Operation of an Ultra-Light Dirigible over Tropical Forest

G. E. Dorrington*

Abstract

In 1995 a dirigible (or non-rigid airship) was flown successfully 30 times over a region of tropical rain forest in Borneo. Some comments are made about the rationale for these test flights. Some aspects of the airship's design are outlined, including: the requirements; the configuration and overall size; the seating arrangement and payload capability; details about the quiet electric propulsion system. Some operational characteristics are then described. Special attention is paid to the influence of wind/gusts in tropical forests and the ability to hold station and/or the feasibility of safe landing on the canopy roof. The preliminary scientific objectives of the project are also outlined. For example, some details about the design of an insect suction trap and its deployment are included. Finally, some comments on future planned work as well as suggestions for further technical developments are also given.

Introduction

The case for biochemical prospecting in tropical rain forests, in order to discover and possibly reap the rewards of new pharmaceutical products, is well presented by Wilson (1993). Indeed, given the undisputed richness of tropical rain forest canopies (in terms of biodiversity) even without Wilson's persuasive arguments one might wonder why such prospecting has not yet fully developed, somewhat like a "Gold Rush". Aside from any negative psychological mindset acting as a damper on prerequisite seed-funding, two real difficulties may account for the apparent delay. The first is the formidable scientific problem of screening and identifying promising chemicals rapidly, *in situ.* The second, similarly demanding, engineering problem is one of accessibility: how is it possible to practically get close to, and sample, a large number of treetop sites spread over many kilometers, without significant disturbance? The latter problem of access has been tackled to date through many widely different techniques, but all these techniques have had limitations, see e.g., Mitchell et. al. (2002) and Sutton (2002).

The idea of using of dirigibles (or airships), or balloons, which can all be classified as Lighter-Than-Air (LTA) platforms, to gain access to the canopy probably stems from fantasy literature. For example, Milne (1926) provides a popular/enjoyable

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* Lecturer in Aerospace Design, Department of Engineering, Queen Mary, University of London, UK,
g.dorrington@qmul.ac.uk

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image of an unsuccessful use of a balloon to collect honey from a tree top. However, one of the first, serious proposals to use an LTA platform for canopy science appears to be attributable to Mitchell (1986), who wrote:

"Whilst using a large dirigible owned by Goodyear to investigate atmospheric pollution above industrial areas of the Mediterranean, I began to wonder whether airships or similar lighter-than-air craft could be adapted to provide a means of exploring the canopy. Such a craft would be powered by two quiet engines and be capable of carrying several people and their equipment anywhere over the rainforest within reasonable range of its base. The finance and technology would be no different from those required for the creation of a new vehicle for plumbing the ocean depths. Unpredictable wind conditions over a the forest would, at certain times, make the operation of such a craft extremely difficult but I have no doubt that modern technology has the capability to come up with solutions. Operating in conjunction with an existing forest research programme, the machine could systematically photograph the forest roof with cameras using special infra-red film to reveal vast amounts of information on the stage of flowering and fruiting and leaf production at present totally unobtainable on any significant scale. It could float over specific trees from which regular samples could be taken, whilst at the same time sensors could reveal the meteorological conditions... The need for such a vehicle to enable humans to explore this vast biological frontier is undoubted."

It was not long before this vision began to take shape. In 1986, a French team led by Hallé began "Operation Canopee" which first involved to use a large hot-air filled, piston engine powered dirigible, a Colt AS-261, (with a volume of about 7400 m^3), to carry and deposit an inflated raft (called the "Radeau des Cimes") on top of the canopy in French Guiana, Hallé (1990). Five other highly successful campaigns have subsequently taken place in various locations throughout the world and the system employed has been considerably developed, Hallé (2002).

In comparison with the scale and budget allocated to Operation Canopee, another relatively modest LTA canopy exploration venture was also undertaken by the author, although it has not been widely reported, Dorrington (1995-2002). Specifically, the author flew a single-seat, helium-filled dirigible over forest in Sumatra in 1993, and then another two-seat, helium-filled dirigible over forest in Borneo in 1995, This Borneo venture, coined "Project Hornbill", provides the central theme of this paper and this subject precedes a more general discussion about possible future LTA platforms.

