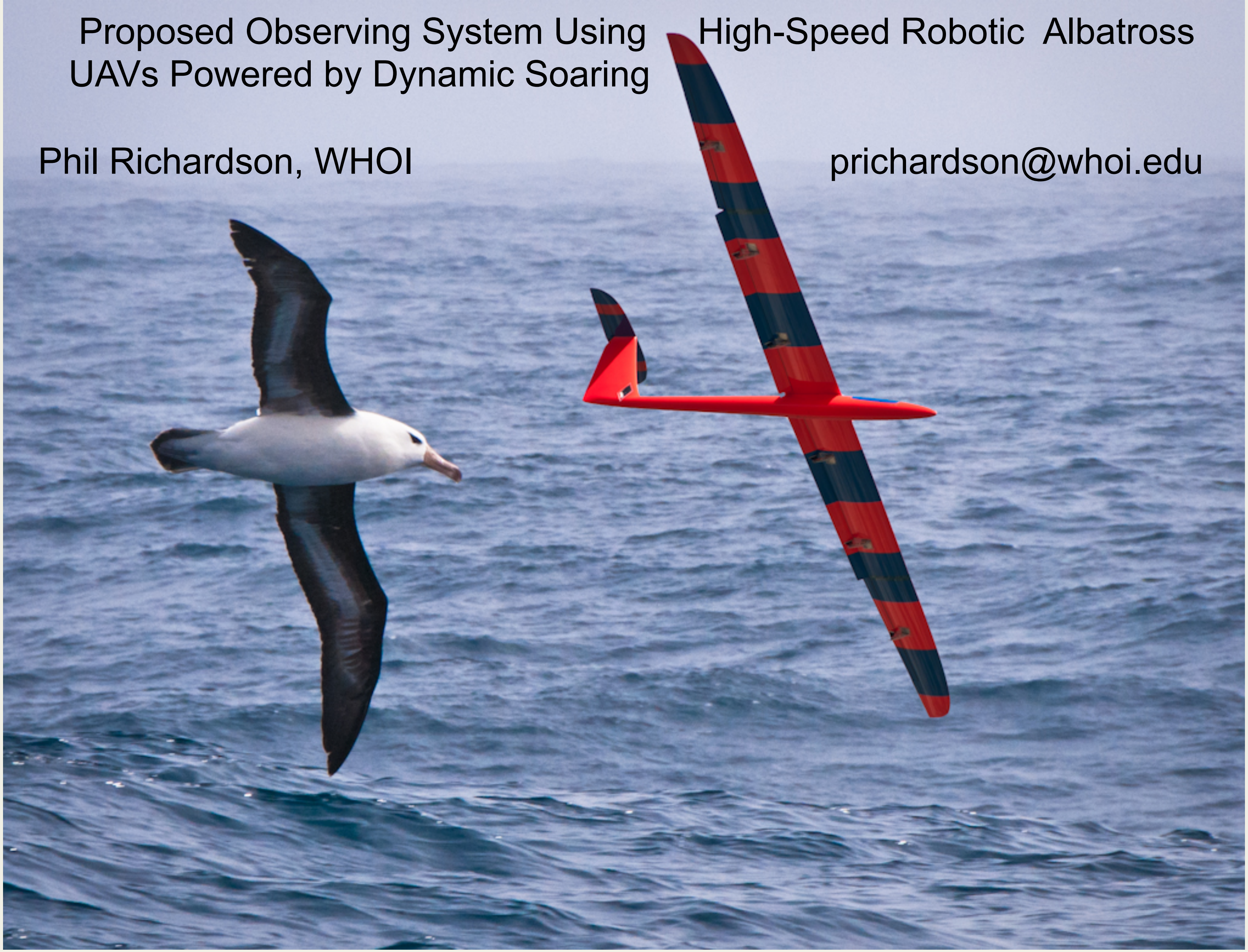
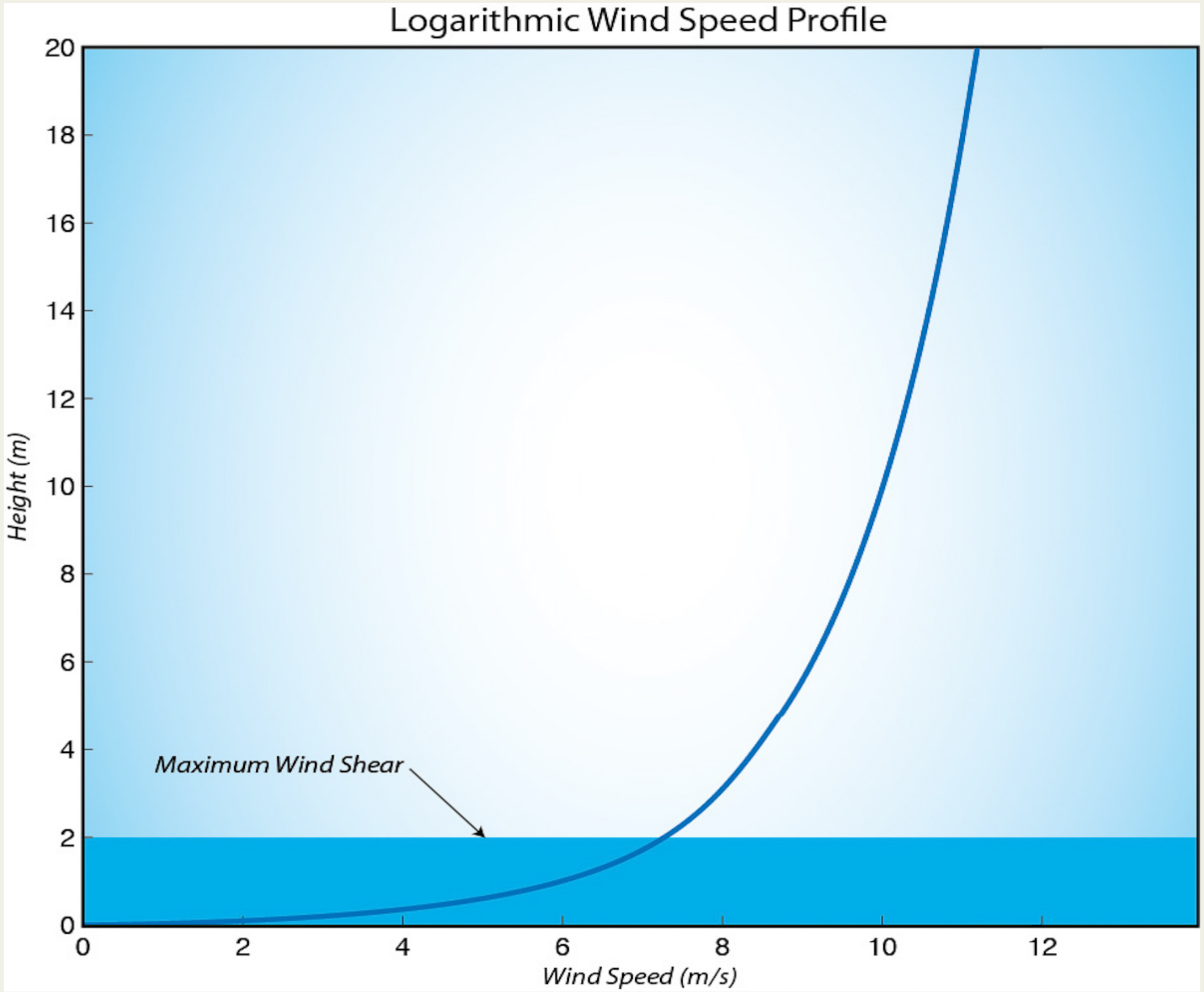


