

# Towards Flight Testing of Remotely Controlled Surfkites for Wind Energy Generation

Bas Lansdorp, Richard Ruiterkamp, Wubbo Ockels  
*Delft University of Technology, The Netherlands*

Non-powered flight vehicles such as kites can provide a means of transmitting wind energy from higher altitudes to the ground via tethers. Although there is increased world wide interest for systems to extract wind energy from higher altitudes with kites, research into kite properties such as the coefficients and the stability is limited. Such research is required to increase the knowledge on kites, which would enable the design of purpose-built kites for energy extraction. This paper presents one of the concepts for wind energy extraction from high altitudes; the Laddermill. Furthermore it presents the hardware that was built to do such tests, test procedures for kites and early results of testing of commercially available surf kites.

## I. Introduction

**E**NERGY is an important asset in modern society. Most energy is generated from non-renewable resources such as coal, gas, oil, and uranium. In recent years, there has been a push towards greater use of renewable energy sources by governments worldwide, resulting in regulations for the amount of renewable energy a country should produce. In the year 2000, 1.2% of the consumption of Dutch electricity came from renewable sources <sup>[1]</sup>. In 2000, the Dutch government set new targets to comply with the Kyoto protocol, which aims to reduce the Dutch CO<sub>2</sub> emissions. The broad target is to generate 5% of the electricity demand from renewable sources by 2010, increasing to 10% by 2020 <sup>[1]</sup>. Among the sources that are considered “renewable” that can potentially be used for large-scale energy production are solar, hydroelectricity, wind, and biomass. Unfortunately, these technologies can only supply small amounts of energy per installed unit. The Laddermill [2], a novel concept for extracting wind energy from high altitudes, aims to produce a quantum leap in “environmentally clean” electricity generation. The Laddermill concept, which will be explored in more detail later, has renewed interest in kite and tether dynamics.

Wind energy has been used for several hundreds of years, and Holland is famous for its windmills used for mechanically powering pumps and equipment. The current windmill design arose from the Hallady-Perry windmill design of the 1920s and 1930s. Since then, significant steps have been made in power output and efficiency. Modern wind turbines are now placed well above the ground at altitudes up to 120 m to take advantage of the fact that both wind speed and steadiness increase significantly with altitude. The power generated by wind turbines does not merely increase linearly with wind speed, but rather by the cube of the wind velocity. Hence, doubling the wind speed increases the available power by eight times. Figure 1 shows the average wind over 20 years versus the altitude for the Netherlands.

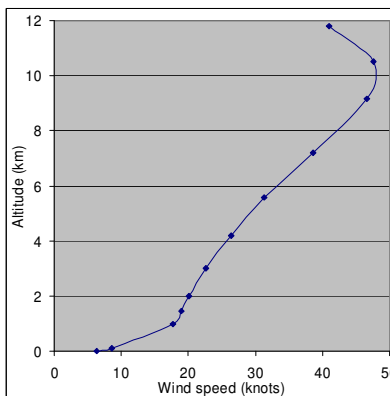
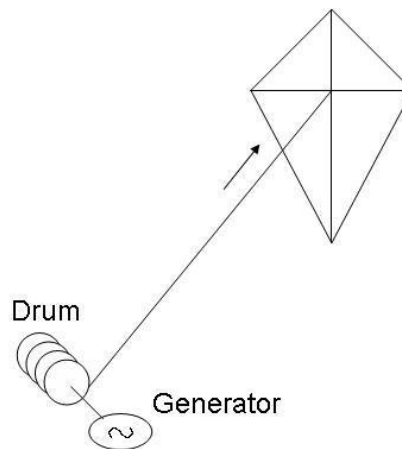


Figure 1: Average windspeed over the Netherlands versus the altitude.<sup>[2]</sup>

It is this fact that has lead many researchers to propose various concepts for extracting electricity from higher altitudes [3-14] and a large number of patents in this area [15-26]. All of the above-mentioned systems feature a generator that is located high up in the air. This means that a large payload and a conductive tether must be supported, adding to the weight and cost of the system. In addition, the forces necessary to lift the apparatus do not provide any useful power. An alternative concept was proposed by Ockels [2], called the Laddermill, where power is generated by wings or kites that drive a ground based electric generator by means of the cable or tether. The concept relies on using the high altitude winds to do useful work on the ground, rather than trying to capture the wind energy at altitude, convert it to power, and then transmit the electricity to the ground. This distinction in operation is what makes the Laddermill a practically realizable system. The Laddermill will be described in more detail in the next section.

