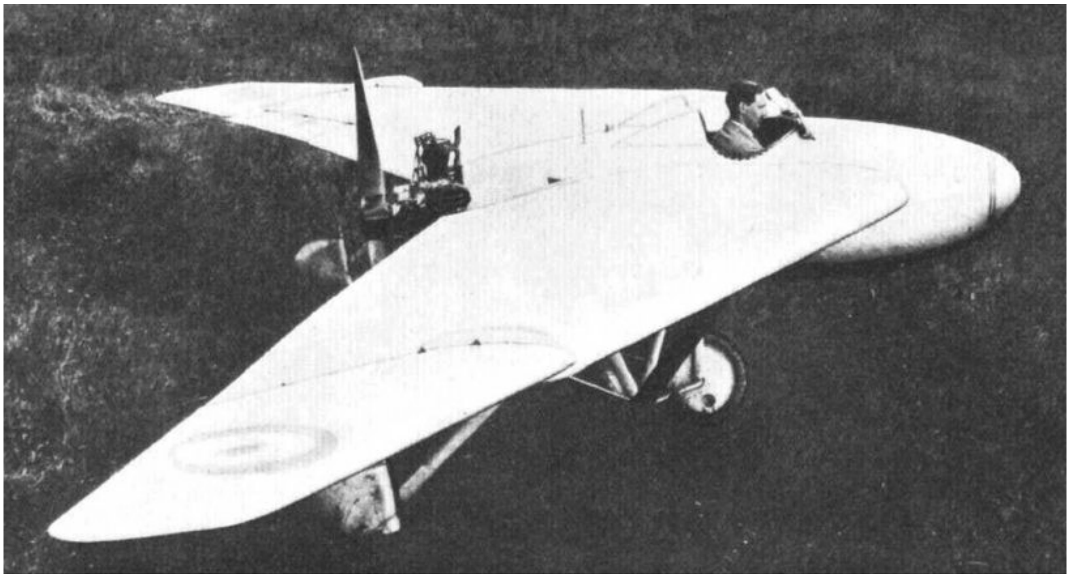
No. 353 NOVEMBER 2015

T.W.I.T.T. NEWSLETTER



Capt., later Prof. Geoffrey T. R. Hill's Westland Pterodactyl lb, first flown in mid-June 1928, was, perhaps, the most visually pleasing of this series of tailless aircraft produced by Westland under his design leadership. Source: http://aviadejavu.ru/Site/Crafts/Craft22263.htm

T.W.I.T.T.
The Wing Is The Thing
P.O. Box 20430
El Cajon, CA 92021

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PRESIDENT'S CORNER

This issue completes Phil Barnes' article on Dynamic Soaring. I hope everyone enjoyed it. If anyone has any comments now that the full text has been published, I would be glad to hear from you and pass it along to Phil for his comments.

I recently had a request for back copies of the newsletters in hard copy. When I starting putting the package together I found we didn't have some issues still available in that format due to earlier requests eating into the small number of extras printed each month. However, in contacting the member I found he would be able to take the issues on a CD and that I could get them on only one disk. This solved the problem of missing copies and also got him the complete set without having to download individual issues from the web site.

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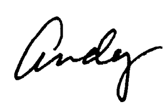
As winter starts showing its face I hope everyone has a warm workshop to work on your favorite project or start a new one.



Dynamic Soaring Update

J. Philip Barnes, Technical Fellow, Pelican Aero Group, San Pedro, CA 90731

(Continued from the October 2015 issue)

We next study data and theory representing the wind speed (w) and its profile. Courtesy of the Department of Meteorology, University of Reading, UK, Figure 11 is an interesting snapshot of a real-time update of the distribution of wind speed at 10m elevation in the southern hemisphere. Antarctica sits in the middle of the graphic, and the color contours reveal that the albatross flies in 10-20 m/s winds as it circumnavigates Antarctica. Figure 12 compares our originally-assumed *exponential* wind profile to the *logarithmic* representation[2] founded on theory and discovered after publication of our earlier paper. Fortuitously, as seen in Figure 13, the wind gradients (w'≡dw/dz) at the above-water elevations visited by the albatross (1 to 15 m) were found to be close overall to those of the logarithmic profile. However, in updating our trajectory modeling to reflect a faster wind, a much more aggressive strategy than that originally assumed must be adopted by the albatross to hold or gain its position against the wind.