Conceptual illustration of a robotic albatross UAV dynamic soaring over the ocean. A photo of a Kinetic 100DP glider flown by Spencer Lisenby at Weldon Hill, California was superimposed onto a photo of a black-browed albatross soaring over the Southern Ocean. Photos by Phil Richardson

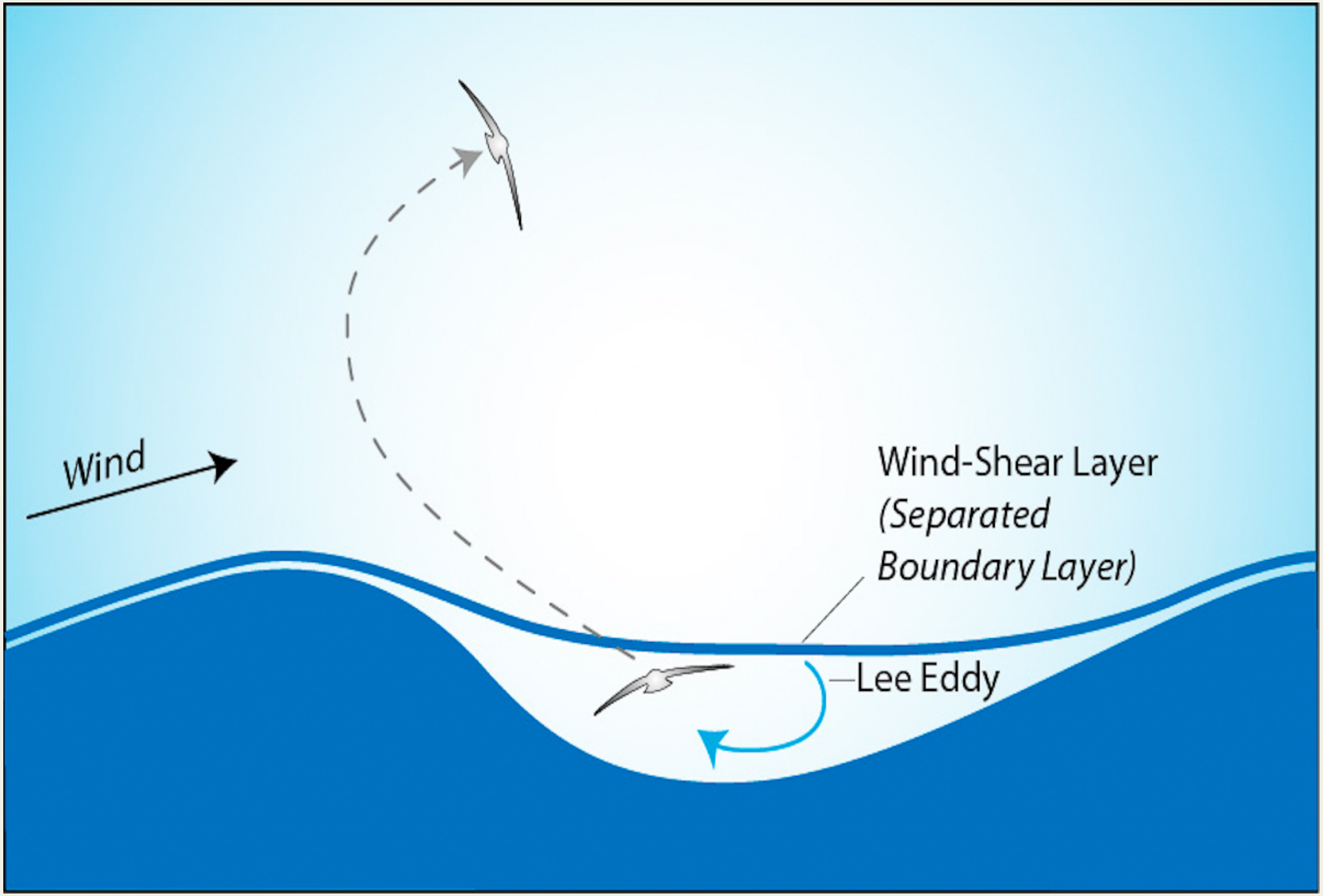
Abstract

Proposed Observing System Using High-Speed Robotic Albatross UAVs Powered by Dynamic Soaring