## II. The Laddermill

The Laddermill concept makes use of lifting bodies, called kites or wings, connected to a cable that stretches into the higher regions of the atmosphere. The lower part of the cable, about 10% of the total length is wound around a drum. The tension that the kite creates in the cable pulls it off the drum, thus driving the generator, as shown in Figure 2.



**Figure 2: Simple illustration of the Laddermill principle.**

When the kite is ascending, the attitude of the kite is such that it generates high lift. This can be done by increasing the apparent wind by using crosswind power [27] and/or by increasing the angle of attack, see Figure 3a. Once the cable has been pulled off the drum, the cable must be retrieved. In order to generate a surplus of energy per cycle, the lift of the kite has to be reduced. This can be achieved by refraining from using crosswind power and by lowering the angle of attack. A high ratio between the cable tension when ascending and descending will increase the power output and efficiency of the Laddermill. Only the lower ~10% of the cable will be retrieved. The rest of the cable with the wings or kites attached will always remain airborne during normal operation. In case of windless conditions the whole Laddermill will be retrieved. Preliminary simulations show this will occur about 40 times per year.



**Figure 3a: An illustration of the kite motion during ascent. Figure 3b: Artist impression of a Laddermill near a large city.**

The actual Laddermill will have several wings connected in the upper section of the cable. An artist impression of the Laddermill is shown in Figure 3b.

The installed power of a Laddermill can be higher than that of conventional windmills. Since the wings are high up in the air, their size is not limited like the blades of a conventional windmill. Large controllable kites are thus an enabling technology for the Laddermill. Higher installed power will lead to a larger cable diameter and a larger, ground-based, generator. Larger single-unit outputs are expected to decrease the cost per kWh. Figure 4 shows a successful Laddermill test where about 1 kW of power was generated using a 10 m<sup>2</sup> Peter Lynn Bomba surfkite. The kite is controlled by a drag flap mechanism [28].

At this moment, surfkites are ideal lifting surfaces for the Laddermill. They are commercially available, cheap and have good performance. A wealth of experience has been developed by pilots that show that they can survive crashes very well. Furthermore, they exist in a wide variety of sizes and models. Many of the requirements for surfkites are identical to requirements for ideal Laddermill wings: high L/D, low mass, low cost and high strength. On the other hand, some features of surfkites are not required for the Laddermill. One of them is water relaunchability: when a kite surfer crashes his kite on the water, he has to be able to re-launch it by himself. Another is the limitations of the human pilot; if the kite is too reactive, the pilot can't fly it anymore.

Because of these undesired design features of surfkites, development of a kite designed especially for the Laddermill is required. This requires a thorough understanding of existing kite technology. For this reason, a test procedure for kites is proposed and initiated in this paper.



**Figure 4: Preliminary Laddermill testing with a 10m2 Peter Lynn Bomba surfkite controlled by a drag flap control mechanism**

### **III. Requirements for Testing**

It is important to gain an understanding of the relevant properties of surfkites that distinguish differences in performance. In testing of airplanes, the following properties are considered important:

- Lift and drag as a function of angle of attack and sideslip.
- Static stability margins
- Dynamic stability of the rigid body motion (pitch, roll and yaw).

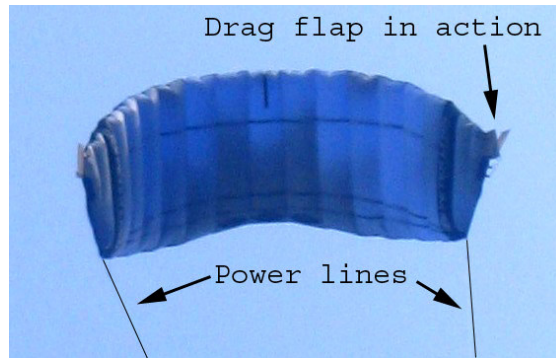
These properties are also likely to be very important for kites. For kites, pitch stability is especially important, because a negative angle of attack will lead to a frontstall. Although the angle of attack is a straightforward property to understand in the case of an airplane wing, it is less so for surfkites. The angle of attack can change independently along the span of the kite due to the effects of flexibility. It will be necessary to make a definition of the angle of attack of a kite that in some way conveys important information about the lift/drag properties.

