GEOSTROPHIC FLIGHT CONCEPT FOR ZERO-EMISSION SOLAR AIRSHIPS

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Abstract

The inherent big volume and large envelope surface of airships makes them ideal candidates for solar flight. In order to obtain sufficient power from the solar cells a large surface is required which is available on the upper side of an airship envelope. Due to the power limitations of the solar airship, the availability of accurate and reliable weather forecast data is essential for trajectory optimization and flight safety. The objective of this paper is to study the performance of a non-contaminant recreational airship solar flight by using accurate weather forecasting data and an electric propulsion system powered by solar cells. The concept of geostrophic flight is introduced as a flight whose trajectory is determined in advance based on accurate weather forecast data. Geostrophic flight is performed mainly over the planetary boundary layer, where the wind is barely affected by the Earth's surface friction and can be very well approximated by the geostrophic wind. In this paper a conceptual design of the solar airship "Zero" has been made based on airship AU-12 as a reference. Results show that the performance of "Zero" in terms of payload and speed is similar to the one of the reference airship AU-12. The introduced technique of the guaranteed covered area (GCA) has been modelled for a 3-hour solar flight starting from Barcelona, for every month of the year 2008. It is shown that the average GCA range for the months between October and February is about 190 km, whereas the GCA range between March and September rises to 230 km, concluding to a seasonal dependency of the range using geostrophic flight. This paper shows that recreational airship solar flight is feasible with current technology. Moreover, the availability of accurate short and midterm weather forecast data can make the 21st century airship flight safe and reliable.

1. INTRODUCTION

Two main factors make airships ideal candidates for solar-powered flight. Firstly, due to the inherent big volume of the airship, the large surface required to obtain enough power from the solar cells is available on the envelope's upper side. Secondly, as the lifting force on the airship is produced mainly by buoyancy, a possible loss of solar power is not critical since the solar airship can remain aloft even with no means of propulsion. The performance of an airship depends greatly on weather conditions. This is even more dramatic for solar-powered airships due to the power constraints imposed by the still limited efficiency of solar cell technology. This makes the availability of accurate and reliable weather forecast data essential for trajectory determination, range assessment and flight safety. In this paper the concepts of geostrophic flight and guaranteed covered area (GCA) are introduced to determine the trajectory and range of a solar-powered airship. Geostropic flight is defined as a flight with a trajectory determined in advance, and that is performed mainly over the planetary boundary layer (PBL). The GCA of a solar-powered airship is defined as the effective area that can be reached by an airship given its initial position, time, flight altitude and flight duration.

A preliminary design of “Zero”, a recreational solar-powered airship, has been carried out using the two-seat airship AU-12 from the russian manufacturer RosAeroSystems as a reference [1]. Results show that in terms of payload and speed the performance of “Zero” is similar to the one of the reference airship AU-12. The GCA for “Zero” has been modelled for a 3-hour flight starting from Barcelona, performed for every month of the year 2008.

2. AIRSHIP ELECTRIC FLIGHT

Airships were the first aircrafts to be powered with electric engines and, therefore, the first to perform zero emission flights. More specifically, the first electric-powered flight in history was conducted by Albert and Gaston Tissandier in 1883. The Tissandier brothers constructed a 1062 m^3 volume airship propelled by a battery-powered electric motor. The motor produced a power of 1.1 kW at 180 rpm and drove a large two-bladed pusher propeller through reduction gearing. The maximum speed achieved in calm air conditions was only 4.8 km/h since the power to weight ratio of the engine was still very low and no better than the one achieved by Giffard in 1852, who performed the first controlled airship flight [2]. One year later in 1884 Charles Renard and Arthur Krebs duplicated this feat with their electric-powered airship *La France*, which notably was also the world's first fully-controllable airship. *La France* was the first airship that could return to its starting point in light wind conditions and represented a vast improvement over earlier models. It was 50.3 m long, its maximum diameter was 8.2 m, and it had an envelope volume of 1869 m^3. Like the Tissandiers' airship, an electric battery-powered motor propelled *La France* producing 5.6 kW, which was five times the available power of the Tissandier’s airship. The first flight of *La France* took place on August 9, 1884. After a fully controlled flight of eight kilometers and 23 minutes, Renard and Krebs landed successfully at the same point where they had taken off [2].

