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(71) Applicant: **BAE SYSTEMS PLC** [GB/GB]; 6 Carlton Gardens, London SW1Y 5AD (GB).

(72) Inventors: **BROOKS, Paul**; Prismatic Ltd, 2 Omega Park, Alton Hampshire GU34 2QE (GB). **DIXON, Jonathan David**; Prismatic Ltd, 2 Omega Park, Alton Hampshire GU34 2QE (GB). **SERGISON, Darryl James**; Prismatic Ltd, 2 Omega Park, Alton Hampshire GU34 2QE (GB).

(74) Agent: **BAE SYSTEMS PLC, GROUP IP DEPT**; 87 Farnborough Aerospace Centre, Farnborough, Hampshire, GU14 6YU (GB).

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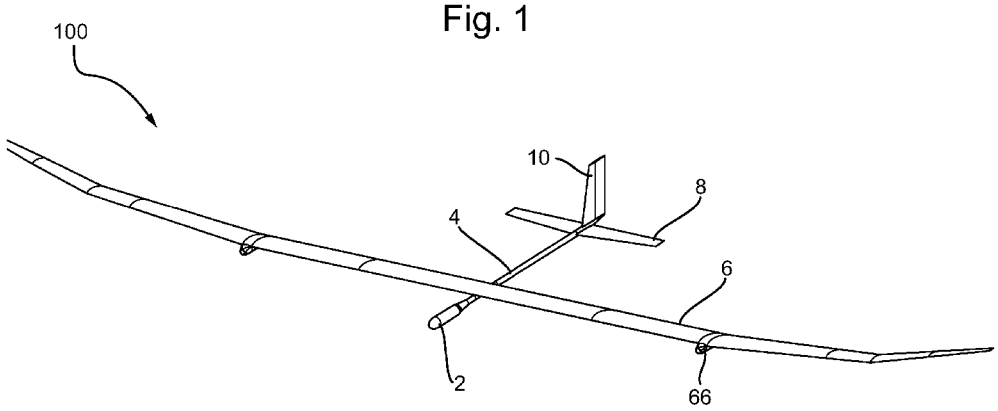
(54) Title: METHOD OF FLYING AN AIRCRAFT

Fig. 1



(57) Abstract: The present invention provides a method of flying a solar-powered aircraft, comprising: controlling the aircraft to leave the ground immediately prior to a period of substantial darkness; and without landing the aircraft after it leaves the ground, maintaining flight of the aircraft through the period of substantial darkness until a period of substantial light, such that at least one battery is used to power the aircraft for a greater duration at the beginning of the flight than in the middle or at the end of the flight. The present invention also provides a control system for performing the method.

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METHOD OF FLYING AN AIRCRAFT

FIELD OF THE INVENTION

The present invention relates to a method of flying a solar-powered aircraft; particularly, but not exclusively the aircraft is a high altitude long endurance aircraft. The invention also relates to a control system for a solar-powered aircraft and a solar-powered aircraft having the same.

BACKGROUND

High altitude long endurance (HALE) aircraft are known. These are typically powered by combination of photovoltaic (PV) cells and rechargeable batteries. The power source is selected depending on the intensity of light striking the aircraft's PV cells. For example, during the day, the PV cells are used, and at night the batteries are used to power the aircraft's engines. There is a desire to increase the amount of time for which such aircraft can stay aloft.

SUMMARY

According to an aspect of the present invention, there is provided a method of flying a solar-powered aircraft, the method comprising:

controlling the aircraft to leave the ground immediately prior to a period of substantial darkness; and

without landing the aircraft after it leaves the ground, maintaining flight of the aircraft through the period of substantial darkness until a period of substantial light, such that at least one battery is used to power the aircraft for a greater duration at the beginning of the flight than in the middle or at the end of the flight.

Advantageously, taking off prior to a dark period ensures the batteries are new and at peak performance during the dark period. Therefore, at the time of the light period it is less critical that the batteries are degraded in performance as here the photovoltaic cells can power the aircraft.

The method may comprise controlling the aircraft to leave the ground in autumn, wherein the period of darkness is winter; and

without landing the aircraft after it leaves the ground, maintaining flight of the aircraft through winter, such that the at least one battery is used to power the aircraft for a greater duration per day than at least one photovoltaic cell in the first three months of the flight.

A duration of the flight is preferably greater than about 90 days. Even more preferably, the duration of the flight is greater than about 180 days. Even more preferably, the duration of the flight is about 1 year.

The method may comprise controlling the aircraft to leave the ground in May in the southern hemisphere or November in the northern hemisphere.

The method may comprise maintaining the flight of the aircraft through winter, spring and summer without landing in-between, and landing the aircraft in autumn, such that the at least one battery is used to power the aircraft for a greater duration per day at the beginning of the flight than at the end of the flight.

The method may comprise landing the aircraft at the same location from which it left the ground.

The method may comprise controlling the aircraft to leave the ground at a low latitude and controlling the aircraft to fly to a high latitude where the flight is maintained.

The aircraft may be an unmanned high altitude long endurance aircraft. Alternatively, the aircraft may be a spacecraft.

According to a second aspect of the present invention, there is provided a control system for a solar-powered aircraft comprising at least one battery and

at least one photovoltaic cell, the control system comprising a processor configured to:

generate a control signal to control the aircraft to leave the ground immediately prior to a period of substantial darkness; and

without landing the aircraft after it leaves the ground, generate a control signal to control the aircraft to maintain flight through the period of substantial darkness until a period of substantial light, such that at least one battery is used to power the aircraft for a greater duration at the beginning of the flight than in the middle or at the end of the flight.

The processor may be configured to:

generate a control signal to control the aircraft to leave the ground in autumn; and

without landing the aircraft after it leaves the ground, generate a control signal to control the aircraft to maintain flight through winter, such that the at least one battery is used to power the aircraft for a greater duration per day than the at least one photovoltaic cell in the first three months of the flight.

A duration of the flight is preferably greater than about 90 days. Even more preferably, the duration of the flight is greater than about 180 days. Even more preferably, the duration of the flight is about 1 year.

The processor may be configured to generate a control signal to control the aircraft to leave the ground in May in the southern hemisphere or November in the northern hemisphere.

The processor may be configured to generate a control signal to control the aircraft to maintain flight through winter, spring and summer without landing in-between, and generate a control signal to land the aircraft in autumn, such that the at least one battery is used to power the aircraft for a greater duration per day at the beginning of the flight than at the end of the flight.

The processor may be configured to generate a control signal to land the aircraft at the same location from which it left the ground.

