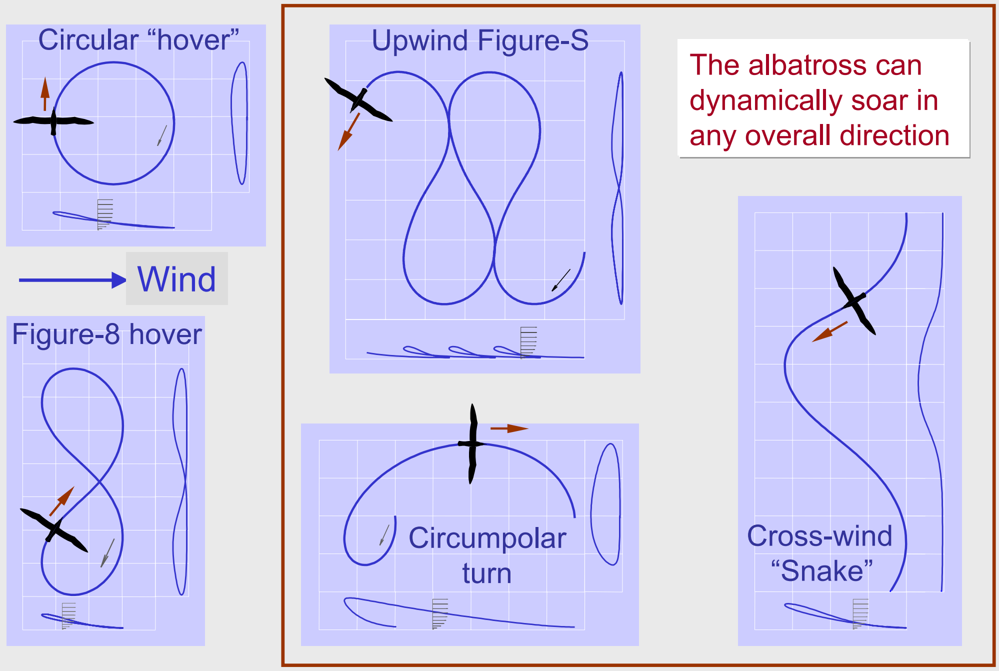
To aid our simulations, we will use simple but powerful math models to "schedule" two of the seven maneuver parameters (3 angles, 3 coordinates, and airspeed), first in accordance with the dynamic soaring rule, and second in such a way as to obtain the desired overall net motion over the water. These schedules are differentiated where applicable (for example to obtain gamma dot and psi dot). Then, given initial conditions (airspeed and elevation at the bottom of the zoom, pointed across the wind), the equations of motion to reveal the response of the remaining maneuver parameters. The iterative scheduling process is complete once the desired net motion is obtained, while matching the initial and final values of both kinetic and potential energy.

Since all dynamic soaring maneuvers are periodic, we can expect the sine wave to be our best mathematical friend in scheduling the climb and bank angles. However, we need to distort the sine wave to meet all of our objectives. Starting with a basic sine wave versus dimensionless time, we can apply a sin-squared adder to adjust the amplitudes. Also, by defining an auxiliary time which adds a bump to the real time, we can accelerate or delay the half-way point. A further auxiliary time simulates a dwell at the beginning and end of the cycle. Resulting schedules for flight path and roll angles, tailored to follow the dynamic soaring rule, might look like this.