The rapid improvement of internal combustion engines in the late 19th century made them to become most suitable for aerial propulsion. These new engines offered much higher power to weight ratios than their equivalent heavy electric motors. Moreover, the range and autonomy using internal combustion engines were not as limited as they were when using heavy electric batteries. Thus, *La France* was the last manned electric-powered airship.

A first theoretical proposal for solar-powered manned airships was made by Khoury and Mowforth in 1978 [3]. In their work the concept of the *Sunship* was introduced. The idea basically consisted of covering the envelope surface of a conventional helium airship with an array of flexible thin film solar cells (Figure 1). Khoury justifies his idea with these words: “Solar energy is attractive in an environmental conscious age. Sunlight is a renewable, free, non-polluting and non-inflammable fuel. A solar-powered airship would not require re-fuelling when operating in remote sunny areas of the world or at high altitudes”. Khoury defines a solar-powered airship as “an airship that attains its power for propulsion primarily from solar energy, albeit in conjunction with on-board energy storage for operations at night and in windy conditions” [4].

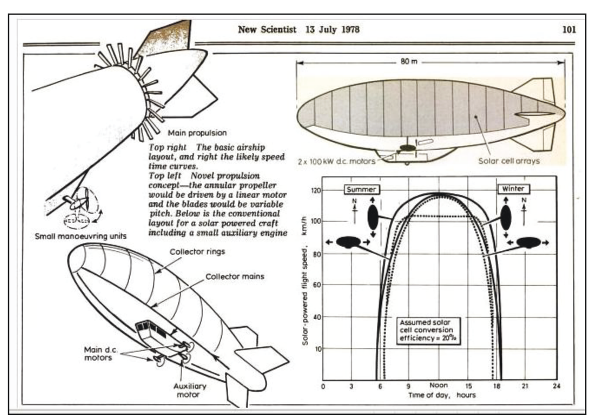

Figure 1. Khoury’s *Sunship*, 1978 [3].