The processor may be configured to generate a control signal to control the aircraft to leave the ground at a low latitude and control the aircraft to fly to a high latitude where the flight is maintained.

According to a third aspect of the present invention, there is provided a solar-powered aircraft comprising:

the control system according to the second aspect;

at least one battery for powering the aircraft during periods of darkness; and

at least one photovoltaic cell for powering the aircraft during periods of light.

The solar-powered aircraft may be an unmanned high altitude long endurance aircraft. Alternatively, the solar-powered aircraft may be a spacecraft.

It will be appreciated that features described in relation to one aspect of the present invention can be incorporated into other aspects of the present invention. For example, an apparatus of the invention can incorporate any of the features described in this disclosure with reference to a method, and vice versa. Moreover, additional embodiments and aspects will be apparent from the following description, drawings, and claims. As can be appreciated from the foregoing and following description, each and every feature described herein, and each and every combination of two or more of such features, and each and every combination of one or more values defining a range, are included within the present disclosure provided that the features included in such a combination are not mutually inconsistent. In addition, any feature or combination of features or any value(s) defining a range may be specifically excluded from any embodiment of the present disclosure.

BRIEF DESCRIPTION OF THE DRAWINGS

Embodiments of the invention will now be described by way of example only and with reference to the accompanying drawings.

Figure 1 is a perspective view of an aircraft according to embodiments of the present invention;

Figure 2 is a system diagram of a power supply for an aircraft according to embodiments of the present invention;

Figures 3a and 3b are graphs showing the effect of altitude and latitude on average wind speed and cruise speed of an aircraft as shown in Figure 1;

Figure 4 is a graph showing the effect of multiple discharges on battery capacity;

Figure 5 is a graph showing the average length of night during each month of the year at a medium latitude; and

Figure 6 is a graph showing the power required to fly an aircraft as shown in Figure 1 as a function of altitude.

For convenience and economy, the same reference numerals are used in different figures to label identical or similar elements.

DETAILED DESCRIPTION

Generally, embodiments herein relate to a method of flying a solar-powered aircraft so as to maximise the aircraft's time in the air (flight time). While solar-powered long endurance aircraft are known, the method that follows is an improved and optimised method of operating them that minimises the number of or capacity of batteries needed to fly for a predetermined amount of time.

A solar-powered aircraft 100, specifically a high altitude long endurance (HALE) unmanned aeroplane, is shown in Figure 1. While a HALE aircraft 100 is shown here, it would be readily appreciated that the present invention is applicable to other types of aircraft, such as high altitude balloons, medium altitude long endurance aircraft, or spacecraft.

A HALE aircraft 100 typically operates at altitudes of around 20,000 m. Long endurance means a non-stop flight having a duration of greater than about 24 hours, but preferably greater than about 1 month. Even more preferably, a long endurance aircraft 100 is capable of sustained flight for up to about 90 days. Even more preferably, the aircraft 100 is capable of sustained flight for up to about 180 days. In an exemplary embodiment, the aircraft 100 is capable of sustained flight for up to at least 1 year. Sustained flight means the period between the aircraft 100 taking off and landing (or ceasing controlled flight) is not interrupted by the aircraft 100 landing.

The aircraft 100 includes a wing member 6 having a wing span of about 35 metres and a relatively narrow chord (i.e. of the order 1 metre). The wing member 6 is coupled to a fuselage 4. To aerodynamically balance the aircraft 100, a horizontal tailplane 8 and a vertical tail fin (or vertical stabilizer) 10 are coupled to the rear of the fuselage 4. A payload module 2 is coupled to the front of the fuselage 4, i.e. the nose of the aircraft 100. An engine 66 having a propeller is mounted to the wing member 6 on both sides of the fuselage 4.

The aircraft 100 is of lightweight construction. For example, the fuselage 4, wing member 6, payload module 2, tailplane 8 and tail fin 10 are made of a monocoque carbon fibre laminate skin structure. In other words, the skin forms the aircraft's body. In other embodiments, the body is substantially made of a light weight metal, such as titanium, titanium alloy, aluminium or aluminium alloy.

The aircraft 100 may be manned or unmanned. It may be controlled to take off, manoeuvre and land from a control station. Alternatively, the aircraft 100 may comprise a processor configured to generate control signals used to control the aircraft's control surfaces (i.e. ailerons, elevators and flaps) such that it takes off, manoeuvres and lands. The aircraft 100 may be controlled to land at the same airfield from which it took off. In an alternative embodiment, the aircraft 100 is intentionally crashed instead of being landed, due to the weight of aircraft 100 being minimised by not including landing gear.

Turning to Figure 2, the engines 66 are powered by a combination of PV cells (otherwise known as solar panels) 68a-c mounted to the upper surfaces of the wing member 6 and a battery 62 (or plurality of batteries) disposed inside the wing member 6. A battery 62 comprises a plurality of cells. Collectively, the PV cells 68a-c and the battery 62 form a power supply. In other embodiments, the battery 62 is disposed inside the fuselage 4. In other embodiments again, the battery 62 is disposed inside a nacelle having the engine 66 installed therein. The PV cells 68a-c may also be disposed on the outer surface of the fuselage 4 and/or the horizontal tailplane 8 and/or the vertical tail fin 10. While a plurality of PV cells 68a-c are shown, in some embodiments aircraft 100 includes a single PV cell 68a.

A first switch 64 is disposed between the battery 62 and the engine 66. When the first switch 64 is open, current cannot flow between the battery 62 and the engine 66, and therefore the engine 66 cannot be powered by the battery 62. When the switch 64 is closed, current is able flow between the battery 62 and the engine 66, such that the engine 66 is powered by the battery 62.

The aircraft 100 may comprise a sensor for determining the amount of power generated by the PV cells 68a-c. When the power level drops below a threshold, the first switch 64 is closed such that the engine 66 can be powered instead by the battery 62. The power generated by the PV cells 68a-c is reduced in low light conditions, such as night.

A second switch 65 may be disposed between the PV cells 68a-c and the battery 62. When the second switch 65 is open, current is unable to flow between the PV cells 68a-c and the battery 62, and therefore the PV cells 68a-c are unable to charge the battery 62. When the second switch 65 is closed, current is able to flow between the PV cells 68a-c and the battery 62, and therefore the PV cells 68a-c are able to charge the battery.

The aircraft 100 may comprise a sensor configured to measure the charge of the battery 62. If the charge exceeds a threshold, the second switch 65 is opened to prevent the battery 62 from being charged further.