Parameters that are important to know to determine the properties of the kite, are the windspeed, position of the kite, line length, apparent wind speed at the kite and the tether tension and orientation on the ground.

For power generation, it is also important to know the control authority that can be achieved over the kite, because the kite is required to fly geometric patterns. The accelerations that can be generated by the steering mechanism have to be determined. In this way, steering mechanisms can be compared for reactivity of the kite, but also for power consumption.

### **IV. Steering Mechanism Hardware**

For energy production, it is important that the kite is connected to the ground by only a single line. This is important because a single line has less drag than two or more lines. It also helps to simplify the ground handling, as well as reducing overall costs. Since it is also required that the kite be steerable from the ground, a steering mechanism at the kite is required. Several kite control mechanisms have been developed and tested. One was based on drag flaps mounted under the kite, as shown in Figure 5.



**Figure 5: Flight testing of a kite with drag flaps for steering control.**

This control mechanism had quite low control authority and only roll-stable kites could be controlled by it. This is due to the fact that the drag flaps are fixed in position relative to the kite aerodynamic center.

Another control mechanism that was developed was based on changing the angle of attack of the wingtip of the kite. This is achieved by mounting two servos under the kite, as shown in Figure 6. Each servo moves the opposite wingtip inward by pulling a line. This control actuator worked reasonably well, but it did not provide the full control authority required to steer the kite over the full flight envelope. Another disadvantage is that the total angle of attack cannot be changed effectively with this control mechanism.



**Figure 6: Servo location for remote control of kite angle of attack.**

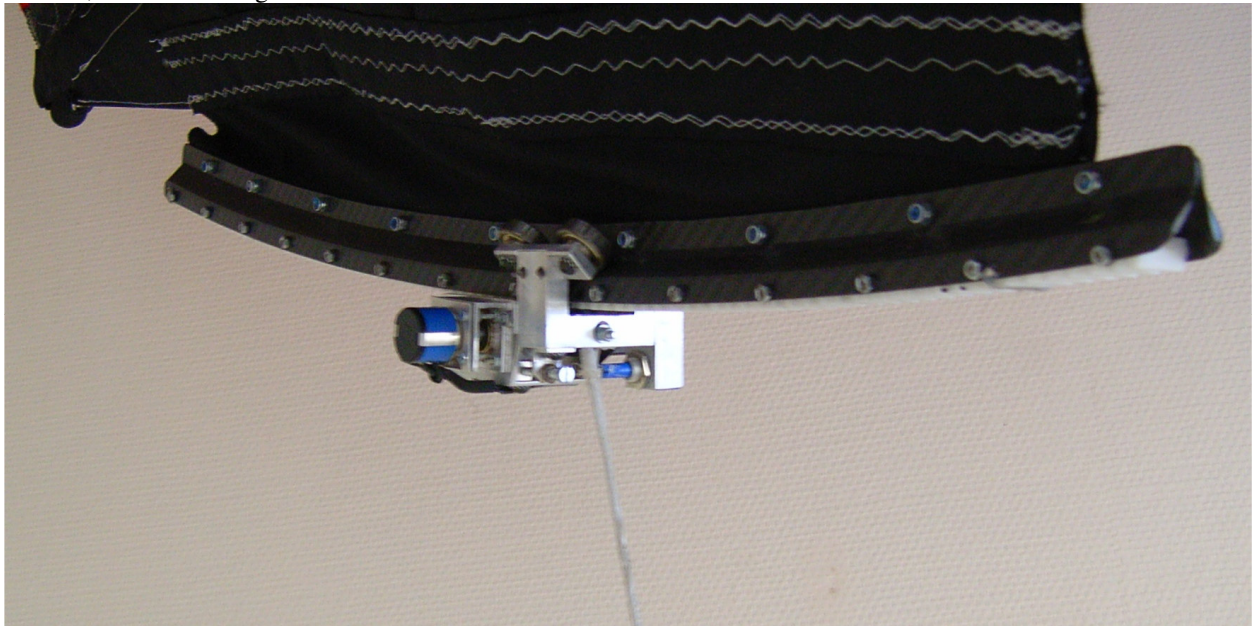
The final kite control mechanism that has been tested is based on changing the attachment point position on the sides of the kite. Figure 7 shows the first design of this system. The system shown in Figure 7 is simple, but increases the weight of kite more than the previous control actuators. The attack angle can be changed by moving the towpoints in the same direction, whereas moving them in asymmetrically allows the kite to be steered.