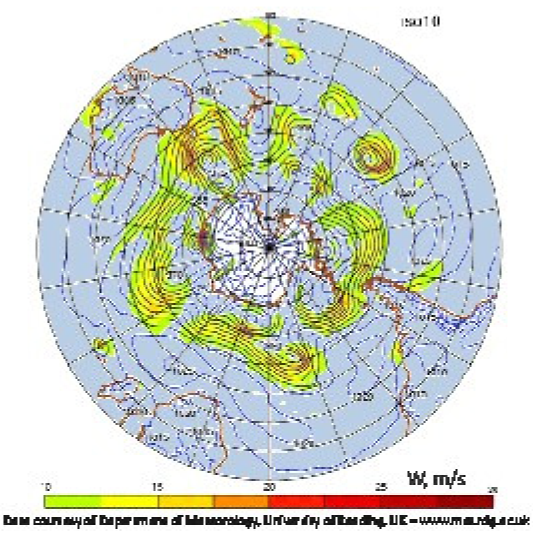


Figure 11. Data, wind at 10m elevation.

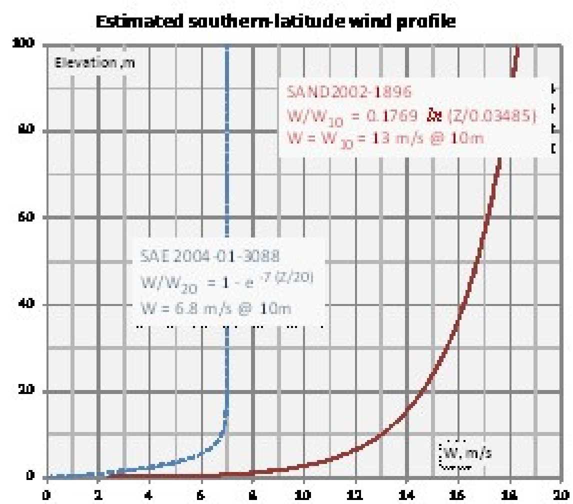


Figure 12. Wind profiles compared.

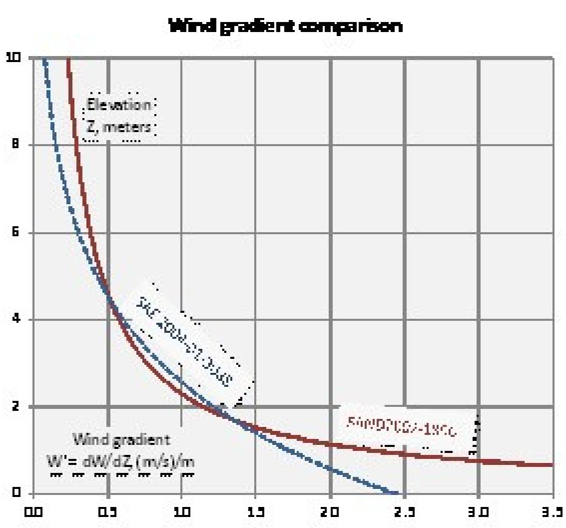


Figure 13. Wind gradients compared.

Given the wind and its gradient, together with the dynamic soaring thrust (T) and definitions of the maneuver angles (ψ,γ,φ), we are in position to analyze a generalized dynamic soaring trajectory. In Figure 14, we first look from the side to fit a local "roller coaster loop" radius of curvature, and observe that the acceleration toward the center of that circle, as first shown by Isaac Newton for any circle, is given by the product of the peripheral velocity (V) and angular rate (dγ/dt). Similarly, we can look down upon the trajectory to fit a horizontal circle with acceleration toward its center given by the product of the airspeed "shadow" (Vcosγ) and heading rate of change (dψ/dt). The third acceleration, that along the flight path, is obtained from the dynamic soaring thrust, opposed by drag (D) and weight component (Wsinγ). These instantaneous accelerations, using Newton's Law for the three orthogonal directions, apply to the albatross relative to the current "layer" of air which is carried downstream at the wind speed (w) of the current elevation. Knowing this, we can then track the trajectory in terms of the rates of change of the three coordinates (x,y,z), with (x) directed downwind and (z) directed "up."