Albatrosses exploit the vertical gradient of wind velocity (wind shear) above ocean waves to gain energy for long distance energy-neutral dynamic soaring at typical albatross airspeeds of 16 m/s. Recently, pilots of radio-controlled gliders have exploited the wind shear associated with winds blowing over mountain ridges to achieve very fast glider speeds, reaching a record of 224 m/s (500 mph). A two-layer model of dynamic soaring suggests that maximum glider airspeed is around 10 times the wind speed of the upper layer for wind speeds > 5 m/s. In principle, a glider could soar at a speed of 100 m/s in a wind speed of 10 m/s and cross the Atlantic in less that a day. It is suggested that recent high-performance RC gliders and their pilots' expertise could be used to help develop a high-speed robotic albatross UAV (unmanned aerial vehicle), which would be useful for measurements of the atmospheric boundary layer, the sea surface, and air-sea interactions. Such a UAV would exploit air-sea interactions for dynamic soaring. One can imagine that future fleets of such UAVs could routinely survey large areas of the ocean. The fastest survey mode would be along diagonal lines with respect to the wind, at maximum possible travel velocities of around 86 m/s (in 10 m/s wind). In practice probably somewhat slower travel velocities could be realized but still much faster that typical albatross diagonal travel velocities of around 14 m/s.

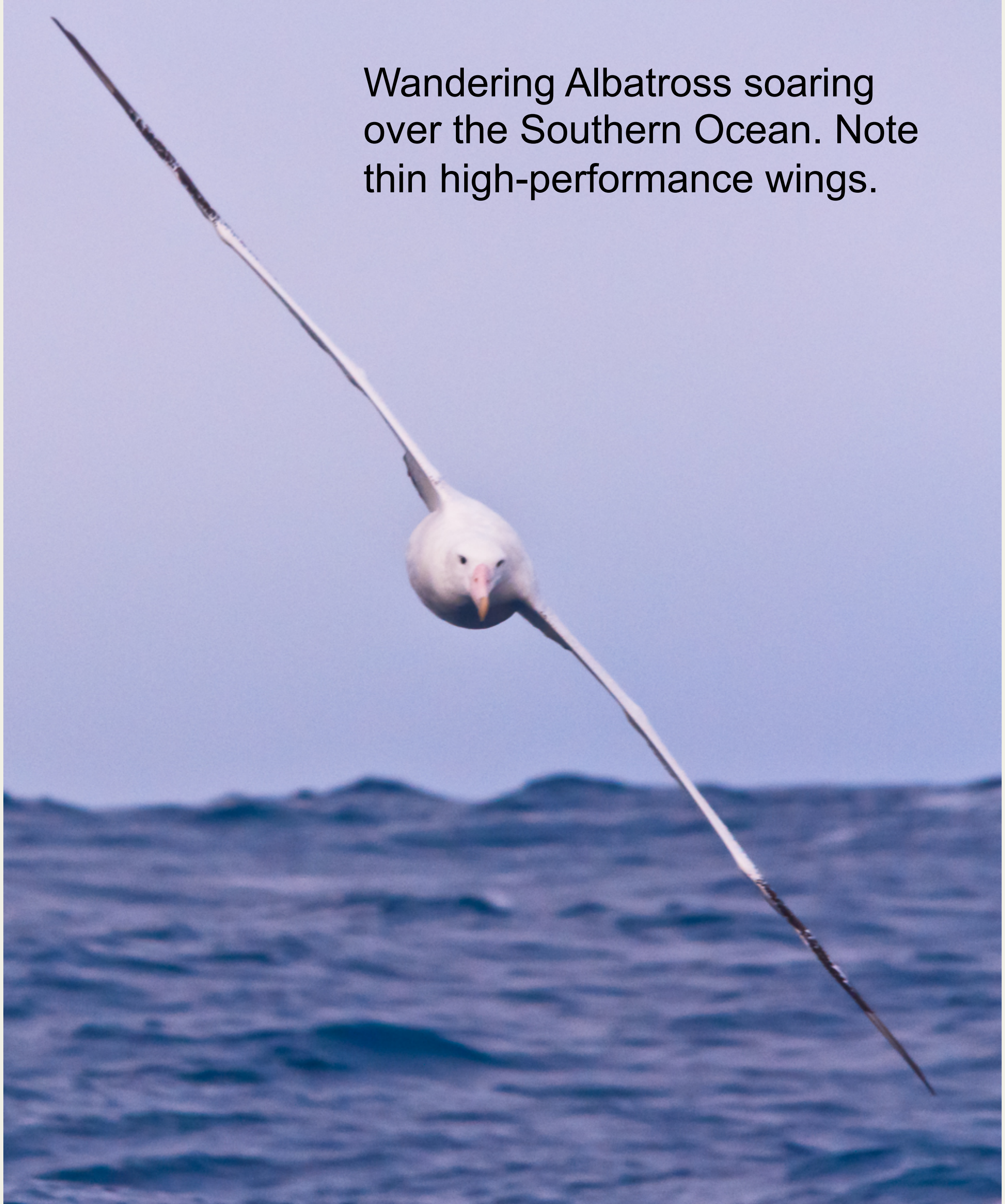


Most aerodynamic models of dynamic soaring use a mean wind profile over a flat ocean. Limitations are that most of the wind shear near the ocean is missed due to the glider's wing span and the glider remains in the relatively stronger wind higher above the surface, which causes a large leeway and makes soaring upwind difficult.