**Figure 7: Mechanism used to move the tether attachment point position. This system was operated by remote control.**

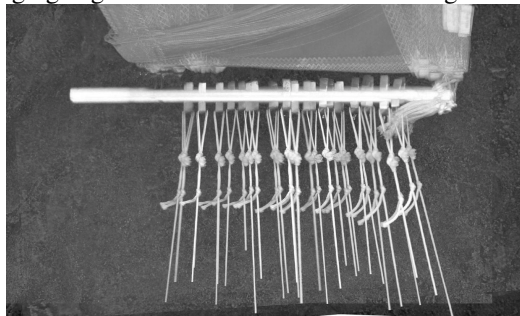


Several design iterations were required to give a light-weight final design for the attachment point control mechanism, as shown in Figure 8.



**Figure 8: Final control actuator for moving the tether attachment points.**

The kite control mechanism is strong, has good towing speed, and is lightweight. The car is driven by a tooth wheel and a gear rack and the standard  $270^\circ$  potmeter is replaced by a 10 stroke one to increase the stroke of the car. The rail is curved to follow the changing angle of the line when the attack angle changes, as shown in Figure 9.



**Figure 9: Changing angle between line and rail**

More information on the steering mechanism can be found in [29].

## **V. Sensors**

Several sensors and electronics are required for reproducible, meaningful tests. The following parameters are measured:

- Force vector in the tether at ground level
- Steering input from the joystick
- GPS position of the tether ground connection
- Wind speed at ground and direction (4m altitude)
- Apparent wind speed at the kite
- GPS position of each wing tip
- Position of the tow points on the rails.
- 3D accelerations of each kite wingtip

The line vector on the ground is measured by means of a 3-D load cell assembly that measures the force in Cartesian coordinates, as shown in Figure 10. The system can measure the forces in three directions independently because of the large difference in stiffness of the thin beam elements in Figure 10 that connect the load cells to the line connection in the middle. The thin beam will easily deflect in radial direction but not in the axial direction. Since the three beams are all perpendicular to each other, any line tension vector will be decomposed in three perpendicular forces in the load cells, such giving the angles and the total force.



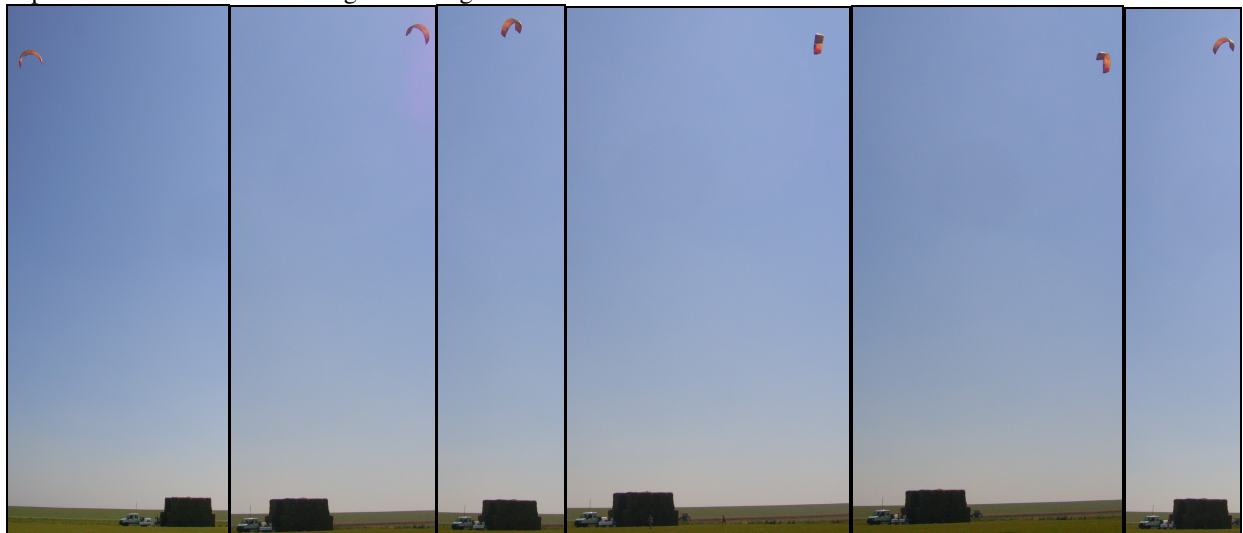
**Figure 10: Load cell for measuring the line tension vector.**