The operation of a solar-powered aircraft 100 designed to operate for extended periods of time, such as a solar-powered HALE unmanned aerial vehicle (UAV), is dependent on the time of year of its operation and the performance of its power system, as explained with reference to Figure 2. Operation of a solar-powered aircraft 100 is more difficult during winter periods when the Sun is low in the sky, the nights are long and the winds are both stronger and higher in altitude.

The performance of the battery 62 (or batteries) tends to degrade with the number of charging/discharging cycles undertaken and the depth of these cycles such that an old battery 62 cannot provide the same level of performance as a fresh battery 62.

Therefore, for any operational location there will be an optimum time at which to launch a solar-powered aircraft 100 if the aircraft if the flight time is intended to be about a year in duration to make the best use of the battery 62.

The level of difficulty associated with an aircraft 100 maintaining altitude above the significant prevailing winds can be emphasised by comparing two cases – Equatorial and mid-latitude. Near the Equator there are no strong jet stream winds. This is illustrated in Figure 3a, where the strongest winds (~55 knots) are found at an altitude of 15 km in August. The slowest winds and most stable winds across the measured altitude range tend to be found in May. A second, smaller, peak in wind speed as a function of altitude is found between 20 km and 25 km. Here, winds in January are strongest, with speeds of about 38 knots.

Figure 3b, illustrating wind speed as a function of altitude at a mid-latitude (24.55 degrees North), shows that away from the equator wind speed at the

altitudes which a HALE aircraft 100 tends to operate when on station tend to be higher and less consistent throughout the year. Predominantly, high wind speed (up to ~110 knots in January) can be found at altitudes between 7 km and 15 km. Summer months demonstrate much lower wind speeds (~15 knots) at these altitudes, but in the summer the wind speed rises to ~38 knots at very high altitudes (e.g. between 20 km and 25 km).

Therefore, Figures 3a and 3b demonstrate that the winds at the altitude which a HALE aircraft 100 tends to operate tend to be slower and more consistent through the year close to the Equator. At higher latitudes, the jet stream results in high speed winds at altitudes between 7 and 15 km predominantly in the winter months.

For each location shown in Figures 3a and 3b, there are times of year when the ability to fly at altitudes above the high wind speeds that prevent a persistent presence (i.e. long flight time) is more challenging. The higher latitude case (e.g. Figure 3b) is significantly worse due to the long nights and low Sun angles in winter that coincide with the worst wind conditions. As demonstrated, taking off in or around winter at high latitudes is not optimal.

In general, the capacity of the battery 62 degrades the more it is cycled, as illustrated by the long-term testing of Lithium ion batteries, suitable for HALE aircraft 100, in Figure 4.

The capacity reduction also increases the greater the depth of the discharge. Therefore, the capacity reduction is reduced if the battery 62 is not fully discharged on each cycle.

The approach is to consider the requirements of the battery 62 as a function of time of year in terms of maintaining altitude above the significant winds and the through-life capacity of the battery 62 as it is cycled.

The energy required from the battery 62 changes as a function of time of year, with the summers having longer days and shorter nights as shown in Figure 5. While summer has the highest average duration of sunlight per day, winter has the lowest average duration of sunlight per day. Spring has an average duration of sunlight greater than that of winter but less than that of summer. Autumn has an average duration of sunlight less than that of summer but greater than that of winter. This length of night combines with the need to fly higher during the winter due to the stronger jet stream winds as shown in Figures 3a and 3b.

Therefore during the winter months, due to the increased periods of darkness, the battery 62 is discharged more completely and so the rate of degradation of capacity increases. During the summer, the rate of degradation can be effectively zero as the battery 62 may only be being depleted to 60% of its maximum depth of discharge.

At the time of year when the highest capacity of battery 62 is required (winter) the battery 62 should be in its best condition. In other words, it would be optimal if the battery 62 had not endured many cycles (preferably not any deep cycles) prior to winter. The high degree of discharge through the winter will degrade the capacity faster but by spring (e.g. March, in the northern hemisphere) a lower capacity will be required, and this will continue to be the case through to autumn (e.g. October, in the northern hemisphere). Towards the end of the operational year, the demands on the battery 62 will increase rapidly and the aircraft 100 is likely to require a battery exchange for ongoing operation.

For higher latitude year-long operations, the aircraft 100 should be launched towards the end of the autumn to make best use of the new battery 62 through the demanding winter period. Therefore, by the time the summer months come around, the battery 62 is of a relatively poor quality, but this does not matter so much because in these months there is more sunlight to rely on and so the PV

cells 68a-c are used to power the engines 66 for longer durations per day than in winter months.

As previously explained, launching and recovering an aircraft 100 in winter from a high latitude is not optimal due to the inconsistent and unfavourable wind and weather conditions. Therefore, it has been found that flight time can be maximised, by minimising power usage, by launching a long-endurance aircraft 100 near the equator (i.e. low latitudes) in, or immediately prior to, winter, where launch and recovery conditions are good and consistent, and then flying to the stratosphere above poorer tropospheric conditions at higher latitudes.

The seasons are winter, spring, summer and autumn. The months that define winter, in the northern hemisphere, are December, January and February. In the southern hemisphere, these are the summer months. The months that define spring, in the northern hemisphere, are March, April and May. In the southern hemisphere, these are the autumn months. The months that define summer, in the northern hemisphere, are June, July and August. In the southern hemisphere, these are the winter months. The months that define autumn, in the northern hemisphere, are September, October and November. In the southern hemisphere, these are the spring months.

While year-long operations are described above, it would be readily appreciated that the same concept could be applied to solar-powered aircraft 100 with a medium endurance, such as of the order of between 6 and 24 hours. Such an aircraft 100 may have relatively small PV cells 68a-c and a lower capacity battery 62 than a long-endurance aircraft, but its flight time may still be extended to without having to improve the power system. Here, the user selects to control the aircraft 100 to take off just before night begins (i.e. dusk) so that the battery 62 is used immediately and exclusively. Therefore, the battery 62 is degraded during the daytime the next day, but here the PV cells 68a-c are able to be used to power the aircraft 100 instead of the battery 62. The user would be naturally prejudiced against launching a solar-powered

aircraft 100 at dusk, where the PV cells 68a-c would cease to be effective in powering the aircraft 100.

Spacecraft, such as crew capsules, space stations and satellites can be operational for months or years at a time. Where an astronomical body, such as the Earth or Moon, is present between the spacecraft and the Sun, the PV cells 68a-c of the spacecraft will not receive light and it may have to rely on batteries 62 for its power source. Therefore, a spacecraft faces similar challenges to a long-endurance aircraft in that the batteries 62 become degraded and limit the flight time of the spacecraft. Therefore, for a flight time of greater than 9 months to be achieved optimally (i.e. without adding weight by having more batteries or battery capacity than necessary), it would be beneficial to begin the spacecraft's journey immediately prior to a point in the journey where it is known that the spacecraft will be in darkness.