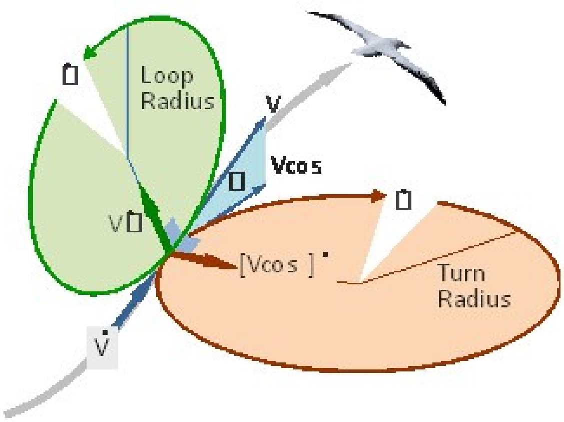


Figure 14. Orthogonal Accelerations.

$$\frac{D}{W} = \frac{L}{W}\frac{D}{L} = n_n \frac{D}{L} \qquad (08)$$

Thrust group — Drag group

$$n_t \equiv \dot{V}/g + \sin\gamma = \overbrace{T/W}^{\text{Thrust group}} - \overbrace{n_n(D/L)}^{\text{Drag group}} \qquad (09)$$

$$n_n \equiv \frac{L}{W} = \frac{(V/g)\,\dot{\gamma} + \cos\gamma + (w'V/g)\sin^2\gamma\cos\psi}{\cos\phi} \qquad (10)$$

$$\dot{\psi} = \tan\phi(g/V + \dot{\gamma}/\cos\gamma) + w'\{\sin\gamma\tan\phi\cos\psi - \sin\psi\}\tan\gamma \qquad (11)$$

$$C_L = n_n W/(\tfrac{1}{2}\rho V^2 S) \qquad (12)$$

$$D/L \approx (C_{Do}/C_L) + C_L/(3A) \qquad (13)$$

$$\begin{cases} \dot{x} = w - V\cos\ \ \cos & \text{downwind} \\ \dot{y} = V\cos\ \ \sin\ \ w & \text{crosswind} \\ \dot{z} = u + V\sin & \text{vertical} \end{cases} \qquad (14)$$

Figure 15. Dynamic soaring equations of motion.

Next, EQs (8-to-14), grouped in Figure 15 as the *Dynamic Soaring Equations of Motion*, non-dimensionalize the forces and relate the airspeed, wind gradient, normal load factor (n_n), bank angle (φ), tangential load factor (n_t), heading rate (dψ/dt), lift coefficient (c_L), drag-to-lift ratio (D/L) and coordinate rates (dx/dt, dy/dt, dz/dt). Now stepping back for a broader view, we observe that the albatross uses its tail and wingtip variable geometry for complete control of its flight path angle (γ) and roll angle (φ) or heading (ψ). Given any two of the maneuver angles, and where necessary their rates, the equations of motion together with the airspeed (V) will determine all other instantaneous rates for the trajectory. Here, a pair of maneuver angles such as (γ, ψ) or (γ, φ) can be scheduled to satisfy the *Dynamic Soaring Rule* while also yielding overall motion in a direction such as downwind, crosswind, or upwind. Such scheduling can be taken, for example, versus heading (ψ) or a dimensionless time (τ ≡ t/tc) where (t_c) represents the cycle duration. In Figure 16, we model the most challenging maneuver of the albatross' repertoire, that of "snaking" upwind on shoulder-locked wings. At upper left are found the schedules γ(τ) and ψ(τ). Both are math modeled using $\sin^m(\tau\pi)$. The required bank angle (φ) is then calculated with a formula from our earlier study[3]. Both schedules are readily differentiated to yield the heading rate (dψ/dt) and rate of change (dγ/dt) of flight path angle. At mid-left, we see that the total specific energy (E/g) is conserved.

At the top-center we show three orthographic views of the trajectory, including "wind off" for the plan view. The objective of penetrating upwind, while observing the dynamic soaring rule and preserving total energy overall, requires maximizing the time spent headed upwind and minimizing the time spent headed crosswind or downwind. The strategy must also include optimizing the airspeed to enhance dynamic soaring thrust, both upwind and downwind, while preserving aerodynamic efficiency in the form of the lift-drag ratio (L/D) and avoiding a large altitude excursion which would promote greater downwind drift. Furthermore, the trajectory must yield reasonable bank angles and a peak normal load factor consistent with wing structural limits. At bottom left we see that the maneuver includes 2g and 3g turns.

The chosen trajectory then consists of a 21^{o} left "tack" upwind, rapid diving right turn across the wind, and rapid climbing left-hand turn, returning to the original tack. Although the maneuver rates and angles (γ, ψ) are scheduled with symmetry, the right-hand turn at the top of the maneuver is taken at lower airspeed (V) than the left-hand turn taken at the bottom. Thus the lower turn radius [r ≈ V/(dψ/dt)] is larger, leading to overall crosswind drift. This is best illustrated by the "wind off" trajectory (dashed curve) seen at the top-center of the figure.