Maneuver Repertoire


Grey-headed Albatross
Drake Passage

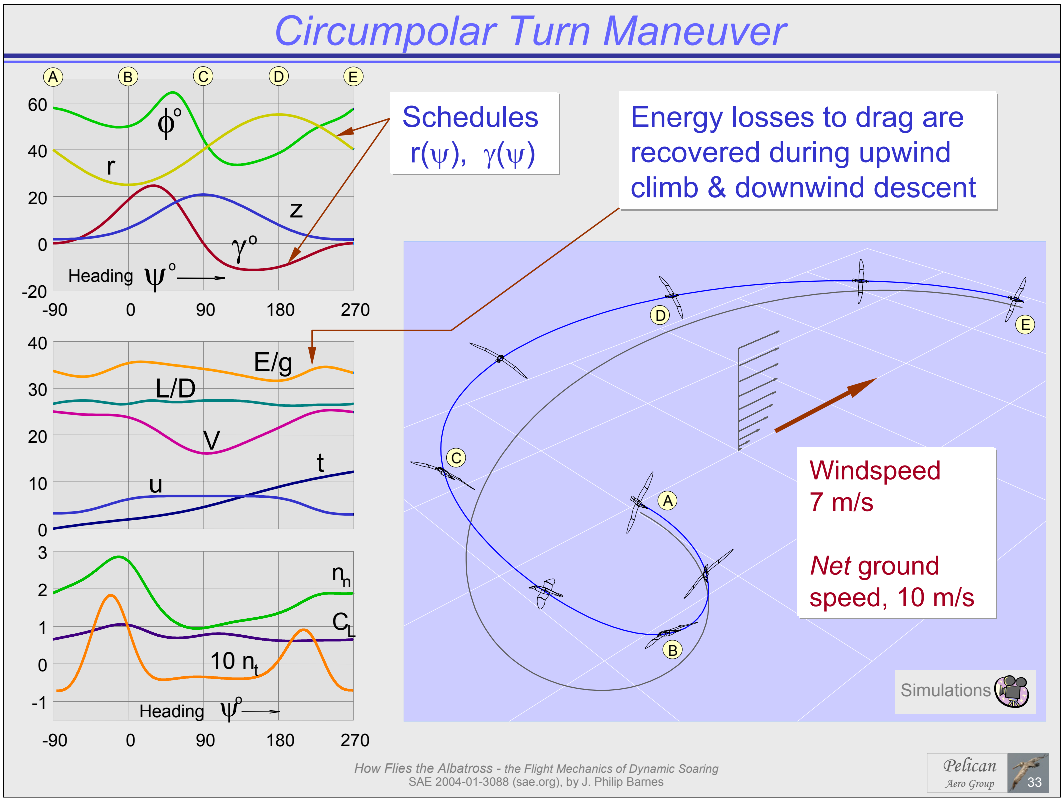
Maneuver Repertoire ~ Observed or Imagined



Here we have imagined a family of maneuvers, each of which has been simulated on the computer and documented in the paper for those interested. For example, the albatross can hover, so to speak, without drifting overall downwind, with a circular or figure-8 groundtrack. It can travel overall directly across the wind, overall straight downwind, or overall directly upwind. As you see, the key word is “overall,” because the albatross is obligated to execute upwind climbs and downwind dives as part of its overall net soaring motion.

In short, although the wind is blowing to the right for these examples, the direction the wind is blowing is of no consequence to an albatross as it soars on shoulder-locked wings from any point A to any point B, overall.

Our real-time simulations will focus on the maneuvers which make either downwind, crosswind, or upwind overall progress.



Now we'll focus on the circumpolar turn maneuver, which which the albatross makes rapid progress overall, straight downwind. The albatross uses this maneuver to travel around the globe several times per year. We'll schedule the turn radius (r) with heading and then calculate the required bank angle for the turn radius. We also schedule the flight path angle (gamma) with a distorted sine wave which follows the dynamic soaring rule. The equations of motion will then reveal the response of all other maneuver parameters, including the airspeed and trajectory.

Most significantly, notice that the energy lost to drag in crosswind flight is restored during the upwind climb and downwind descent. And also, note that the energy is conserved at the end of the cycle.