Assuming a straight cable, the load cell assembly will give the position of the kite. Each wingtip of the kite also has a GPS chip to determine the position. The real wind speed can be estimated from the difference between the apparent wind and the velocity of the kite. However, these measurements will be noisy, requiring a suitable filter to be developed. The wind speed at ground level will also be measured with an ultrasonic wind sensor.

The apparent wind speed will be measured by two pitot tubes, one at each wingtip of the kite. It is expected that leading edge of the kite will always be facing the wind but this has yet to be demonstrated. The commands for the servo motors that control the tow point position are stored, and the resulting motion of the tow points is recorded. Since the rail is quite long (70 cm) there can be significant delay between the control signal and the actual position of the tow point.

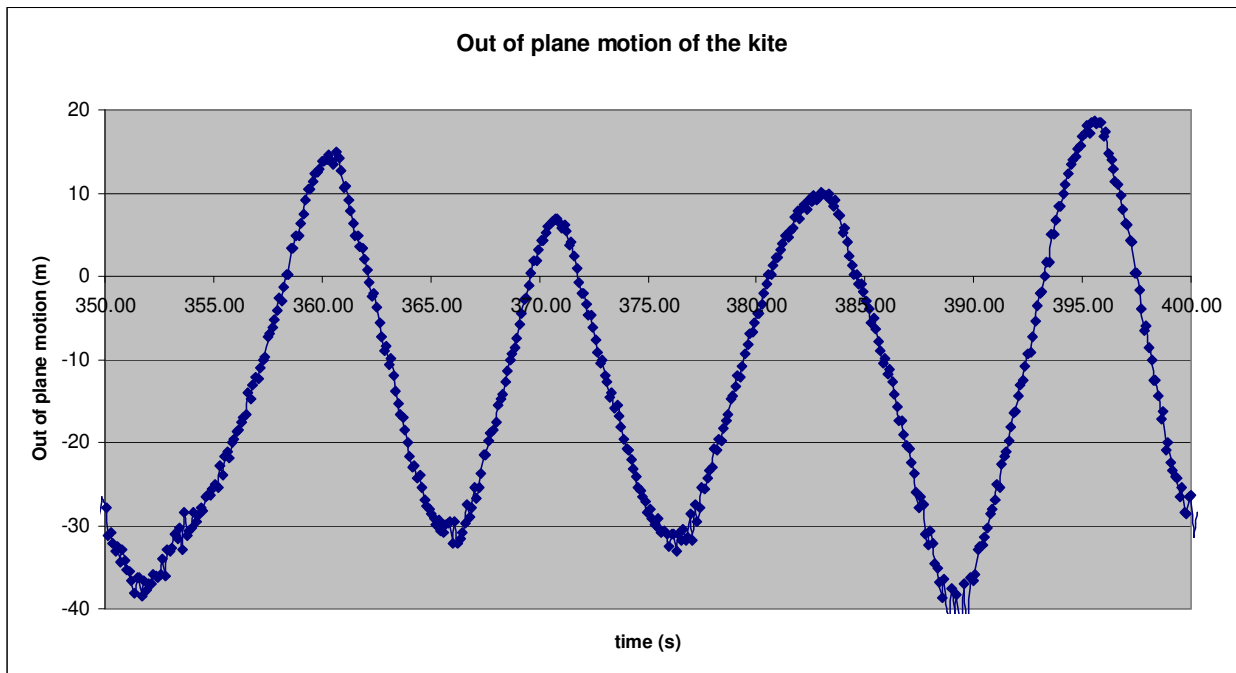
## VI. Testing

Initial testing has commenced and the time data series can be generated. All sensors are operational, except the apparent wind speed sensor. It is shown that the apparent wind speed can be estimated with a filter in reference [30]. A picture of a successful test is given in Figure 11.