"Project Hornbill"

"Phase 1" of Project Hornbill involved the operation of an electric powered dirigible, "D-4", over a reserve of pristine tropical rain forest near the Danum Valley Field Centre (DVFC) in southern Sabah, about 65 km north west of Lahad Datu. Thirty successful flights were made, ranging up to 3 km from the take-off point, with safe return in all cases, between January and April 1995.

It is important to bear in mind that D-4 was designed and built by the author within the university sector, with the near-voluntary support of several staff and students between June and November 1994. No major item was subcontracted, and nearly all the dirigible (including the helium containing envelope) was made in-house to keep manufacturing costs low - less than a typical European family car (say). The final design was not certificated in anyway for airworthiness, although many guidelines of that certification process were observed. The dirigible was subsequently flown in DVFC, by the author and one other passenger (on 3 occasions), under an experimental (ultra-light) category, with the special approval of the Malaysian Department of Civil Aviation, see also acknowledgements.

The objective of Phase 1 was to demonstrate that the free-flight of a helium-filled dirigible was feasible close to the canopy, to determine whether it would be useful for scientific studies, and, if so, to select which scientific tasks should be carried-out in the intended "Phase 2". In many ways this demonstration was successful, although there were inevitably some technical drawbacks that required correction. Unfortunately, no scientific user with funding was found (and/or forthcoming) to undertake Phase 2, and today the D-4 airship is no longer serviceable. Some of the lessons of Phase 1, however, may have value to anyone attempting to embark on a similar venture, especially if/when canopy prospecting (discussed above) becomes close to reality.

Design of "D-4"

At present there is no formal certification classification of "ultra-light dirigible/airship". Here the term is used loosely to describe a powered LTA platform of less than about 500 m^3 volume (an arbitrary limit). D-4 actually had a design helium capacity of about 400 m^3 to yield a buoyancy of about 3700N and a payload of about 180kg - which is similar to the upper-range of two-seat micro/ultra-light flexible wing aircraft that have there own formal certification rules and governing organisations. An approximate mass breakdown of the airship is given in Table 1, although it should be noted the actual breakdown varied between flights.

D-4 was relatively small compared to most contemporary airships, but the the term small is misleading: the envelope had an overall length of about 21.4m and a maximum diameter of about 6.4m, which is larger than a double-decker bus (say). The configuration was somewhat similar to the designs of Santos Dumont, in particular the "Baladeuse" flown about a century ago, since it had a separate, hanging, rigid keel structure 9.1m in length, see Figure 1.

The envelope/hull did not have to incorporate a ballonet (which is typical in most airships including the designs of Santos Dumont), because the keel structure was sufficiently long to prevent the envelope/hull from buckling when the helium volume fell. The envelope itself was made from 18 gores of polyester reinforced Melinex™ laminate (of about 200 g/m^2) that were thermally bonded together. Some shrinkage of the gores during bonding makes it difficult to estimate the helium volume exactly, but it was probably not less than 384 m^3. Despite being made in-house, the helium retention was relatively good, with a leakage rate of less than about 0.05 m^3 per hour. However, signs of UV degradation were apparent after 3 months. The lifetime of the envelope is hard to estimate, but it was probably safely limited to about 6 months. It is not known exactly fast the laminate lost its strength, but after 4 years storage in a wooden box, in DVFC, it was certainly unusable and the bonded joints had broken-down completely.

Pilot and passenger were seated in a tandem configuration within the fabric covered keel, which was assembled in four separable sections made from 6061-T6 aluminium alloy tubing riveted together using pop-rivets and gusset plates. The keel was hung from the envelope using Dyneema™ rigging lines in such a way that its position could be moved in longitudinal direction using a small crank, so that the pitch (nose up/down) attitude could be trimmed in flight.

A large rudder and fin with a combined area of about 9.25 m^2 was hung from the rear of the envelope to compensate for the aerodynamic tendency of the envelope/hull to yaw (turn laterally), as well as to permit yaw manoeuvres.