Nevertheless, by tracking the limits of the "wind on" trajectory (solid curves, top-center and bottom-right), we see that the albatross makes overall progress of 2.9 m/s upwind against a 13 m/s headwind, while drifting laterally at 3.4 m/s. Presumably, the albatross will periodically "mirror image" the maneuver to cancel the lateral drift overall, assuming its final goal is direct upwind progress.

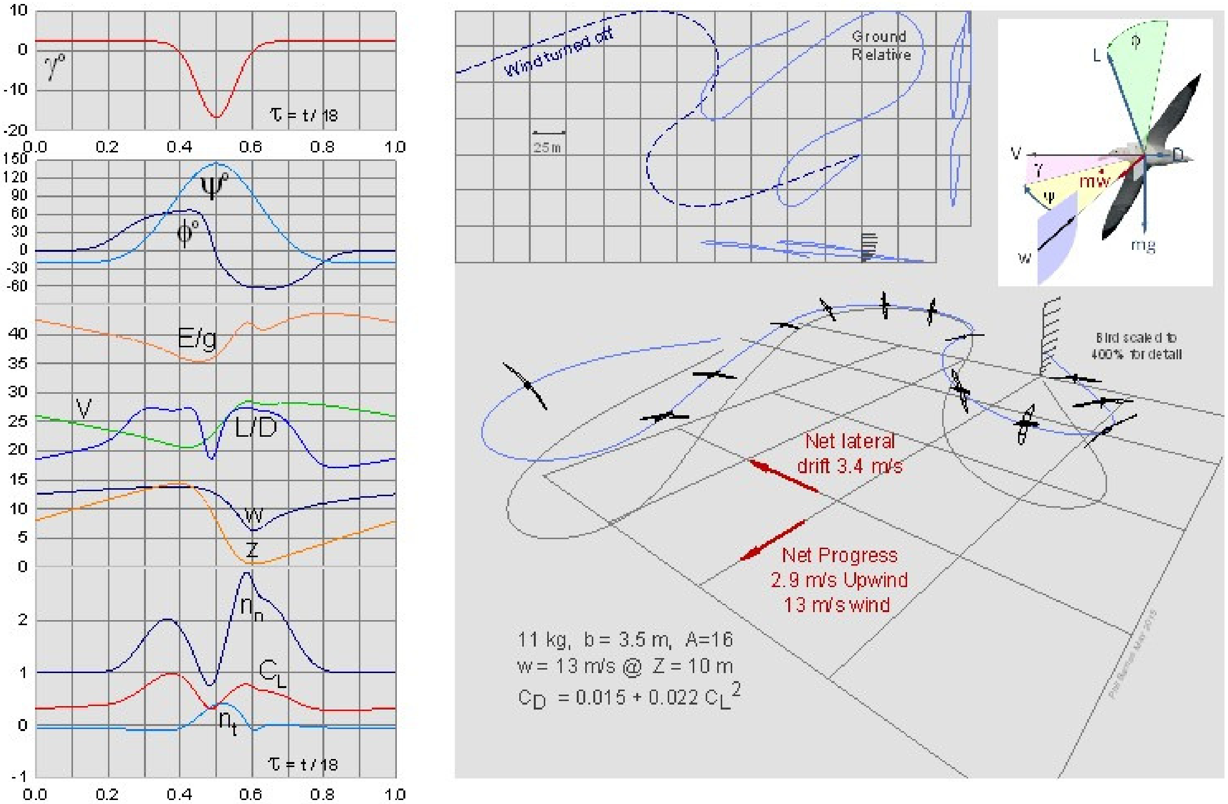


Figure 16. Upwind snake maneuver.

Returning to mid-left of Figure 16, we see that the airspeed (V) cycles between 20 and 26 m/s, with lift-drag ratio (L/D) averaging about 23. These and other trajectory parameters exhibit a "bump" as the wind (w) of 13 m/s at elevation (z=10m) passes through a minimum of 6 m/s at the minimum elevation of about 1m. Conservation of cycle energy is quite sensitive to this minimum modeled elevation which is shortly followed by significant energy gain. With our albatross' wingspan specified as 3.5m and with the bank angle exceeding 60°, one wingtip will be under water unless the albatross times, as it may well do, the dip in elevation to coincide with a wave trough. This suggests our original assertion that dynamic soaring is possible over a wave less sea may have to be reconsidered.