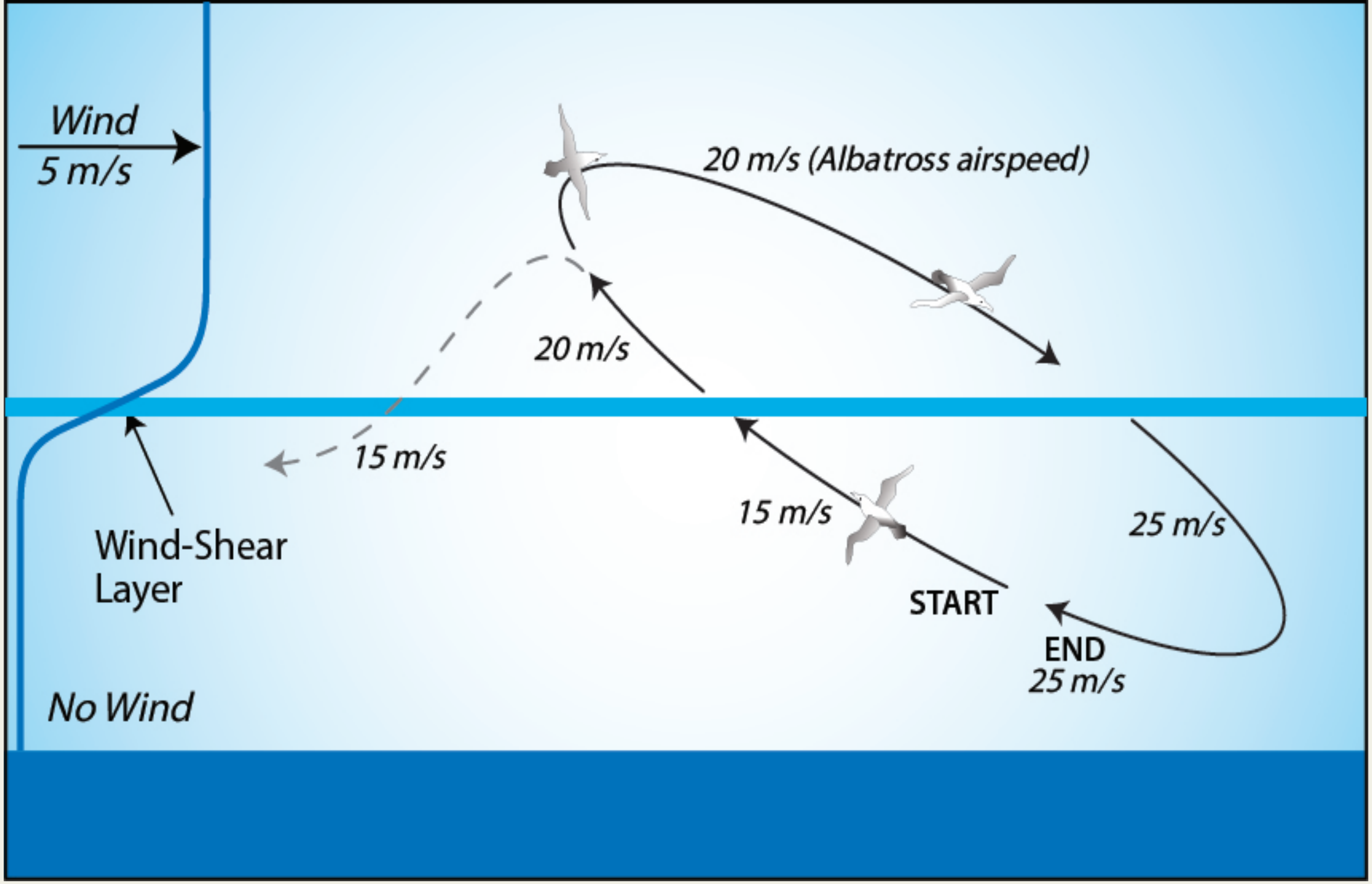
Albatrosses typically soar by starting in a lee eddy located downwind of a wave, turning upwind and climbing across the wind shear layer that has detached from the wave crest. On crossing the wind-shear layer the bird's airspeed abruptly increases and the bird gains energy. The bird then turns downwind and descends across the wind shear layer gaining another increase of airspeed and energy. Image after Pennycuick 2002


Wandering albatross soaring over the Southern Ocean



Wandering Albatross soaring over the Southern Ocean. Note thin high-performance wings.

Wandering albatross soaring over the Southern Ocean. Note wing tip in water in wave trough.