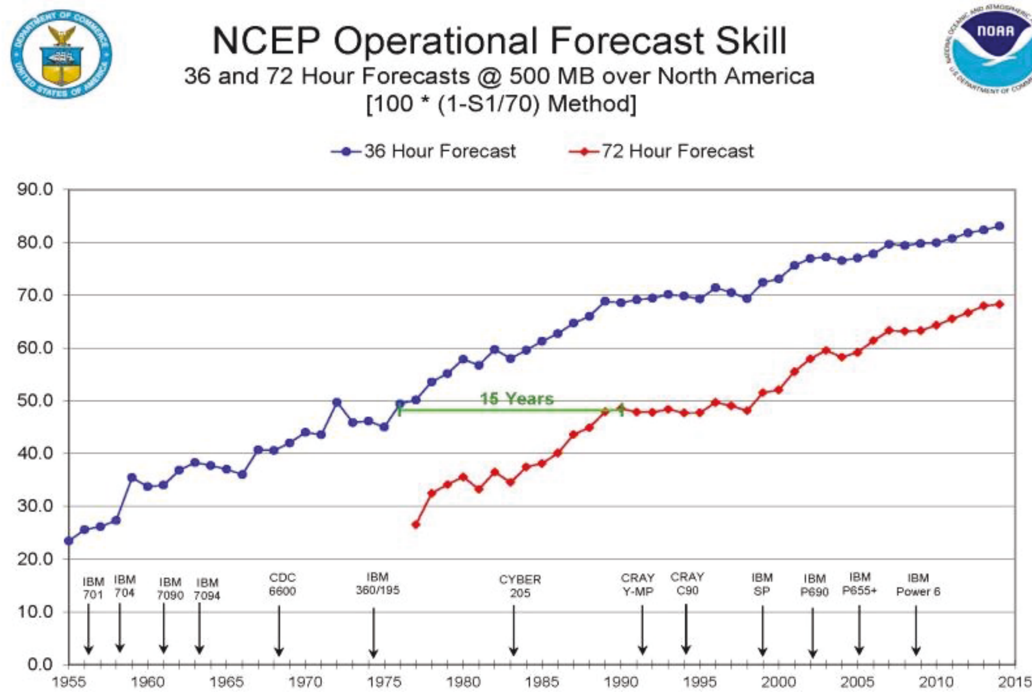

Figure 2. Skill of the 36-hour (blue) and 72-hour (red) 500 hPa geopotential height forecasts, using the Global Forecast System model (GFS), produced at NCEP, January 2015 [8].

The proposed *Sunship* would be 80 m long with a diameter of 23 m and a total hull volume of about 22000 m^3. Considering the maximum direct solar energy available at an altitude of 1000 m at solar noon and using reasonable values for the different efficiencies involved, the theoretical maximum attainable speed would be 83 km/h. The maximum speed would increase to 101 km/h if diffuse and reflected solar radiation would also be considered for an airship totally covered with solar cells [4]. The first and only solar-powered manned airship built to date is the *Nephelios* [5]. This single passenger airship was designed and developed by French students and made its maiden flight in December 2009. *Nephelios* is 22 m long and is powered by an array of flexible solar cells placed on the top of its envelope. The panels have a peak power of 2.4 kW which allows a maximum speed of about 40 km/h.

3. WEATHER FORECASTING FOR AIRSHIP NAVIGATION

The use of the winds for air navigation goes back to the early era of balloons and airships. In 1910 the German meteorologist Hugh Hergesell already anticipated in his book "Mit Zeppelin nach Spitzbergen" (With Zeppelin to Spitzbergen) that for a hypothetical trip to the North Pole by airship "a special method for navigation should be developed where the track to follow had to be chosen by taking into account a weather forecast chart, in order to use the favorable winds instead of going against them" [6]. Subsequently and until the disappearance of the great airships in the 1940s the use of weather forecast data was common practice in airship route planning. However, the available weather forecast in the first half of the 20th century was of poor quality. Until the advent of computers and numerical models it was not possible to make accurate short and medium term weather forecasts [7].

Weather predictions using numerical models have dramatically improved since their origin. The remarkable progress in forecasting over the past 60 years is illustrated by the record of skill of the 500 hPa geopotential height forecast produced at the National Centers for Environmental Prediction (NCEP) [8]. Forecast skill scores, expressed as percentages of perfect forecasts, have improved steadily over the past 60 years and each introduction of a new prediction model has resulted in further improvement as shown in Figure 2. For a 36-hour forecast of the 500 hPa geopotential height using the Global Forecast System model (GFS), the skill score was almost 85% in 2014.

A distinction is made between numerical weather forecast models whose geographic area or domain covers the whole planet (global model, e.g. the GFS) and models that only cover a specific area (limited-area models or regional models, e.g. the North American Mesoscale Model (NAM) [9]). Regional models produce better forecasts given the higher spatial resolution of the grid that is used to compute the forecasts. The NAM model is currently run with a 12 km horizontal resolution grid and with 3-hour temporal resolution. Since 2009 the NCEP has calculated monthly averaged statistics of the root mean square error vector (RMSEV) of the 850 hPa wind forecast using the NAM model [8]. This is done by comparing the predicted with the real wind vector values, obtained by radiosondes at different forecast horizons. The mean RMSEV of the 850 hPa wind for the 2009–2014 period is 3.7 m/s for a 12-hour forecast horizon. Therefore, for a typical recreational flight of three hours, the wind error for a 3-hour forecast would be 0.92 m/s assuming linear error depedency with time. This value is within an acceptable range for airship trajectory computation considering a typical airship cruising speed of 20 m/s. Given the limited range and autonomy of recreational solar-powered airships, regional weather forecast models should be considered for potential use in airship trajectory determination.