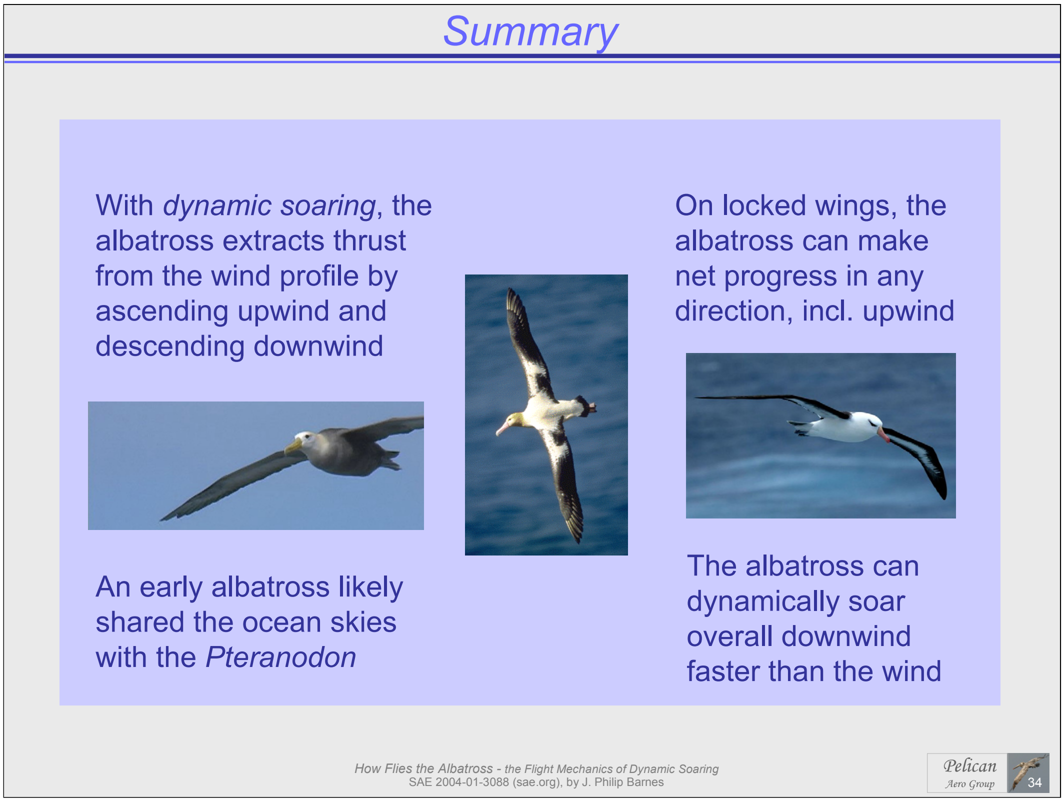
Consistent with the Dynamic Soaring Equation (p. 28), the tangential load factor (Nt) is alternately positive and negative as energy is alternately gained and lost.

Some interesting facts about the circumpolar turn maneuver:

The albatross pulls almost 3-g in the upwind turn.

The L/D is almost constant and near optimal throughout the maneuver.

The overall speed downwind is 40% faster than the wind itself.



In summary, we have explained how the albatross extracts thrust from the wind profile to enable sustained soaring on locked wings in any net direction.

We showed that the albatross can fly overall downwind faster than the wind itself.

Whereas the albatross has graced our blue planet for tens of millions of years, we “modern” humans have only been here about 0.1-million years, and our impact has been pronounced just within the last 0.001-million years.

We close with an excerpt from “Part the Second” of Coleridge’s poem. Let us not bring upon ourselves the lonely fate of the ancient mariner.

From *The Rhyme of the Ancient Mariner* ~ Part the Second

And the good south wind still blew behind;
But no sweet bird did follow,
Nor any day, for food or play,
Came to the mariners' hollo!

Let not the albatross vanish from the earth on our short watch

Further Supporting Evidence

“Albatrosses are the unquestioned champions of gliding flight.… Given wind enough, they travel effortlessly in any direction, upwind as well as down, with hardly a wingstroke…. in irregular circles, figure eights, and letter S’s…”

- Oliver L. Austin, Jr., *Birds of the World,* Golden Press, 1961, p. 32

After the paper was written, this book was found at a local library sale and purchased for $1.

About the Author

Phil Barnes has a Bachelor's Degree in Mechanical Engineering from the University of Arizona and a Master's Degree in Aerospace Engineering from Cal Poly Pomona. He has 25-years of experience in performance analysis and computer modeling of aerospace vehicles and subsystems at a major aerospace corporation. He has authored technical papers on aerodynamics, gears, and orbital mechanics. Drawing from his SAE technical paper of the same title, this presentation brings together Phil's knowledge of aerodynamics, flight mechanics, geometry math modeling, and computer graphics with a passion for soaring flight.