The most unique feature about D-4 was its electric propulsion system. Indeed, it is believed that D-4 was only the second electric powered dirigible after "La France" designed and flown by Renard and Krebs in 1884. Gas free recombination lead-acid batteries were used to provide nominal 24V DC power for about 1-2 hours duration. Two electric motors (rated at about 650W each) were used to drive two side-mounted 0.6m diameter propellers that could be vectored through 360 degrees, to provide about 70 N thrust (combined). The reason electric power was used was fourfold: first it was considered to be much quieter than the use of a noisy internal combustion engine in the 1-2hp range; second it permitted intermittent operation, with the motors only operating less than 50% of the time; third there is no change in weight during flight since no fuel is consumed; forth there were no emissions (which might be a problem for certain types of atmospheric science).

As a backup, for forward propulsion, D-4 was also fitted with a large 2.6m diameter propeller that could either be electric/human powered, although this was rarely used. After operations began D-4 was also fitted with two small, laterally facing electric motors (200W each) driving propellers in the tail, and two electric motors (250W each) driving propellers on short sting an the nose of the keel structure, to act as bow and tail thrusters. These thrusters proved to be essential for manoeuvres at low speed or during hover.

For vertical height control, as well the two side-mounted vectored electric motors, the envelope was fitted with a manual helium relief valve and a water ballast tank, to permit overall buoyancy/weight changes as large as 150N (in total) during flight.

Table 1 Approximate Mass Breakdown of D-4

Item	mass (kg)
Pilot	70.5
Observer	56.5 (or 0)
Safety equipment	17
Camera equipment	7
Instruments	3
Envelope	74
Structure and rigging	60
Main propeller	2
Fin and rudder	10
Main electric motors	9
Bow/tail thrusters	7
Batteries	33 (or 77)
Insect suction trap	4
Water ballast	15 (max)

Operation of "D-4"

The principal objective of Phase 1 was to determine whether D-4 (or a LTA platform like it) would be useful for scientific studies of tropical forest, and if so what limitations might exist in this type of operation. Before 1993, no helium-filled airship had been flown over tropical rain forest to the author's knowledge, and it is was not clear whether operations would be possible - with the adverse micro-thermal conditions that were previously suspected (see discussion on atmospheric conditions below).

Inflation of D-4 required about 62 cylinder of helium (92%+ pure) with 6.4 cubic metres per cylinder. A total of about 120 cylinders were used over 3 months, with approximately one-and-a-half cylinders being used for every flight. Ground handling only required two people, and pre-flight preparation took about 1 hour. Most flights took place early in the morning, although a few evening flights were also undertaken.

For take-off and landing D-4 relied on a "pandang" (a flat grass field about 100 m by 100m) in DVFC. Towards the end of operations a smaller area would have been sufficient (40m x 40m say). Most take-offs and landings were essentially vertical movements up to canopy height where the flight was levelled-out. A few flights were made along the Segama river - which had the advantage of a strong local lapse rate that improves vertical stability, Dorrington, G. E. and Kröplin B. (1996). The maximum altitude flown was about 450 ft above ground level.

D-4 was successfully stored in the pandang, which had sheltering trees on all sides, for a period of 3 months during the north-east monsoon winds prevailing, and with two major storms passing through.

Thirty flights were made in total with a total flight time of about 21 hours. These flights are listed in Table 2.

Table 2, Chronology of D-4 flights, Jan 7th –March 30th 1995

Flight number	Duration (mins)	Take-off Time
1	5	a.m
2	15 with observer	a.m
3	15 with observer	p.m
4	10 with observer	a.m
5	55	8.30 a.m
6	25	8.30 a.m
7	20	p.m
8	10	a.m
9	10	a.m
10	20	7.30 a.m
11	20 reached 450 ft, 20 km/hr	8.40 a..m
12	35	7.25 a.m
13	60	7.20 a.m
14	75	8.00 a.m
15	34	17.00 p.m
16	20	7.40 a.m
17	60	7.40 a.m
18	45	17.35 p.m
19	112	7.36 a.m
20	70	17.25 p.m
21	80	7.45 a.m
22	10 electrical fault	7.25 a.m
23	58	16.46 p.m
24	85	7.12 a.m
25	73	8.14 a.m
26	72 insect suction trap	8.22 a.m
27	11	16.55 p.m
28	114 insect suction trap	6.34 a.m
29	114 insect suction trap	6.40 a.m
30	85 ditto + soft-landing on tree	7.08 a.m

Scientific uses of "D-4"