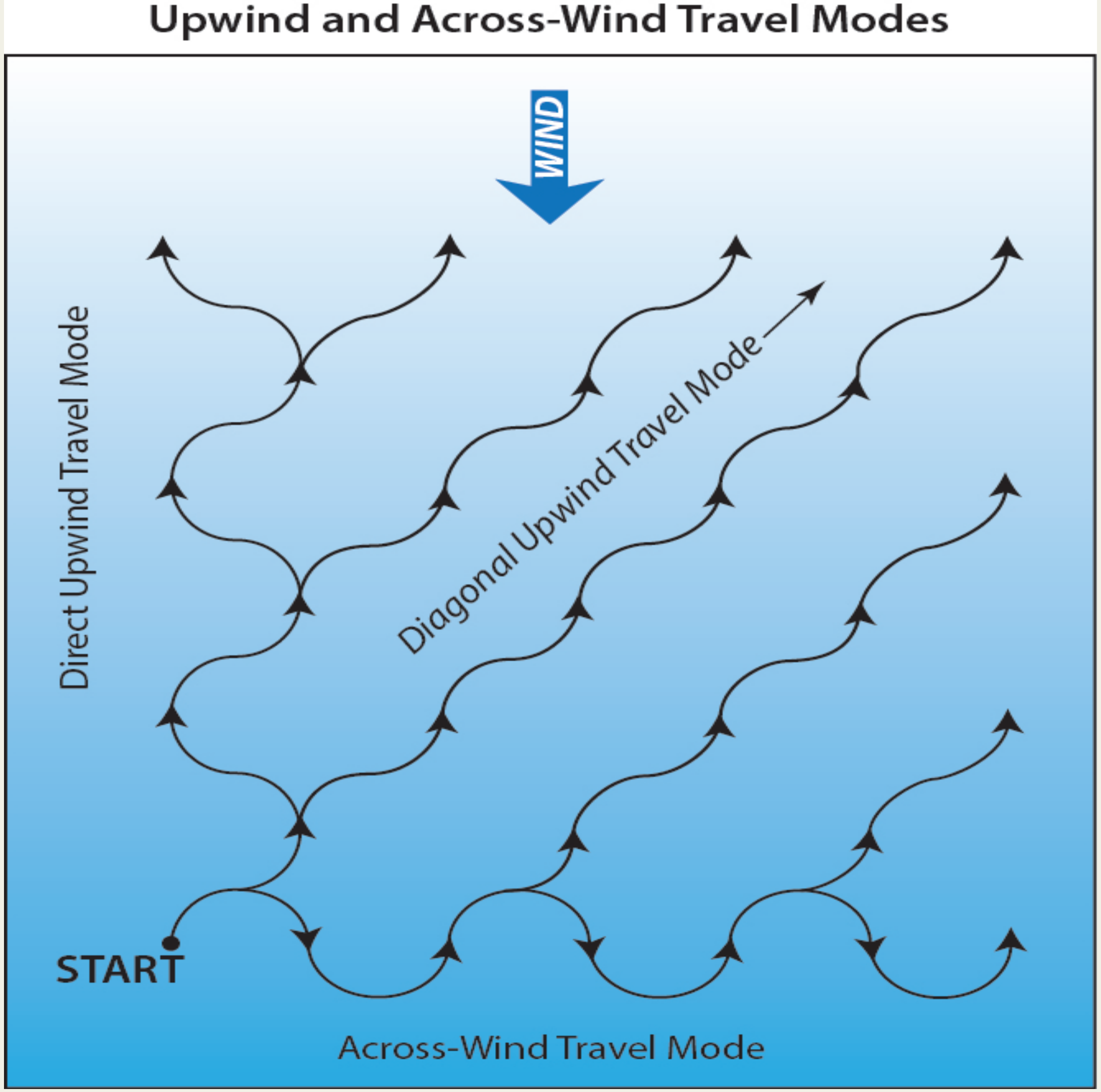


Dynamic Soaring: Rayleigh cycle. Idealized example of the airspeeds of a dragless albatross dynamic soaring through a thin wind–shear layer, which is assumed to consist of an increase in wind speed from zero below the layer to 5 m/s above. The zero speed in the lower layer represents the low wind speed located in wave troughs. This schematic is based on the written description of Rayleigh (1883) who first suggested that a bird could continuously soar in nearly-circular flight on an inclined plane that crosses a thin wind-shear layer. Starting in the lower layer with an airspeed 15 m/s a bird climbs upwind a short distance vertically across the wind-shear layer, which increases airspeed to 20 m/s. The bird turns and flies downwind with the same airspeed of 20 m/s. During the turn, ground speed increases to 25 m/s in a downwind direction and consists of the bird's 20 m/s airspeed plus (tail) wind speed of 5 m/s. The bird descends downwind a short distance vertically across the wind-shear layer, which increases airspeed to 25 m/s. Flying with an airspeed of 25 m/s the bird turns upwind. Thus, one circle through the wind-shear layer increases airspeed and groundspeed from 15 m/s to 25 m/s (two times the 5 m/s wind speed increase across the wind-shear layer). By descending upwind (dashed line) the bird's airspeed would have decreased from 20 m/s back to 15 m/s with no net gain in airspeed. This schematic shows an oblique view of near-circular flight.