Where, in the foregoing description, integers or elements are mentioned that have known, obvious, or foreseeable equivalents, then such equivalents are herein incorporated as if individually set forth. Reference should be made to the claims for determining the true scope of the present disclosure, which should be construed so as to encompass any such equivalents. It will also be appreciated by the reader that integers or features of the disclosure that are described as optional do not limit the scope of the independent claims. Moreover, it is to be understood that such optional integers or features, while of possible benefit in some embodiments of the disclosure, may not be desirable, and can therefore be absent, in other embodiments.

CLAIMS

1. A method of flying a solar-powered aircraft, the method comprising:

controlling the aircraft to leave the ground immediately prior to a period of substantial darkness; and

without landing the aircraft after it leaves the ground, maintaining flight of the aircraft through the period of substantial darkness until a period of substantial light, such that at least one battery is used to power the aircraft for a greater duration at the beginning of the flight than in the middle or at the end of the flight.

2. The method according to claim 1, comprising controlling the aircraft to leave the ground in autumn, wherein the period of darkness is winter; and

without landing the aircraft after it leaves the ground, maintaining flight of the aircraft through winter, such that the at least one battery is used to power the aircraft for a greater duration per day than at least one photovoltaic cell in the first three months of the flight.

3. The method according to claim 1 or claim 2, wherein the duration of the flight is greater than about 90 days.

4. The method according to claim 2 or claim 3, comprising controlling the aircraft to leave the ground in May in the southern hemisphere or November in the northern hemisphere.

5. The method according to claim 2, 3 or 4, comprising maintaining the flight of the aircraft through winter, spring and summer without landing in-between, and landing the aircraft in autumn, such that the at least one battery is used to power the aircraft for a greater duration per day at the beginning of the flight than at the end of the flight.

6. The method according to any one of the preceding claims, comprising landing the aircraft at the same location from which it left the ground.

7. The method according to any one of the preceding claims, wherein the method comprises controlling the aircraft to leave the ground at a low latitude and flying the aircraft to a high latitude where the flight is maintained.

8. The method according to any one of the preceding claims, wherein the aircraft is an unmanned high altitude long endurance aircraft.

9. The method according to any one of claims 1 to 6, wherein the aircraft is a spacecraft.

10. A control system for a solar-powered aircraft comprising at least one battery and at least one photovoltaic cell, the control system comprising a processor configured to:

generate a control signal to control the aircraft to leave the ground immediately prior to a period of substantial darkness; and

without landing the aircraft after it leaves the ground, generate a control signal to control the aircraft to maintain flight through the period of substantial darkness until a period of substantial light, such that at least one battery is used to power the aircraft for a greater duration at the beginning of the flight than in the middle or at the end of the flight.

11. The control system according to claim 10, wherein the processor is configured to:

generate a control signal to control the aircraft to leave the ground in autumn; and

without landing the aircraft after it leaves the ground, generate a control signal to control the aircraft to maintain flight through winter, such that the at least one battery is used to power the aircraft for a greater duration per day than the at least one photovoltaic cell in the first three months of the flight.

12. The control system according to claim 10 or claim 11, wherein the duration of the flight is greater than about 90 days.

13. The control system according to claim 11 or claim 12, wherein the processor is configured to generate a control signal to control the aircraft to leave the ground in May in the southern hemisphere or November in the northern hemisphere.

14. The control system according to any one of claims 10 to 13, wherein the processor is configured to generate a control signal to control the aircraft to maintain flight through winter, spring and summer without landing in-between, and generate a control signal to land the aircraft in autumn, such that the at least one battery is used to power the aircraft for a greater duration per day at the beginning of the flight than at the end of the flight.

15. The control system according to any one of claims 10 to 14, wherein the processor is configured to generate a control signal to land the aircraft at the same location from which it left the ground.

16. The control system according to any one of claims 10 to 15, wherein the processor is configured to generate a control signal to control the aircraft to leave the ground at a low latitude and control the aircraft to fly to a high latitude where the flight is maintained.

17. A solar-powered aircraft comprising:

the control system according to any one of claims 10 to 16;

at least one battery for powering the aircraft during periods of darkness; and

at least one photovoltaic cell for powering the aircraft during periods of light.

18. The solar-powered aircraft according to claim 17, wherein the solar-powered aircraft is an unmanned high altitude long endurance aircraft.