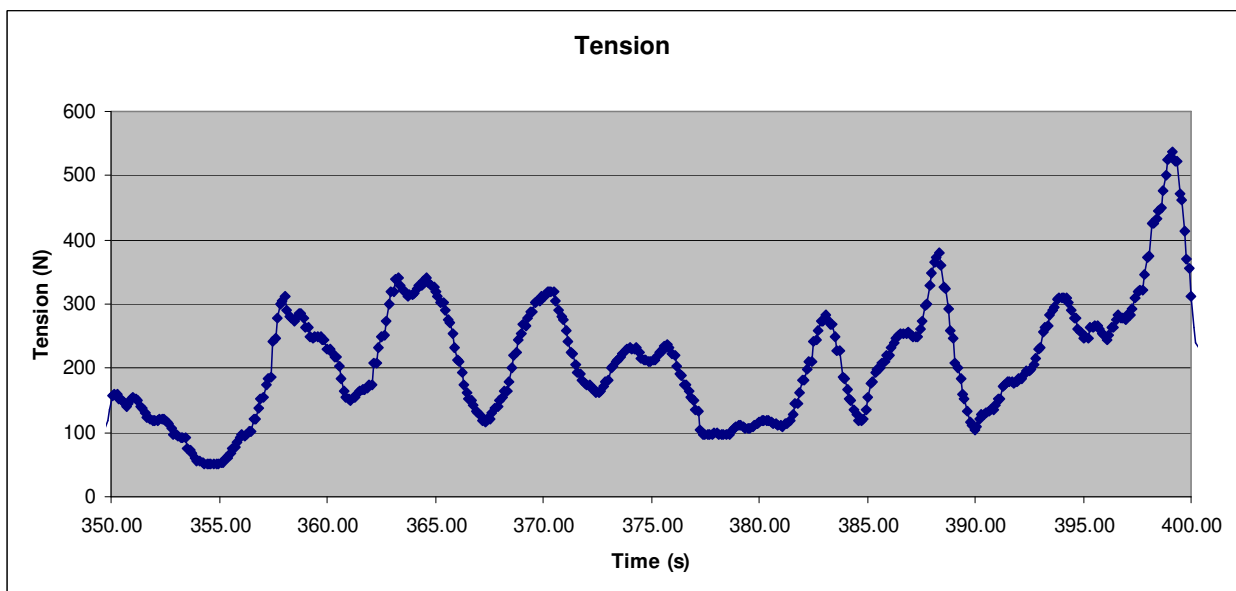


**Figure 11: Surfkite testing**

The test was performed with 90 m line length. In Figure 12 the data of the out of plane force sensor on the ground, transformed to the out of plane deviation from the downwind direction can be seen. Figure 13 shows the tension.



**Figure 12: Out of plane motion of the kite**



**Figure 13: Tension**

## VII. Conclusions

Detailed investigation of the data should result in useful data such as the lift and drag dependency on the attack angle, and many other properties that are considered to be essential for design of airplanes. Knowledge of such data will enable design of better kites.