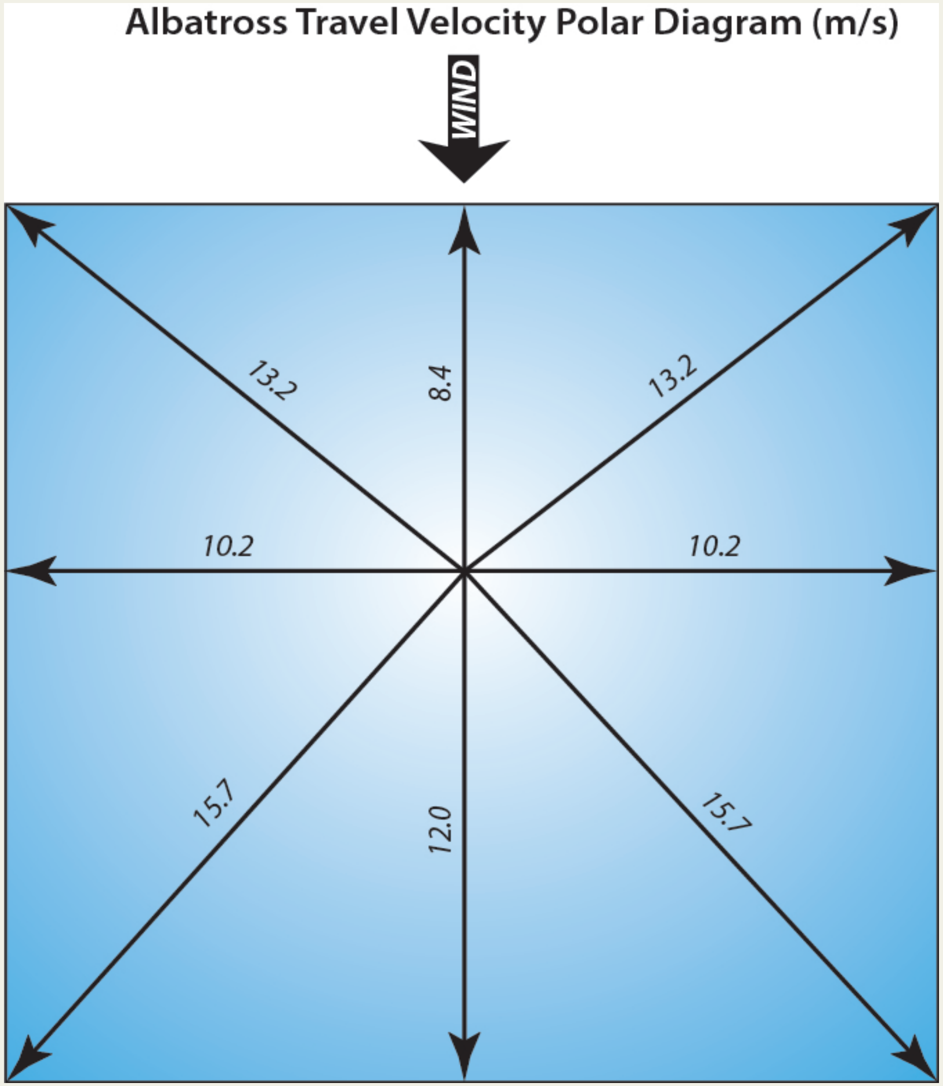
Rayleigh Cycle Two-Layer Model

Airspeed gained in the Rayleigh cycle by crossing the wind-shear layer is balanced by the loss of airspeed due to drag of the air acting on the bird. Drag was modeled with a quadratic drag law in which the drag coefficient is proportional to the lift coefficient squared. Two homogenous layers were assumed—a lower layer representing wave troughs of zero wind speed and an upper layer of uniform wind blowing over wave crests. A thin wind shear layer is sandwiched between the upper and lower layers.

The essential assumptions in the Rayleigh cycle model are that 1) an albatross (or UAV) soars in nearly circular loops along a plane tilted upward into the wind, 2) the plane crosses the wind-shear layer at a small angle with respect to the horizon so that vertical motions can be ignored, 3) the average airspeed and average glide ratio can be used to represent flight in the circle, and 4) conservation of energy in each layer requires a balance between the sudden increase of airspeed (and kinetic energy) caused by crossing the shear layer and the gradual loss of airspeed due to drag over each half loop, resulting in energy-neutral soaring.



Schematic examples of upwind and across-wind modes of dynamic soaring created by linking 90° and 180° turns into snaking flight patterns. The 16.0 m/s cruise speed of a wandering albatross was used to calculate a 10.2 m/s mean travel velocity through the air in the across-wind and along-wind directions and diagonal travel velocities of 14.4 m/s. Arrow heads are placed at points where the bird crosses the wind shear layer when headed either upwind or downwind and thereby gains airspeed and kinetic energy.