19. The solar-powered aircraft according to claim 17, wherein the solar-powered aircraft is a spacecraft.

Fig. 1

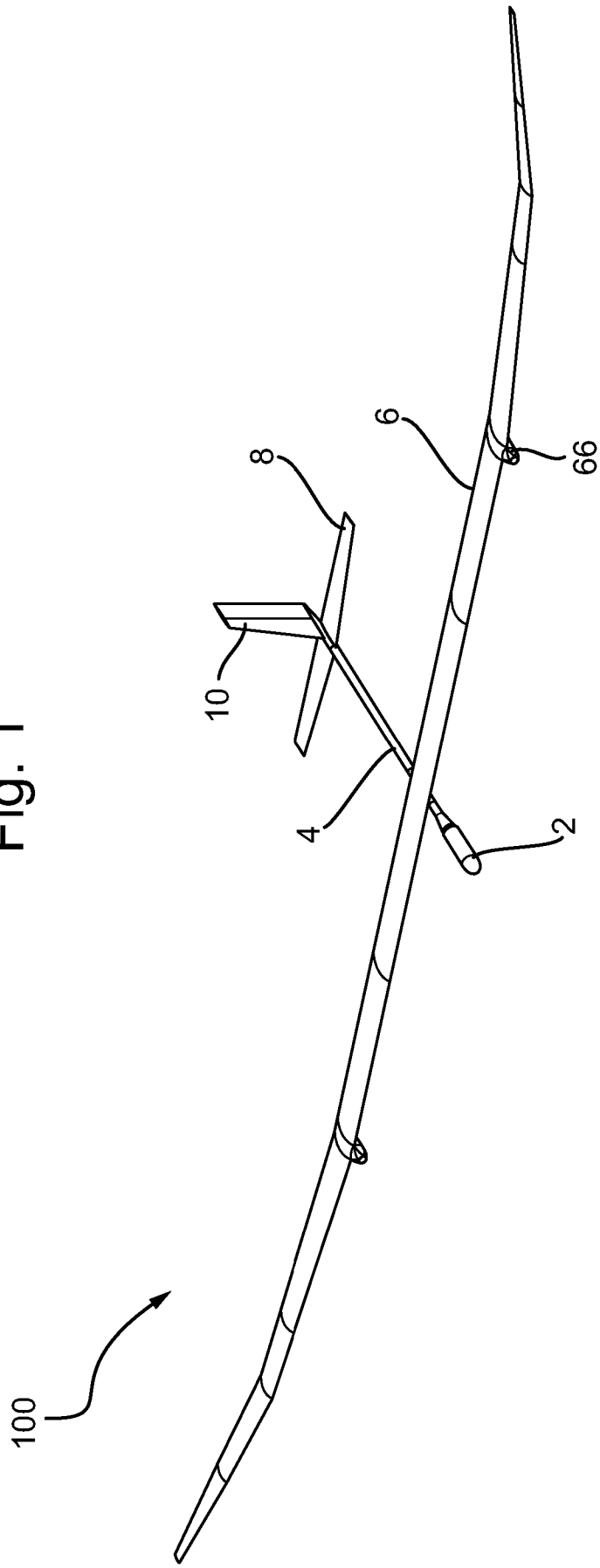


Fig. 2

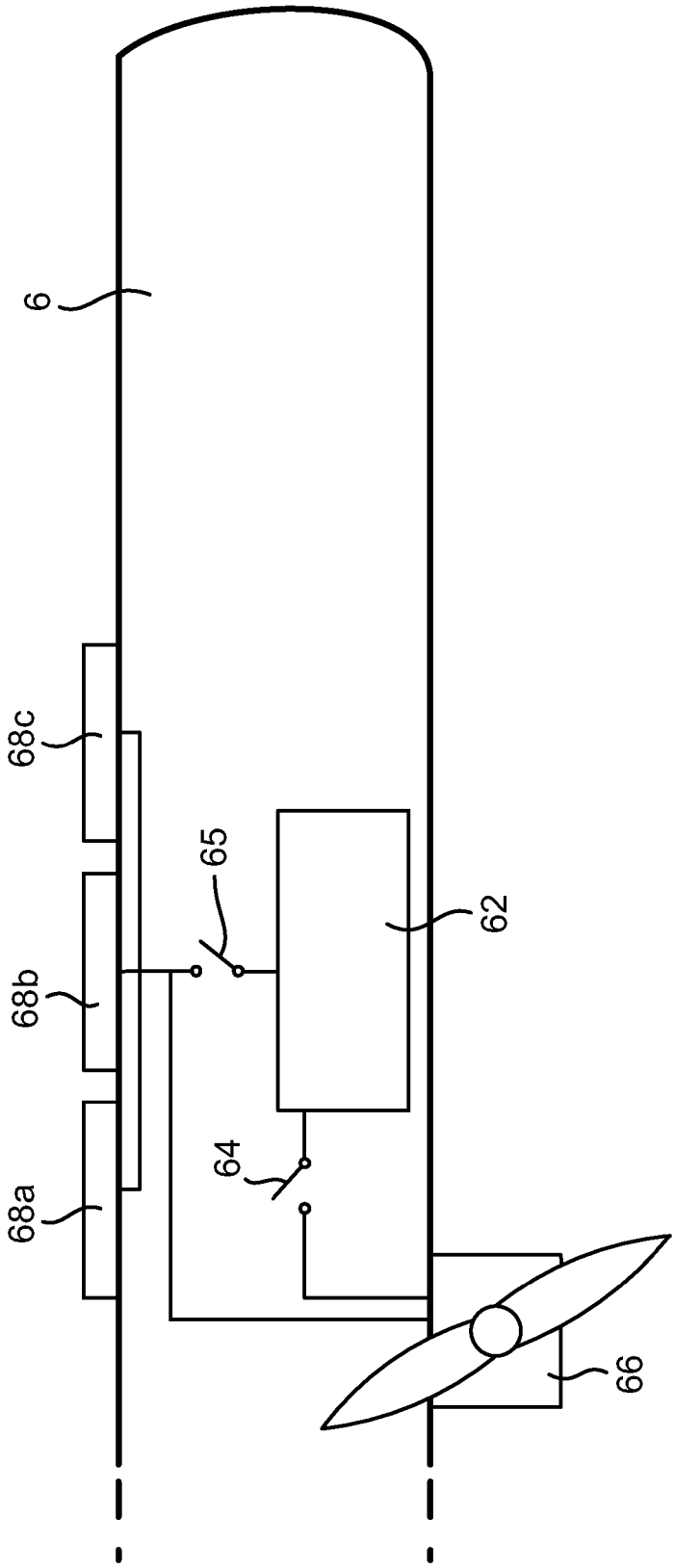
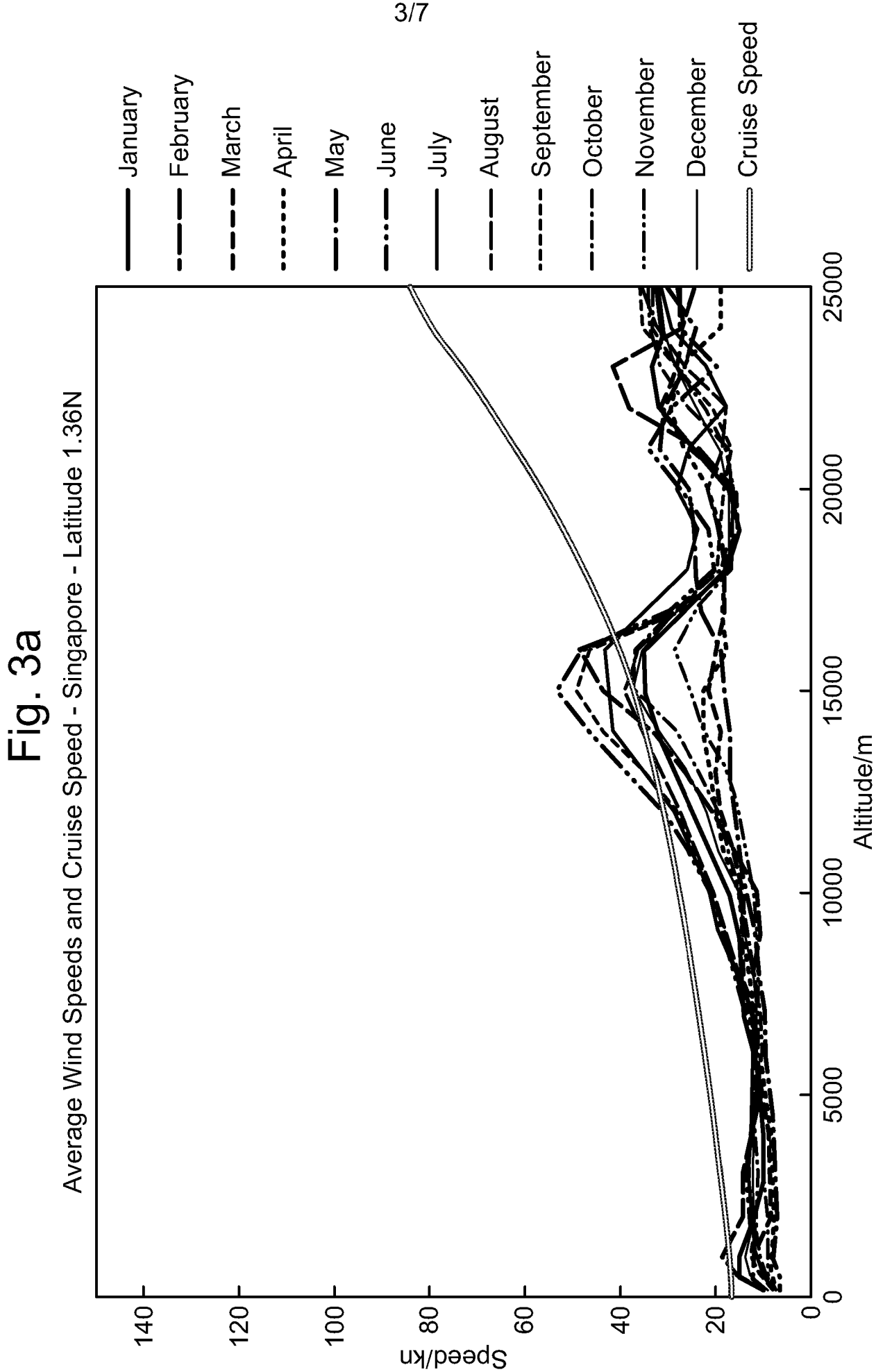