Towards the end of the flight test sequence some small scientific experiments were carried-out. In particular, an insect suction trap modified from a design of S. Sutton was hung from the side of the envelope, see Figure 2. The suction trap comprised of an aluminium cylinder of about 300mm diameter, and a muslin gauze funnel inside. Air was sucked through the funnel by a small electric motor (50W) and propeller, so that small supra-canopy insects would be collected in a small beaker filled with a 10% alcohol mixture. The insect suction trap was run for about 20 minutes about 2m above four trees about 55-60m above ground level: a Mengaris (*Koompassia excelsa*), a Merbau (*Instia palembanica*), a White Seraya (*Parashorea malaanonan*) and a Strangling Fig (*Ficus*). A small quantity of thrips and fig wasps were collected in this manner, and the samples were given to the local University, see acknowledgements. Of particular interest was the Merbau tree which was flowering. A soft landing was made on this tree, and the dirigible rested softly for about 20 minutes, without any problems, about 10 N heavy.

Based on this final flight, the author believes that flowering-pollination studies, in the upper-crowns of trees, would be one of the most promising missions for a dirigible. The only problem would be one of duration, if any serious science is to be carried-out in situ, then it would have to be limited to be about 20 minutes, or possibly 1 hour early in a morning, but not much longer, because slight breezes tend to built-up in mid-morning – at least that was the prevailing pattern in DVFC.

Of course there are other potentially suitable scientific missions, especially supra-canopy meteorology, as well as close remote-sensing of the canopy roof. A dirigible might also be used for radio-tracking sub-canopy mammals, and to deploy and collect semi-autonomous experimental packages to and from the canopy. Unfortunately, none of these possible experiments were carried-out.

Atmospheric Conditions and Station-Keeping Requirements

One of the principal constraints in the use of ultra-light LTA platforms is the atmospheric condition immediately above the forest canopy. Many observers note that calm or light air conditions prevail just above many canopies for much of the time. Horizontal, time-averaged wind speeds as low as 2 knots are in fact probable over some tropical forests much of the day and night, Aoki et. al. (1978).

Previous studies have modelled the airflow immediately above the canopy as bounder-layer with simple logarithmic velocity distribution, Thompson and Pinker (1975); however, not much information is available on non-steady gusts (of a few seconds duration) and associated micro-meteorological effects, see e.g., Shuttleworth (1984) and Garstang et al. (1990). Gusting is especially important to free-flying LTA platforms operating close to the canopy, since the non-steady forces produced scale with volume of the airship hull, and increase linearly with the gust velocity gradient dU/dt. In order to counter these forces, a free-flying LTA platform would have to have lateral thrusters that can react quickly enough to prevent the platform from drifting sideways, Dorrington (1999).

Vertical air-currents (micro-thermals) are also of importance to free-flying helium filled LTA platforms, because they cannot alter their buoyancy widely – unlike their hot-air counterparts. Again, many observers note that the conditions immediately above the canopy are relatively quiescent early in the morning, but significant buoyancy variations caused by helium temperature rise following solar exposure occur. This interaction, though a trivial thermodynamic problem, is made quite complex by envelope elasticity effects that govern volume changes of the hull, and hence more study and data is required before a fully predictive model can be developed, Dorrington and Kröplin (1996).

Clearly one of the principal operational requirements that should be set early-on in any scientific project using a free-flying LTA platform, is what spatial station-keeping tolerance is acceptable. It is too early to prescribe a practical lower limit on this tolerance, but based on flight tests there seems no reason why a spherical volume of about 5m radius could be maintained for about 20 minutes in light-air conditions. For some scientific missions requiring precise sampling this sort of positional variation might not be acceptable, in which case the platform would have to anchored using tree hooks and/or it might be operated slightly "heavy", so that it rests gently on a suitable tree crown, as was successfully demonstrated during *Project Hornbill*, Dorrington (1996).

From a safety standpoint, it is highly desirable, if not essential, to have a warning system in place to predict and avoid the arrival of unacceptable atmospheric conditions. Part of the solution, here, might be to use an array of anemometers positioned on masts several kilometres around the operating site, providing radio-telemetry about local wind conditions.