4. GEOSTROPHIC FLIGHT

The atmospheric variables to be accurately predicted in order to forecast the trajectory of an airship are temperature, pressure and the zonal and meridional winds along the track. Zonal wind is the wind component along the local parallel whereas meridional wind is the wind component along the local meridian. The lower the prediction horizon of the numerical models is, the higher is the accuracy of the weather forecasting. This is especially interesting for the case of recreational solar-powered airships where flight durations are expected to be no longer than 12 hours and therefore only short-term predictions are needed.

By airship geostrophic flight we understand a flight whose trajectory is determined in advance using accurate weather forecast data, and that is performed mainly over the planetary boundary layer, were the winds are almost geostrophic [10], [11].

By considering the following hypotheses:

- Earth as inertial reference system.
- Negligible aerodynamic lift due to the envelope and fins.
- Horizontal flight.
- Ballonets with enough capacity to adapt their volume to the changing values of air temperature and pressure so the altitude of the airship along the trajectory is practically constant.
- Airship is considered a mass point when considering the forces acting on it.

the trajectory of the airship can be determined by using the equation of motion:

$$\vec{F}_{net} = \vec{T} + \vec{F}_D = M \cdot \vec{a}$$

where $\vec{F}_{net}$ is the net force acting on the airship at any time, $\vec{T}$ is the thrust provided by the airship engines, $\vec{F}_D$ is the drag force due to the relative velocity vector, M is the total mass of the airship and $\vec{a}$ is the acceleration vector.

Expanding the previous equation we obtain:

$$\vec{T} - \frac{1}{2} \cdot \rho_a \cdot |\vec{v}_{rel}|^2 \cdot C_{Dw} \cdot S_w \cdot \frac{\vec{v}_{rel}}{|\vec{v}_{rel}|} = M \cdot \vec{a} = M \cdot \frac{d\vec{v}}{dt}$$

where $\rho_a = \frac{p_a}{R_a \cdot T_a}$ is the air density at cruising altitude, $\vec{v}_{rel} = \vec{v} - \vec{v}_{wind}$ the relative velocity vector, $\vec{v}$ the airship velocity vector, $\vec{v}_{wind}$ the wind velocity vector, C_{Dw} the resistance coefficient, S_w the wet surface of the airship, and $\frac{\vec{v}_{rel}}{|\vec{v}_{rel}|}$ the relative velocity unitary vector.

The above equation is an ordinary differential equation that can be solved, for example, using a second order modified Euler method. This method uses an auxiliary intermediate point to better estimate velocities and accelerations at each iteration step. The algorithm to solve the equation taking into account the geostrophic flight concept would be:

a) At point i the horizontal coordinates $\vec{r}_i$, altitude h_i, ground velocity $\vec{v}_i$ and thrust $\vec{T}_i$ of the airship are known. By using accurate weather forecast data we obtain the vector wind velocity $\vec{v}_{wind_i}$, air temperature T_i , air pressure P_i and thus air density ρ_i for point i. Finally, we can also determine the vector acceleration at point i using the equation:

$$\vec{a}_i = \left(\vec{T}_i - \frac{1}{2} \cdot \rho_i \cdot \left|\vec{v}_{rel_i}\right|^2 \cdot C_{Dw} \cdot S_w \cdot \frac{\vec{v}_{rel_i}}{\left|\vec{v}_{rel_i}\right|}\right) \Big/ M$$

where $\vec{v}_{rel_i} = \vec{v}_i - \vec{v}_{wind_i}$

b) The next step is to consider a time increment $\frac{\Delta t}{2}$ and calculate the horizontal coordinates, velocity and acceleration of an intermediate auxiliary point $i + \frac{1}{2}$. The two first are direct:

$$\vec{r}_{i+\frac{1}{2}} = \vec{r}_i + \frac{\Delta t}{2} \vec{v}_i$$

$$\vec{v}_{i+\frac{1}{2}} = \vec{v}_i + \frac{\Delta t}{2} \vec{a}_i$$

In order to calculate $\vec{a}_{i+\frac{1}{2}}$ we must proceed in a similar way as we did to calculate $\vec{a}_i$:

$$\vec{a}_{i+\frac{1}{2}} = \left(\vec{T}_{i+\frac{1}{2}} - \frac{1}{2} \cdot \rho_{i+\frac{1}{2}} \cdot \left|\vec{v}_{rel_{i+\frac{1}{2}}}\right|^2 \cdot C_{Dw} \cdot S_w \cdot \frac{\vec{v}_{rel_{i+\frac{1}{2}}}}{\left|\vec{v}_{rel_{i+\frac{1}{2}}}\right|}\right) \Big/ M$$

c) Finally, after a time increment Δt we calculate the new position and velocity of the airship at the next point $i + 1$:

$$\vec{r}_{i+1} = \vec{r}_i + \Delta t \cdot \vec{v}_{i+\frac{1}{2}}$$

$$\vec{v}_{i+1} = \vec{v}_i + \Delta t \cdot \vec{a}_{i+\frac{1}{2}}$$

By iterating the algorithm we can advance the airship trajectory. The elapsed flight time is therefore $D = (i - 1) \cdot \Delta t$. The necessity to evaluate the weather variables at each step in the algorithm makes the availability of accurate short-term weather forecast data the key element in geostrophic flight.

Betorz (2011) showed that the usage of a geostrophic flight algorithm similar to the one presented above provides enough accuracy in order to forecast the trajectory of a manned hot air balloon [10]. This validation was done by comparing a reference trajectory followed by a manned hot air balloon over the Pyrenees with a computed trajectory using weather forecast data from the MM5 [12] limited-area mesoscale model. The data was provided by the Servei Metereològic de Catalunya (SMC), the Catalan Meteorological Service [13]. The balloon flight was performed mainly above the planetary boundary layer at an average flight altitude of 2300 m. The actual flight time was 106 minutes (from 6:48 UTC to 8:34 UTC, November 14th 2009) and the trajectory of the balloon was monitored by an onboard GPS receiver. The balloon traveled 94.5 km at an average speed of 53.5 km/h. The actual path of the balloon was also compared to that obtained by the trajectory simulation program Hybrid Single Particle Lagrangian Integrated Trajectory Model (HYSPLIT) of the National Oceanic and Atmospheric Administration (NOAA) [14]. Figure 3 shows the real path of the balloon in red, the computed track using data from the MM5 regional model in blue and the track obtained using HYSPLIT together with the GFS model in green. As expected, the computed trajectory using data from the MM5 regional model predicts the actual path of the balloon more accurately. Table 1 shows some comparative values of the real path and the predicted trajectory using the MM5 wind data. The relative error of the final point (given the absolute error of 2.9 km and the total distance of the real trajectory) is only 3.1%. This value is consistent with the RMSEV wind error results presented in section 3 for the NAM limited-area model.

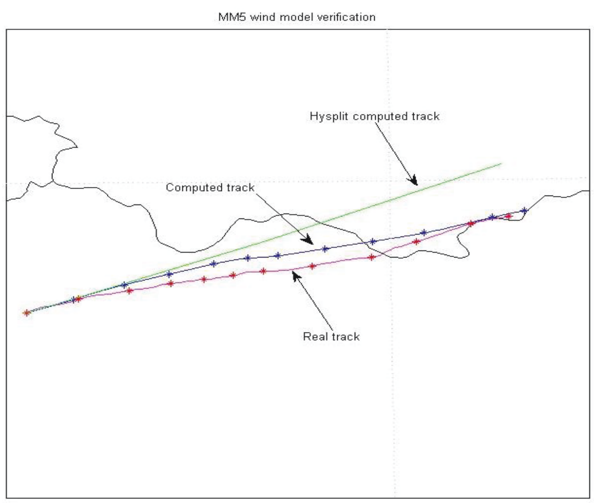

Figure 3. Real and predicted balloon trajectories [10].