Although we will always have more to learn about the dynamic soaring technique of the albatross, we suggest that further study need not be expended on the question of "airspeed" versus "inertial speed." The flight path angle (γ) rarely exceeds 15° in albatross dynamic soaring maneuvers, whereby the groundspeed differs from inertial speed by no more than 3.5%. As seen in Figure 17, the albatross flies into the relative wind, which represents its airspeed. Rarely aligned with the wind, and thus rarely aligned with its ground track, the albatross will most often be seen by a stationary observer to exhibit apparent sideslip. Airspeed may differ from groundspeed often by a factor of two or more. Since, according to Lord Rayleigh, the energy at the disposal of the bird

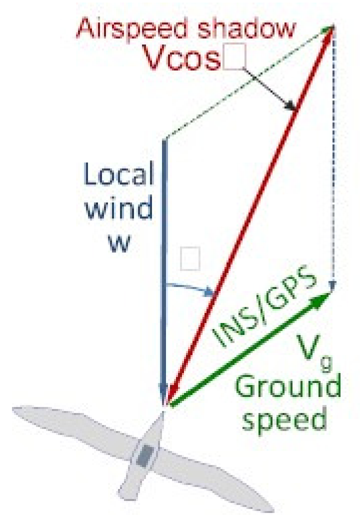


Figure 17. Speed Vectors

depends on its airspeed, the use of "bird backpack" inertial speed (in effect groundspeed) to characterize flight kinetic energy will yield an error factor exceeding 4.0 for the conditions shown in Figure 17. Nevertheless, this does not discount the usefulness of the inertial or GPS data which correctly informs us of the ground track, elevation excursion, cycle time, and distance covered by the albatross. But to use the inertial velocity to draw conclusions as to where energy is gained or lost in the dynamic soaring cycle, the wind vector and profile must be known and the local airspeed at each elevation must be synthesized by vector operations including the climb rate, inertial speed, and wind speed at each elevation under study.

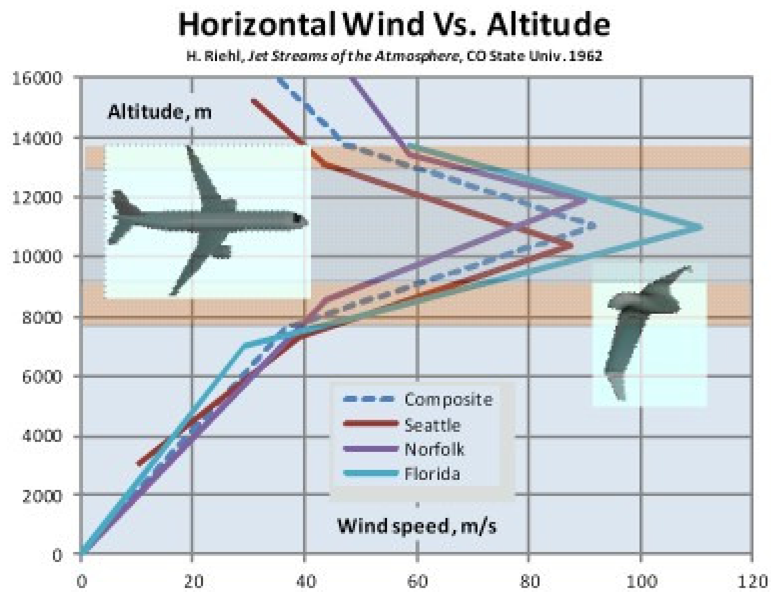


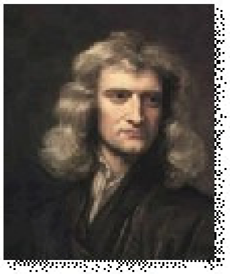
Figure 19. Jet stream wind and wind gradients

Finally, we are led to ask if "flat-terrestrial" dynamic soaring is feasible. Unfortunately, wind gradients near the ground are usually far from adequate to support dynamic soaring. Even in a jet stream (Figure 18), which exhibits the wind speed data[10] of Figure 19, the wind gradients are at best an order of magnitude below those exploited by the albatross. We learned from (Eqs 7,9) that dynamic soaring thrust/weight is proportional to airspeed and wind gradient. Thus, the airspeed for jet stream dynamic soaring must be at least an order of magnitude above that of albatross, while avoiding the transonic drag rise to preserve the necessary high (L/D). Setting both heading (ψ) and tangential load factor (n_t) to zero in (Eqs 7, 9), we obtain a basic criterion for dynamic soaring feasibility by requiring the dynamic soaring thrust to cancel drag overall in a cyclic zoom, whereby w'(V/g)(L/D) sinγ > 1, with significant excess over unity likely required to accommodate the necessary crosswind turns. Of course, a jet stream DSA must avoid commercial transport cruising altitudes, and it must at all altitudes have reliable collision-avoidance autonomy. Fortunately, a 1-km band for dynamic soaring resides near 8.5 km altitude. Jet stream dynamic soaring feasibility will be the subject of further study with simulation.