Future Work

As has been previously pointed-out by the author (1995) several future LTA platforms appear to be worthy of investigation:

1. A quasi-traditional, helium-filled dirigible configuration, of about 400-600 cubic metres volume, where the gondola hangs below (or is attached below) and streamlined hull/envelope. Such a platform would be capable of several kilometres range using quiet electric propulsion system, and be capable of carrying 2 people: a pilot and a scientist/user. The use of tail/bow thrusters would be useful to improve manoeuverability close to the canopy. Clearly a improved dirigible could be fitted with a more advanced electric power system, either Nickel-Metal Hydride or Lithium ion batteries, possibly used in conjunction with a gaseous hydrogen fuel cell. Work on this system has begun, and the author hopes to fly a new dirigible in late 2004.
2. A helium-filled "powered balloon" where a small envelope with a squat shape and diameter of about 8m is used to carry a single pilot-trained scientific user to get closer to more confined pockets in the canopy. Since 1995, some unreported work has been undertaken on this concept by the author, and it appears that a spherical hull shape may present control difficulties during hovering, as well a significantly reduced range - caused by high hull drag. The drag coefficient of a sphere is about 0.2 (based on frontal area) at Reynolds numbers of about 1000,000, but this can be reduced significantly by careful aerodynamic tailoring. A squat, (e.g., ovoid shape), has some advantages in this respect. Some tests on such as a system are planned by the author in 2004.

3. A cable balloon system where essentially a helium-filled envelope is used to carry the weight of one or two scientists and their equipment, along a cable or spider's web of ropes lying over the canopy. This idea has subsequently been tested in Madagascar by Hallé and his team with their "Canopy Bubble", Hallé (2002). The obvious limitation with cable systems is that the freedom and operating range of the platform are reduced from kilometres to hundreds of metres, but for many scientific requirements this limitation may be irrelevant and the absence of free-flight systems may reduce costs and also circumvent the need for full aeronautical certification. Another advantage might be a greater tolerance to wind conditions, although this might be deceptive and same precautions regarding deterioration of wind conditions mentioned above probably need to be adhered to. Here it should be mentioned that a sphere or vertically-stretched spheroid is certainly not an ideal hull shape, since vortex shedding is not uniform, so any cross-wind will cause oscillations – that may become violent in stronger breezes. Hence, again, some careful aerodynamic-tailoring can pay-off significantly – reducing forces and improving safety. Of particular note in this respect is "COPAS", an innovative canopy access scheme being developed at the University of Ulm, Gottsberger, G. and Döring, J. (1995). This system started life as an array of masts and cables, but the loading envisaged was not feasible, so a spherical balloon (made by Ballonfabrik, Augburg) was introduced to offset the central load, Charles-Dominique, P, et. al. (2002). Such a system appears to be fine, provided there are no strong breezes, nor storms, in which case the balloon would have to be deflated, or brought down safely to the ground, since otherwise the unsteady loads might become excessive.

Looking further into the future, we might speculate that small autonomous micro-air vehicles might be used for certain missions, and at the other extreme, large LTA platforms (with helium volumes in excess of 10,000 m^3) capable of carrying several scientists over the canopy for several months, possibly using long legs and claw device to walk over the canopy.

Concluding Remarks

The case for using free-flying LTA platforms in a coordinated canopy science programme is strong, provided the specific scientific needs are substantial. As Mitchell (1986) points out there are technological solutions, and LTA platforms probably will be developed – somewhat analogous to the use of small submarines and bathyspheres to explore the oceans. What is not clear is whether the idea of canopy prospecting is yet ready for fruition, because it is dependent on the emergence of screening techniques that would permit the rapid, in situ, analysis of promising chemicals. Let us speculate, a scientist believes a promising aktinomycete, permitting the development of a new life-saving antibiotic, exists in the soil of epiphyte high in the canopy in certain trees at certain times. How would it be found and identified? The problem seems far worse than finding a needle in haystack. At least one positive thing can be said: the problem of accessibility to the upper canopy is solvable.

Given the current amount of resource going into robotic missions to Mars to look for any signs of life (certainly a worthwhile pursuit), surely it is time for canopy scientists to start seek substantial funding the explore the “high frontier” of tropical rain forest canopies, here on Earth, before they are irrevocably destroyed?