	Lat last point (°)	Lon last point (°)	Total distance (km)	Average speed (km/h)
Real trajectory	42.425	2.773	94.49	53.5
Computed trajectory using MM5 data	42.435	2.806	97.01	55.1

Table 1. Comparative values of the real path and the predicted balloon trajectory [10].

The condition to fly over the planetary boundary layer represents some advantages for the case of solar-powered airships. Temperature decreases with altitude and solar cells tend to have higher efficiencies with lower temperatures. In addition, solar radiation increases with altitude [15], [16] causing the maximum available speed to increase when flying above the PBL. Winds are more constant in intensity and direction in the free atmosphere and should therefore allow the implementation of effective flying strategies. Moreover, fewer turbulences and wind gusts are present [11] which in principle would guarantee a more comfortable and stable flight.

4.1 GUARANTEED COVERED AREA (GCA)

When forecasting the trajectory of an airship using the geostrophic flight concept the predicted weather conditions along the track are taken into account. If the airship is solar-powered, in addition, the solar azimuth, the solar altitude and the airship's azimuth have to be considered at all times in order to estimate the available thrust $\vec{T}$. To better characterize the range of an airship the concept of guaranteed covered area (GCA) will be used. The GCA is defined as the effective area that can be reached by an airship given its initial position, time, flight altitude and flight duration. The GCA is represented on a map by the area enclosed by a closed curve that connects the final points of regularly spaced predicted trajectories. The GCA is obtained from 12 tracks or "radii" (starting from the initial point) that are also included in the GCA map. These 12 "radii" are the trajectories of the forecasted geostrophic flights corresponding to flight conditions of constant airship azimuth (from 0 to 330º with intervals of 30º).The following notation is used to describe a GCA:

NAME_PP_LAT_LONG_FFFF_TT_HHHH_DDMMYYYY

Where:

- NAME is the name of the airship.
- PP is the available cruising power. For a solar-powered flight it is SP. For a conventionally powered airship it is the available cruising power in kW.
- LAT is the initial latitude in degrees.
- LONG is the initial longitude in degrees.
- FFFF is the flight altitude in meters.
- TT is the flight duration in hours.
- HHHH is the flight starting time in hours and minutes.
- DDMMYYYY is the day, month and year of the flight.