Fig. 3a


Average Wind Speeds and Cruise Speed - Singapore - Latitude 1.36N
January
February
March
April
May
June
July
August
September
October
November
December
Cruise Speed
Speed/kn
0
20
40
60
80
100
120
140
Altitude/m
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10000
15000
20000
25000

Fig. 3b

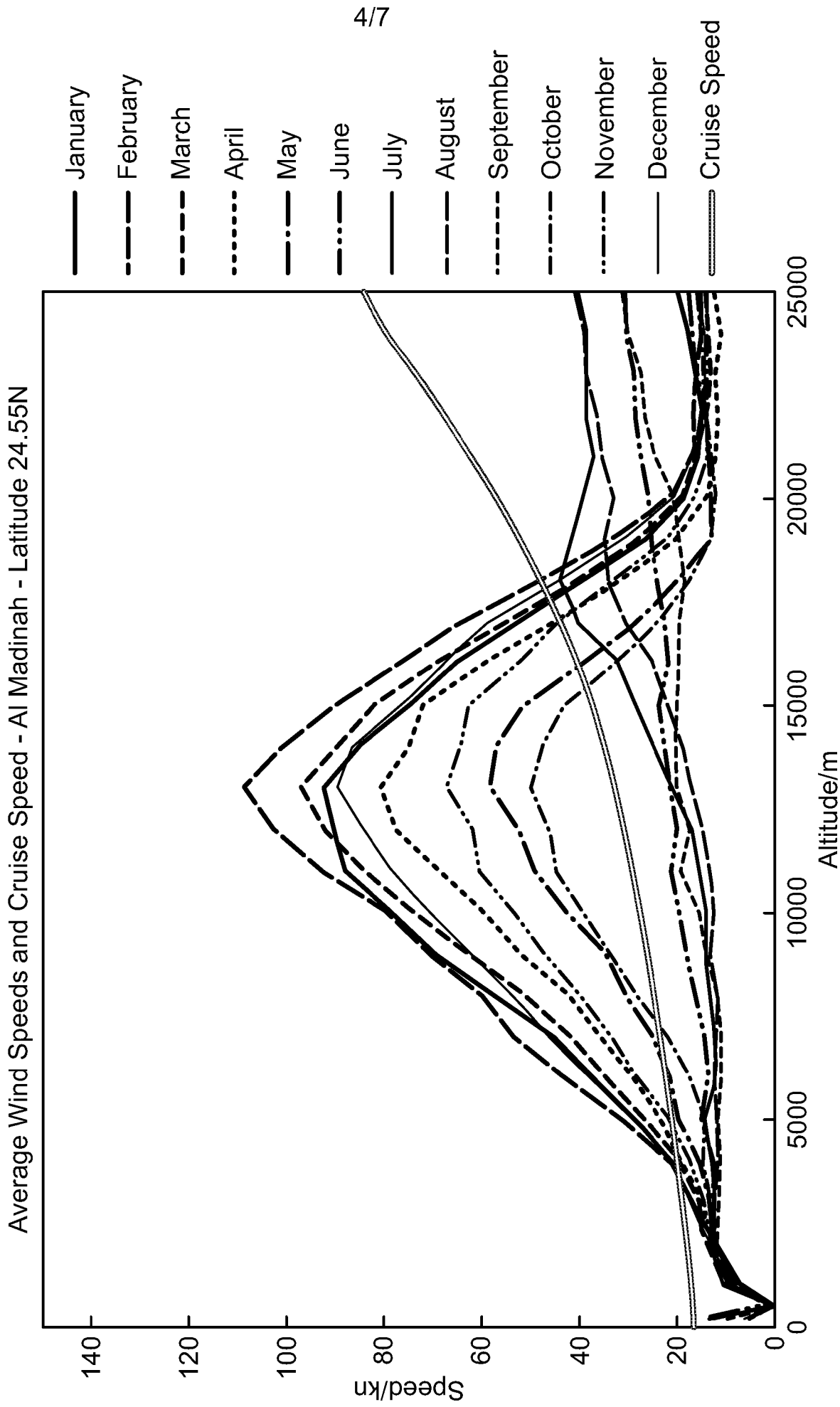
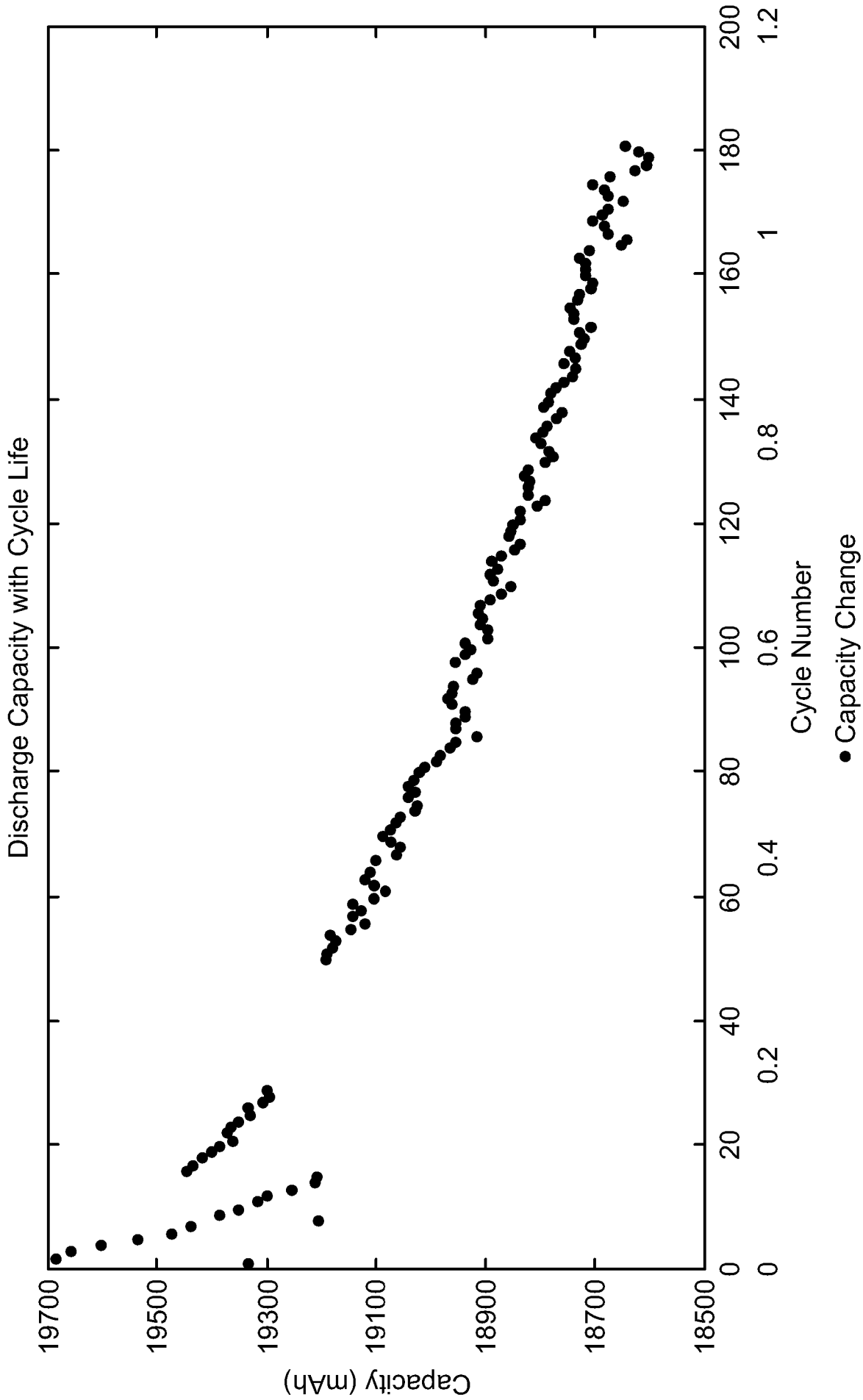