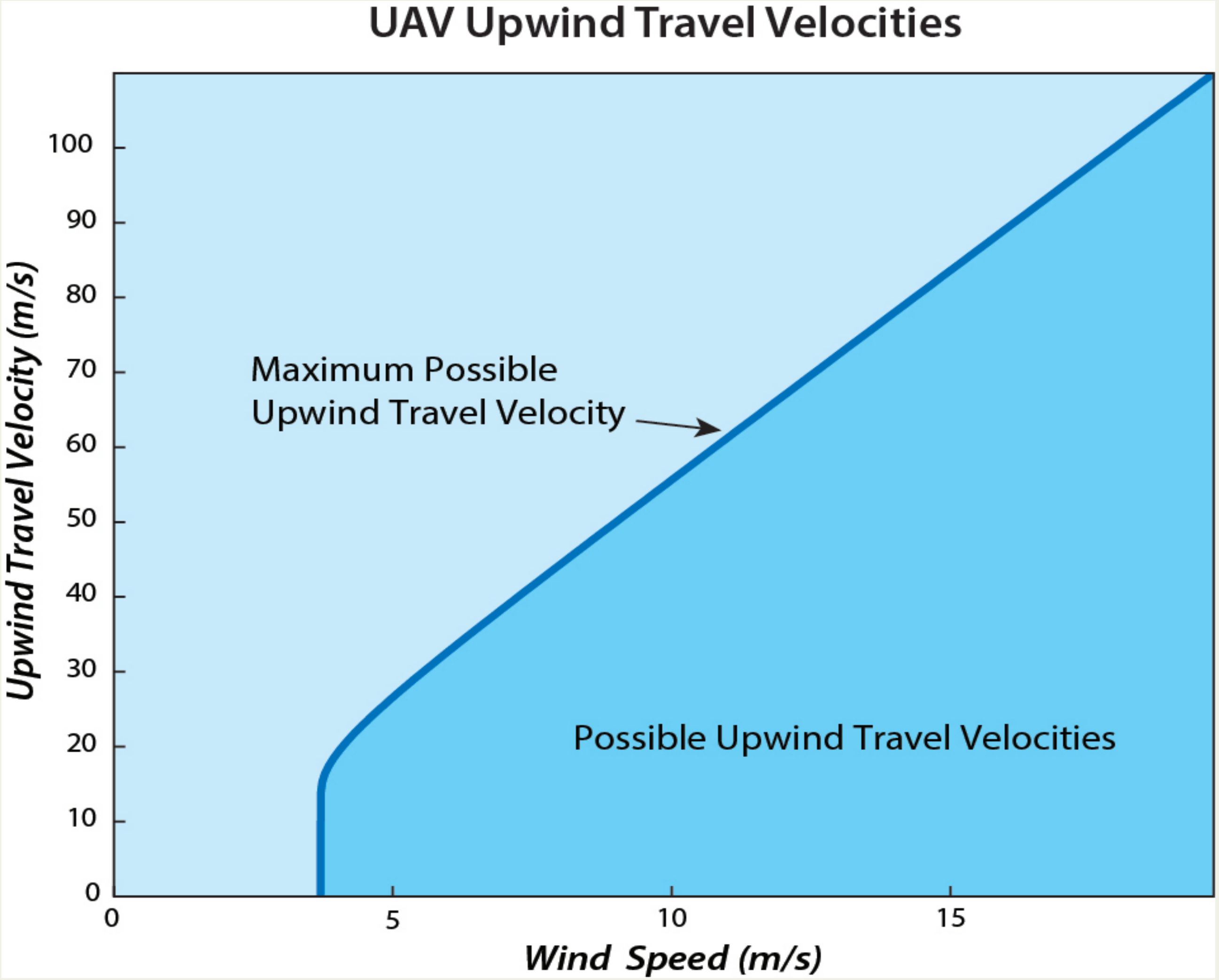


Travel velocity polar diagram of a wandering albatross created using upwind and across-wind dynamic soaring modes. The square shape is a result of the equal travel velocities through the air in the along-wind and across-wind directions. Values of mean travel velocities over the ground have been added to characteristic flight directions. The diagram was created using the cruise airspeed (16.0 m/s) of the bird and the minimum wind speed (3.6 m/s) necessary for continuous dynamic soaring. Values were corrected for leeway (1.8 m/s), which was estimated to be one half of the wind speed, based on assuming that the bird spends equal time in the upper and lower layers.

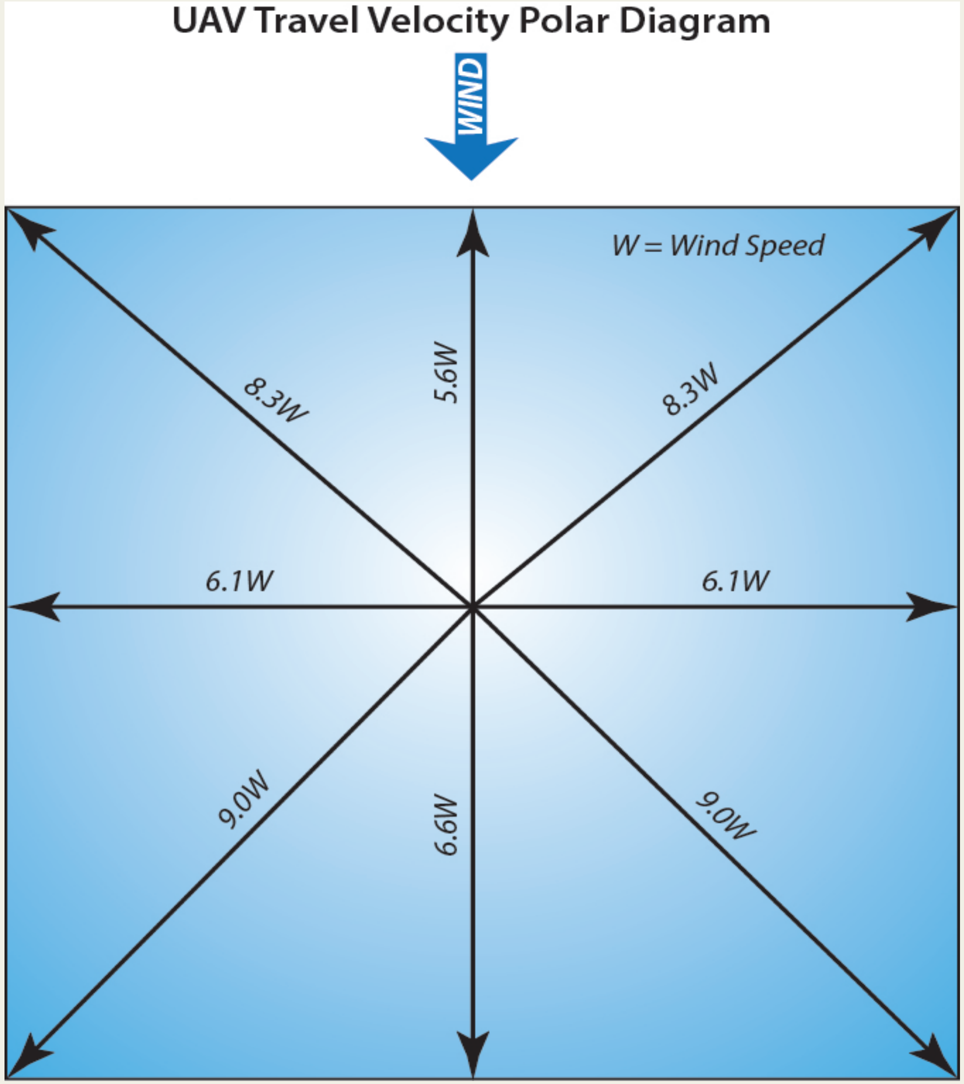
Preparing radio-controlled glider for launch near Weldon Hill, California

Chris Bosley launching Spencer Lisenby's Kinetic 100 into the wind at Weldon Hill

Spencer Lisenby dynamic soaring his Kinetic 100 glider downwind of Weldon Hill. Glider speeds up to 450 mph were measured with radar guns. Wind speed gusts of 50-70 mph were measured near the top of the hill.