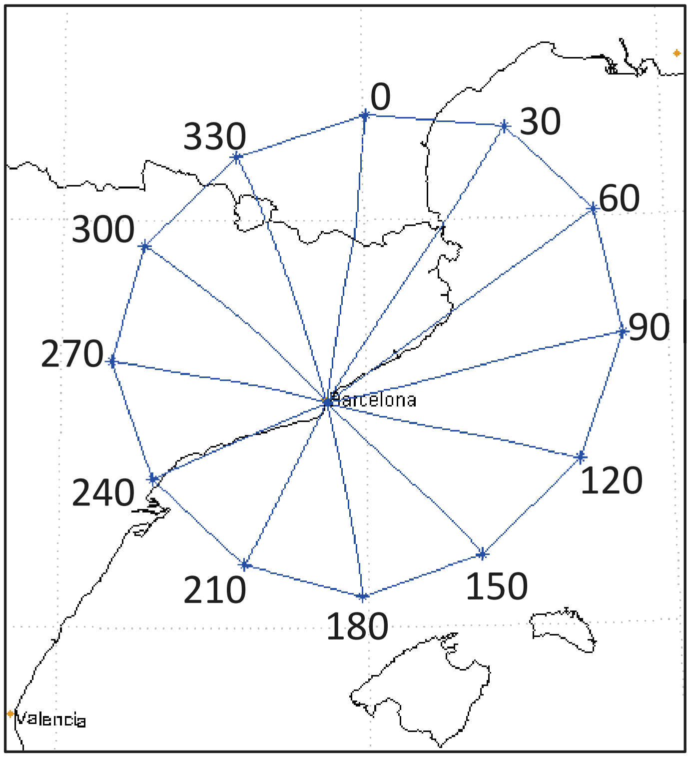

Figure 4. Guaranteed covered area (GCA) example: ZERO_SP_41.38_2.18_2000_02_1100_13102008.

Figure 4 shows, as an example, a guaranteed covered area for the solar-powered airship "Zero". It represents the GCA for "Zero" with starting point in Barcelona, flight altitude of 2000 m, flight duration of two hours and starting time at 11:00 UTC, October 13th 2008.

It is important to clarify that, in general, the GCA is not the area of maximum range since maximum range could be achieved through a variable airship azimuth flight.

5. CONCEPTUAL DESIGN OF "ZERO": A RECREATIONAL SOLAR AIRSHIP

5.1 REFERENCE AIRSHIP

In order to make a conceptual preliminary design of a recreational solar-powered airship a conventional modern airship has been taken as a reference. The reference airship used for this purpose is the AU-12 (Figure 5) from the Russian manufacturer RosAeroSystems [1]. Table 2 shows the technical specifications of this low-volume two-seat certificated airship. The AU-12 was initially designed for visual and instrumental monitoring of gas and oil pipelines, surveillance of roads and urban territories, advertising, high quality aerial photography and rescue operations.

Figure 5. AU-12 during takeoff [1].

Envelope volume	1250 m^3
including air ballonets, up to	312 m^3
Length/diameter ratio	4
Max. envelope diameter	8.47 m
Envelope length	34 m
Net weight	780 kg
Cruising speed	50-90 km/h
Max. speed	100 km/h
Engine type	Rotax-912 ULS.
Max. engine power	73.5 kW
Flight range	350 km
Flying altitude	up to 1500 m
Crew	1 pilot
Commercial payload	1 person+(65-130) kg

Table 2. AU-12 airship technical data [1].

In Table 3 an estimated breakdown of AU-12's total net weight has been made in order to determine the weight of its main subcomponents: hull group, tail group, gondola, and propulsion system. The technical data provided by the manufacturers [1], [17] have been used as well as the weight estimation techniques and formulas proposed by Khoury [4].

Component	Mass (kg)
Hull group	404
Tail group	132
Gondola	123
Propulsion system	121
Total net weight	**780**

Table 3. Estimation of the AU-12 net weight breakdown.

Fuel weight (FW) has to be added to the net weight (NW) in order to obtain the operational empty weight (OEW). The fuel weight has been estimated taking into account the engine performance and fuel consumption graphs provided by the manufacturer [17] and knowing that the maximum autonomy of the airship at full speed is two hours. According to the specifications the fuel tank capacity is 50 liters and therefore the total mass of fuel is 36 kg (with a density of AVGAS 100 LL being 0.721 kg/l). Consequently the OEW is:

$$\mathrm{OEW} = 780 + 36 = 816\ \mathrm{kg}$$

Likewise, the cruising power has been estimated given that the autonomy at cruising speed is six hours and the fuel tank capacity is 50 liters. The value obtained for the cruising power is 43 kW.