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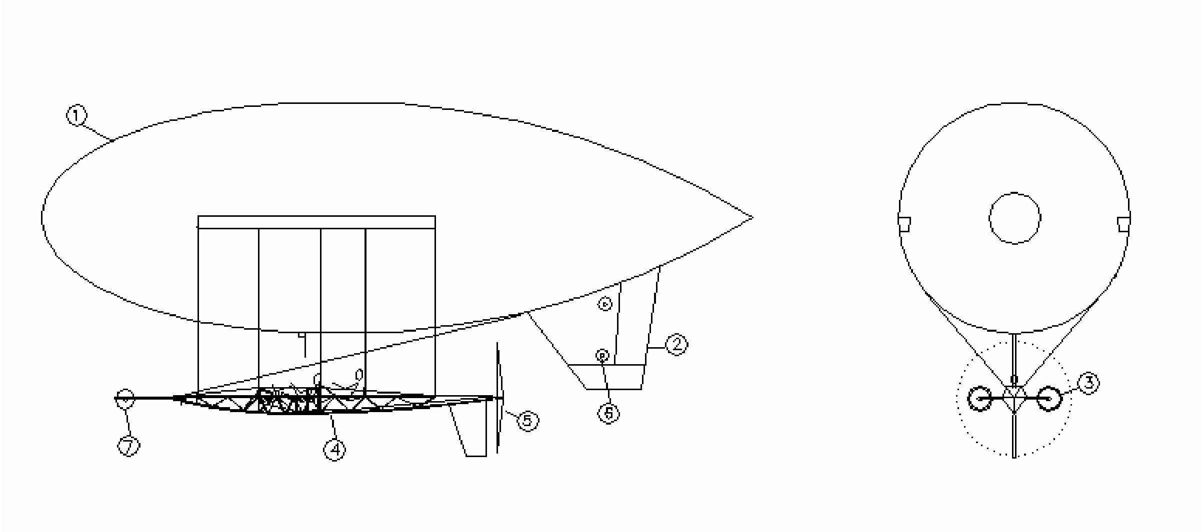

Figure 1, D4 Airship

Key: 1, envelope 400 m^3, 2 tail fin, 3 ducted fan (vectored through 270 degrees), 4 gondola structure (9m length), 5 rear propeller (2.6 m diameter), 6 tail thruster, 7 bow thruster.

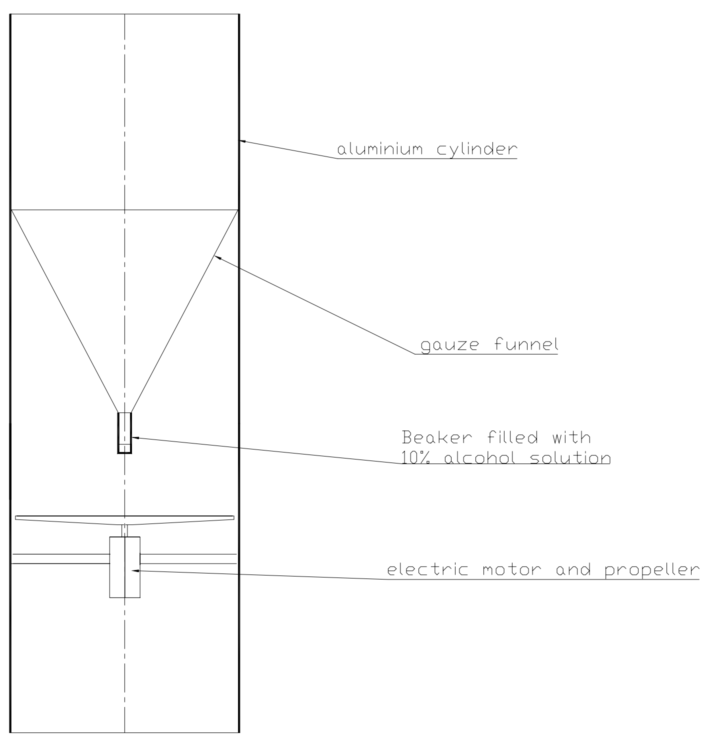

Figure 2, Schematic Sketch of the Suction Trap used on D-4
based on a design of Steven Sutton (not to scale).