Figure 18. Polar and subtropical jet streams
courtesy of National Oceanic and Atmospheric Admin.

IV. Conclusion

For our ongoing study of dynamic soaring, we theoretically validated and quantified Lord Rayleigh's qualitative description with our direct derivation of dynamic soaring thrust. We showed the importance of characterizing flight kinetic energy with airspeed, not inertial speed which, for the albatross, is effectively its groundspeed. We introduced new and/or better characterizations of the wind and its profile in the southern hemisphere, and applied these in a simulation showing the albatross using dynamic soaring to progress overall upwind. We reviewed data representing the wind and its gradients in the jet stream and showed that a dynamic soaring aircraft therein must fly much faster than the albatross, while preserving a high lift-drag ratio. We noted that much remains to be learned about the dynamic soaring of the albatross, including the role of the waves, and we recommended further study of the feasibility and trajectories of jet stream dynamic soaring.



Acknowledgments

This paper is dedicated to Sir Isaac Newton, for his fundamental discovery of the "quantity of motion."

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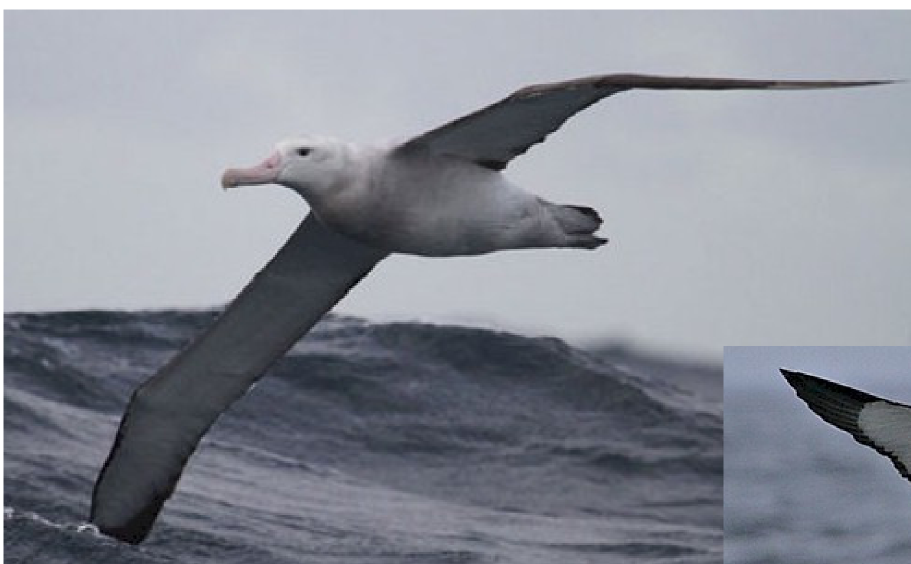
[3] Barnes, J.P., "How Flies the Albatross – the Flight Mechanics of Dynamic Soaring," SAE 2004-01-3088, 2004.

[4] Sachs, G., et.al.,"Dynamic Soaring of Albatrosses Over Land," AIAA 2013-4842, 2013, p. 3-4.

[5] Sachs, G., et.al., "Flying at No Mechanical Energy Cost: Disclosing the Secret of Wandering Albatrosses," PLOS One,
Sept. 2012, Vol. 7, Issue 9, p. 2-5.

[10] Riehl, H., "Jet Streams of the Atmosphere," Colorado State Univ., 1962.

Examples of the Wandering Albatross.



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Tailless Aircraft Bibliography

My book containing several thousand annotated entries and appendices listing well over three hundred tailless designers/creators and their aircraft is no longer in print. I expect *eventually* to make available on disc a fairly comprehensive annotated and perhaps illustrated listing of pre-21st century tailless and related-interest aircraft documents in PDF format. Meanwhile, I will continue to provide information from my files to serious researchers. I'm sorry for the continuing delay, but life happens.

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