## References

- <sup>1</sup>Dutch Ministry of economic affairs, 2001, "Bestuursovereenkomst Landelijke Ontwikkeling Windenergie (Blow)", accessible at <http://apps.ez.nl/publicaties/pdfs/blow-bw1.pdf> accessed 3-11-2004.
- <sup>2</sup>Ockels, W.J., "Laddermill, a Novel Concept to Exploit the Energy in the Airspace," *Aircraft Design*, Vol. 4, 2001, pp.81-97.
- <sup>3</sup>Carpenter, H.G., "Tethered Aircraft Having Remotely Controlled Angle of Attack," US Patent 5,931,416.
- <sup>4</sup>Carpenter, H.G., "Tethered Aircraft System for Gathering Energy From Wind," US Patent 6,254,034.
- <sup>5</sup>Etkin, B., *Dynamics of Atmospheric Flight*, Wiley, New York, 1972.
- <sup>6</sup>Sagrillo, M., "Site Analysis for Wind Generators, Part 1: Average Wind Speed," *Home Power*, Vol. 40, April/May 1994, pp.86-90.
- <sup>7</sup>Roberts, B.W., and Shepard, D.H., "Unmanned Rotorcraft to Generate Electricity using Upper Atmospheric Winds," *Australian International Aerospace Congress*, Brisbane, July 2003.
- <sup>8</sup>Manalis, M.S., "Airborne Windmills: Energy Source for Communication Aerostats," AIAA Lighter Than Air Technology Conference, AIAA Paper 75-923, July 1975.
- <sup>9</sup>Manalis, M.S., "Airborne Windmills and Communication Aerostats," *Journal of Aircraft*, Vol. 13, No. 7, 1976, pp.543-544.
- <sup>10</sup>Riegler, G., and Riedler, W., "Tethered Wind Systems for the Generation of Electricity," *Journal of Solar Energy Engineering*, Vol. 106, 1984, pp.177-181.
- <sup>11</sup>Riegler, G., Riedler, W., and Horvath, E., "Transformation of Wind Energy by a High-Altitude Power Plant," *Journal of Energy*, Vol. 7, No. 1, 1983, pp.92-94.
- <sup>12</sup>Bolonkin, A., "Utilization of Wind Energy at High Altitude," AIAA Paper 2004-5705, Aug. 2004.
- <sup>13</sup>Fletcher, C.A.J., and Roberts, B.W., "Electricity Generation from Jet-Stream Winds," *Journal of Energy*, Vol. 3, 1979, pp.241-249.
- <sup>14</sup>Fletcher, C.A.J., "On the Rotary Wing Concept for Jet Stream Electricity Generation," *Journal of Energy*, Vol. 7, No. 1, 1983, pp.90-92.
- <sup>15</sup>Fry, C.M., and Hise, H.W., "Wind Driven, High Altitude Power Apparatus," US Patent 4,084,102, April 1978.
- <sup>16</sup>Kling, A., "Wind Driven Power Plant," US Patent 4,073,516, Feb. 1978.
- <sup>17</sup>Payne, P.R., and McCutchen, C., "Self-Erecting Windmill," US Patent 3,987,987, Oct. 1976.
- <sup>18</sup>Loeb, A., "Wind Driven Energy System," US Patent 4,124,182, Nov. 1978.
- <sup>19</sup>Lois, L., "Apparatus for Extracting Energy from Winds at Significant Height Above the Surface," US Patent 4,076,190, Feb. 1978.
- <sup>20</sup>Pugh, P.F., "Wind Generator Kite System," US Patent 4,486,669, Dec. 1984.
- <sup>21</sup>Biscomb, L.I., "Multiple Wind Turbine Tethered Airfoil Wind Energy Conversion System," US Patent 4,285,481, Aug. 1981.
- <sup>22</sup>Watson, W.K., "Airship-Floated Wind Turbine," US Patent 4,491,739, Jan. 1985.
- <sup>23</sup>Shepard, D.H., "Power Generation from High Altitude Winds," US Patent 4,659,940, April 1987.
- <sup>24</sup>Rundle, C.V., "Tethered Rotary Kite," US Patent 5,149,020, Sept. 1992.
- <sup>25</sup>Roberts, B.W., "Windmill Kite," US Patent 6,781,254, Aug. 2004.
- <sup>26</sup>Mouton, W.J., and Thompson, D.F., "Airship Power Turbine," US Patent 4,166,596, Sept. 1979.
- <sup>27</sup>Loyd, M.L., "Crosswind Kite Power," *Journal of Energy*, Vol. 4, No. 3, 1980, pp.106-111.
- <sup>28</sup>Lansdorp, B., Remes, B., and Ockels, W.J., "Design and Testing of a Remotely Controlled Surfkite for the Laddermill," World Wind Energy Conference, Melbourne, Australia, Nov. 2005.
- <sup>29</sup>Lansdorp, B., Ockels, W.J., "Development and testing of a steering mechanism for Laddermill kites", China international Wind Energy Exhibition and Conference, to be published.
- <sup>30</sup>Williams, P., Lansdorp, B., and Ockels, W., "Flexible Tethered Kite with Moveable Attachment Points, Part II: State and Wind Estimation," AIAA Atmospheric Flight Mechanics Conference, Aug. 2007.