Average Wind Speeds and Cruise Speed - Al Madinah - Latitude 24.55N
January
February
March
April
May
June
July
August
September
October
November
December
Cruise Speed
Speed/kn
0
20
40
60
80
100
120
140
Altitude/m
0
5000
10000
15000
20000
25000

Fig. 4


Discharge Capacity with Cycle Life
Capacity (mAh)
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19500
19300
19100
18900
18700
18500
0
20
40
60
80
100
120
140
160
180
200
0
0.2
0.4
0.6
0.8
1
1.2
Cycle Number
Capacity Change

Fig. 5

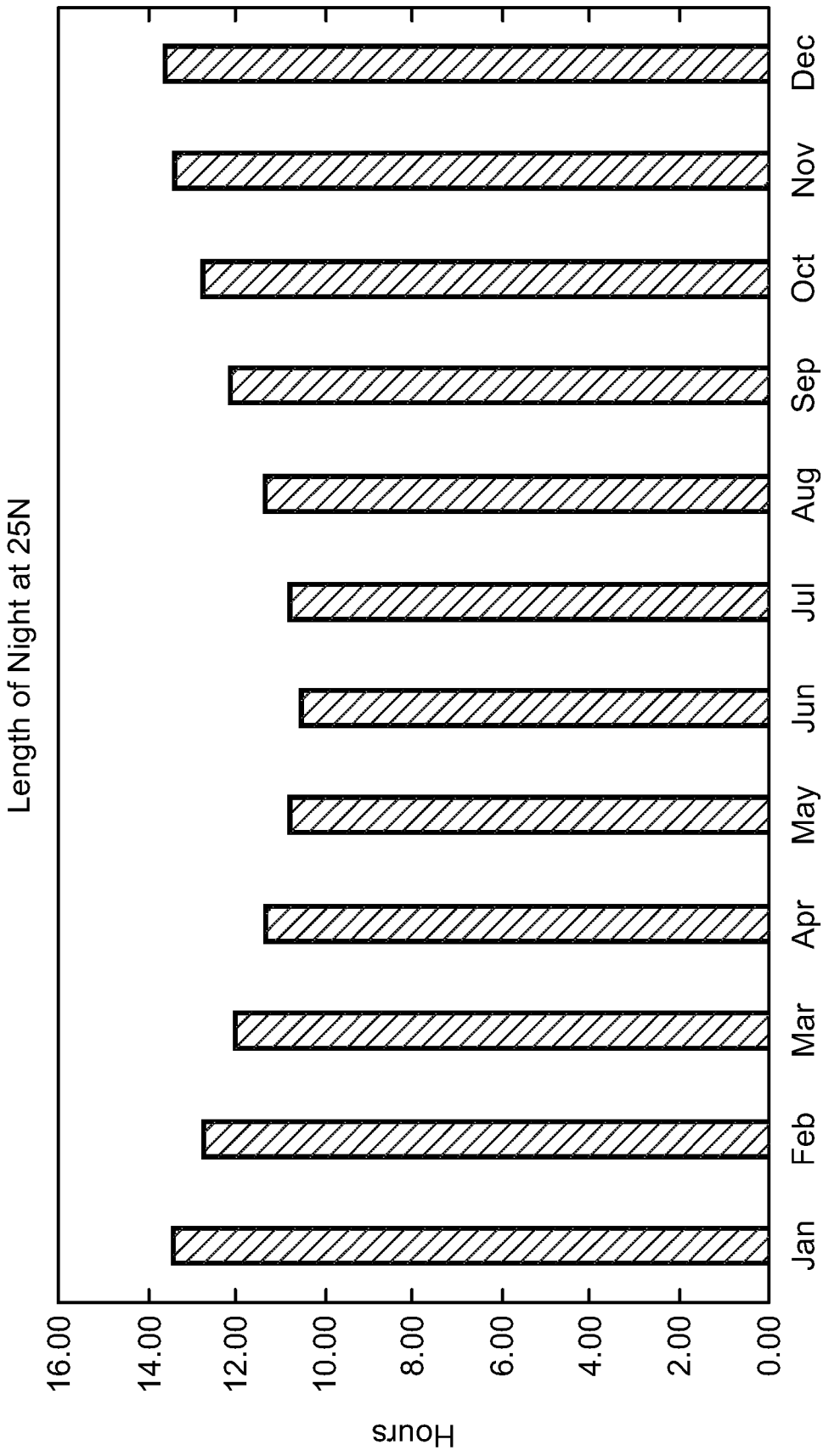
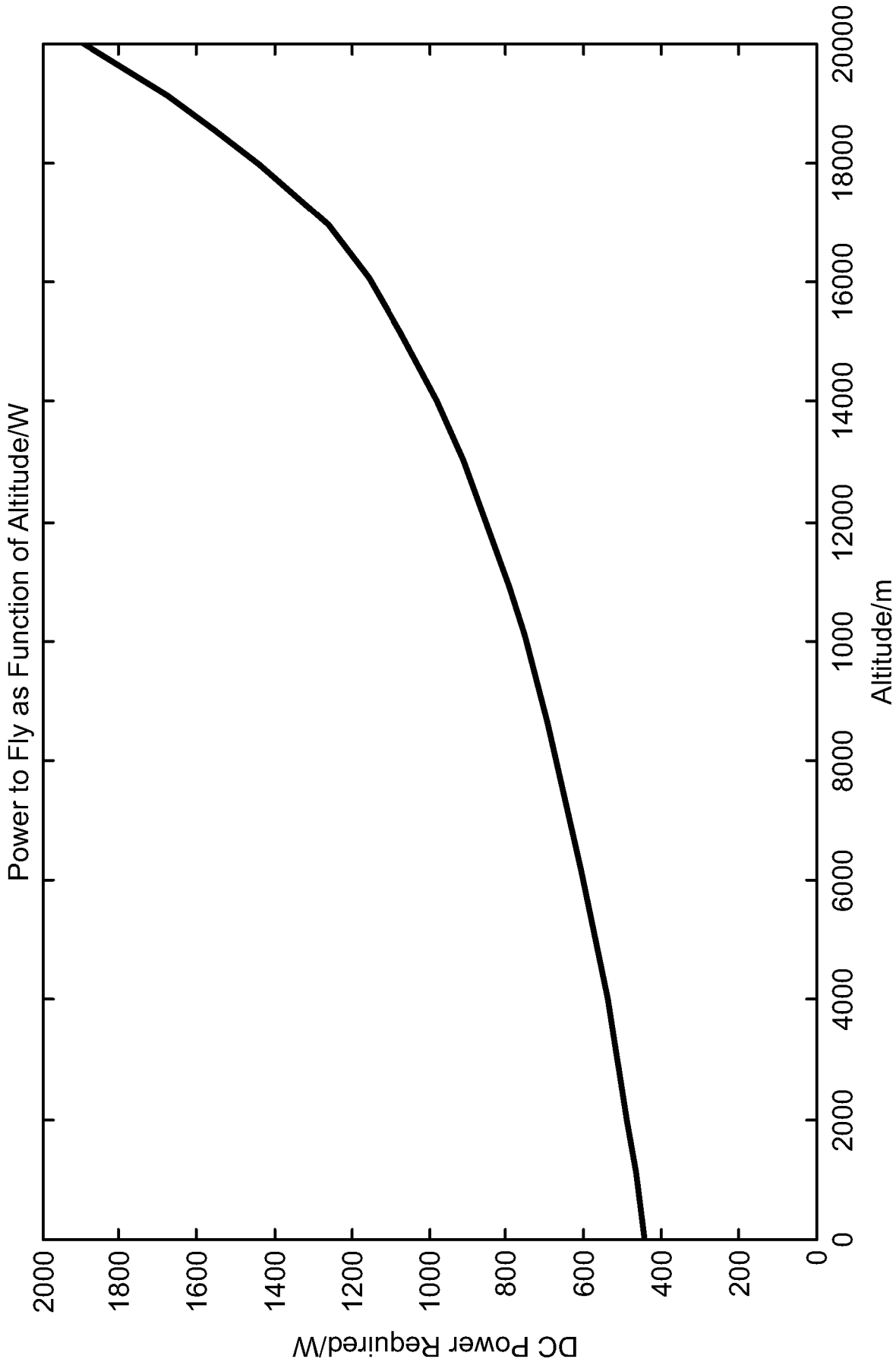

Length of Night at 25N
Hours
16.00
14.00
12.00
10.00
8.00
6.00
4.00
2.00
0.00
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec

Fig. 6


Power to Fly as Function of Altitude/W
DC Power Required/W
2000
1800
1600
1400
1200
1000
800
600
400
200
0
0
2000
4000
6000
8000
1000
12000
14000
16000
18000
20000
Altitude/m

INTERNATIONAL SEARCH REPORT

International application No
PCT/GB2020/050698

A. CLASSIFICATION OF SUBJECT MATTER
INV. B64C39/02
ADD.

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
B64C B64F

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)
EPO-Internal, WPI Data

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 2009/026316 A1 (MILLER GERALD D [US]) 29 January 2009 (2009-01-29) paragraph [0021] - paragraph [0042]	1-19
X	GB 2 504 132 A (ELSON ANDREW CHARLES [GB]) 22 January 2014 (2014-01-22) page 7, line 1 - page 13, line 25	1-19
X	US 2015/183520 A1 (ELSON ANDREW CHARLES [GB]) 2 July 2015 (2015-07-02) paragraph [0052] - paragraph [0076]	1-19

☐ Further documents are listed in the continuation of Box C.

☒ See patent family annex.

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"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
14 May 2020	26/05/2020

Name and mailing address of the ISA/	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Fax: (+31-70) 340-3016	Götsch, Stefan

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INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No
PCT/GB2020/050698

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US 2015183520 A1	02-07-2015	NONE	