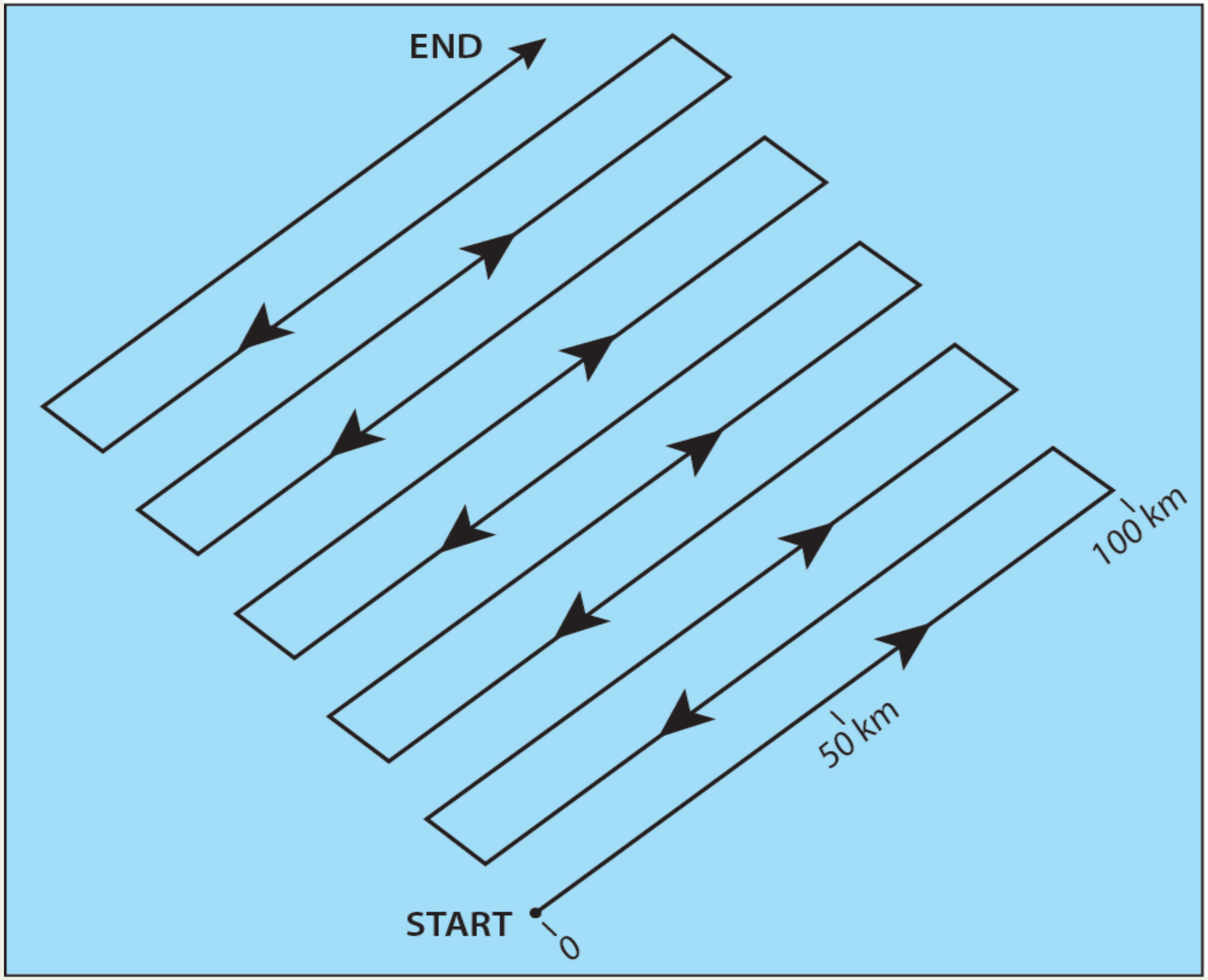


Envelope of maximum possible upwind UAV travel velocities over the ground (corrected for leeway) plotted as a function of wind speed. Velocities were calculated using the upwind mode of the Rayleigh cycle model and by assuming a maximum lift/drag ratio of 30/1 at a cruise speed of 25 m/s (similar to a Kinetic 100 DP glider). The darker blue area indicates all possible upwind UAV travel velocities as a function of wind speed (*W*). The UAV was assumed to be able to obtain the correct amount of energy for each wind speed in order to soar upwind at slower airspeeds than the maximum possible.



Travel velocity polar diagram of a robotic albatross UAV. The square shape is a result of the equal travel velocities through the air in the along-wind and across-wind directions. The diagram was created by assuming a characteristic lift/drag ratio of 30/1, a cruise velocity of 25 m/s (similar to a Kinetic 100 DP glider), and by calculating airspeeds based on the Raleigh cycle model optimized to give the maximum possible airspeed for a given wind speed. Travel velocities have been corrected for leeway and represent velocities over the ground. Specific given values of travel velocity represent the linear relation between travel velocity over the ground and wind speed (*W*) for wind speeds over around 5 m/s. For example, a wind speed of 10 m/s results in maximum possible travel velocities over the ground of 56 m/s upwind, 83 m/s diagonally upwind, and 61 m/s across-wind.

Possible UAV Survey Pattern



Schematic diagram showing a possible UAV survey mode using a combination of upwind and downwind modes of the Rayleigh cycle consisting of diagonal trajectories with respect to the wind direction. Diagonal velocities are the fastest possible travel velocities over the ocean using the upwind (and downwind) mode. They enable rapid surveying of an area for any given wind direction given sufficient wind for dynamic soaring. For example, in a wind speed of 10 m/s the average maximum possible diagonal velocities are 86 m/s

Summary and Recommendations

The results of this study suggest that a robotic albatross UAV could soar over the ocean much faster than an albatross and be useful for many applications. In order to evaluate how effectively an AUV could soar over the real ocean in different wind and wave condition several studies could to be undertaken. First, numerical simulations could be made of the interaction of winds and waves, of the resulting structures in the wind field including updrafts and detached shear layers, and of the optimal dynamic soaring patterns using the wind field over waves. Second, albatrosses could be instrumented to better measure their dynamic soaring techniques in various winds and waves. Specifically, high temporal resolution time series could be obtained of albatrosses' positions, velocities, orientations, accelerations, and airspeeds, and these related to insitu observations of winds and waves. Third, expert pilots of radio-controlled gliders who are experienced in fast dynamic soaring could conduct field tests in order to evaluate fast dynamic soaring over the ocean with high-performance waterproof gliders and to establish safe minimum soaring heights above the ocean surface. These gliders should be instrumented as would be the albatrosses mentioned above. Using the results of the simulations and measurements of albatross and radio-controlled glider flight, a dynamic soaring autopilot could be developed. Finally, a prototype waterproof, instrumented, dynamic soaring UAV with auxiliary power could be constructed and tested over the ocean.

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