Modern airships are designed to have a slightly positive static heaviness. The maximum payload, and therefore the take-off weight (TOW) is variable in airships and depends on the desired maximum operational flight altitude: the higher the maximum flight altitude the lower the maximum payload. Under International Standard Atmosphere (ISA) conditions, the maximum payload for the minimum flight altitude (payload 1) is obtained by filling all the available envelope volume with lifting gas at sea level by completely deflating the ballonets. However, this is only a theoretical reference value since the maximum operational altitude of this payload is zero. On the other hand the maximum payload for the maximum flight altitude (payload 2) is obtained by completely filling the ballonets with air at sea level. In this case, as the airship ascends, the helium gas expands and the ballonets diminish their volume. The maximum flight level of payload 2 will be achieved when the ballonets are completely deflated and the helium gasbags are completely expanded occupying the entire envelope (this altitude is defined as *pressure height*). Considering ISA conditions the values of payload 1 and payload 2 for the AU-12 airship are:

$\mathrm{payload\ 1} = 477\ \mathrm{kg}$ and $\mathrm{payload\ 2} = 154\ \mathrm{kg}$

The maximum flight level for payload 2 $\mathrm{h_{max\ payload\ 2}}$ can be obtained under ISA conditions knowing that at the pressure height the helium has expanded completely:

$$\sigma = \frac{\rho_{\mathrm{air\ max\ altitude}}}{\rho_{\mathrm{air\ sl}}} = \frac{938}{1250} = 0.75$$

$$\rightarrow \quad \mathrm{h_{max\ payload\ 2}} = 2896\ \mathrm{m}$$

For any other payload having a mass between payload 1 and 2 the maximum flight altitude can be calculated by interpolating the altitudes obtained above for payload 1 and 2 (Figure 6).

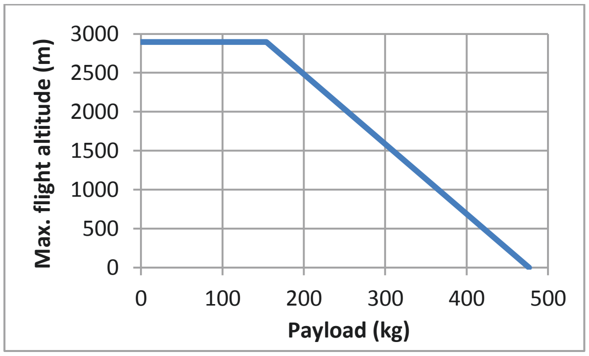

Figure 6. Maximum flight altitude as function of effective payload under ISA conditions.

5.2 "ZERO" REQUIREMENTS AND CONFIGURATION

The requirements for the "Zero" solar-powered airship are the following:

- Two-seat airship with similar payload and flight altitude capability as airship AU-12.
- Same length/diameter ratio as airship AU-12.
- Electrical propulsion system with zero emissions of pollutants.
- Back-up power system in case of malfunction of the primary solar based feeding electric system. The back-up power system must allow the normal operation of the electric engines for at least one hour.

Under these requirements the proposed configuration for the "Zero" airship is the following:

- Solar-powered airship based on the *Sunship* concept [3] with a grid of monocrystalline silicon solar cells (acting as a primary feeding electric system) placed on the upper surface of the airship's envelope. The proposed solar cells are in average 135 microns thick and have an efficiency of 22% according to the manufacturer [19]. They have been used successfully in the Solar Impulse 2 electric aircraft [18].
- Two permanent magnet brushed DC motors D135RAG of the Lynch Motor Company [20]. Each motor has a nominal rated power of 16.8 kW and a peak power of 34.3 kW.
- Back-up power system based on secondary batteries. The selected batteries are lithium polymer batteries with a specific energy of 260 Wh/kg, also used successfully in the Solar Impulse 2 electric aircraft [18], [21].
- Size and dimensions of the envelope and control surfaces proportional to those of the airship AU-12.

5.3 SIZE AND WEIGHTS

The determination of the size and weight of the "Zero" airship given its requirements and general configuration has been done applying an iterative process.

The starting point for the sizing of "Zero" is to consider an airship with the original size and hull dimensions of the AU-12 airship. In this scenario the weights of the hull group, tail group and gondola do not change. The weight of the solar propulsion system can be estimated taking into account the following considerations:

- The weight of the solar cells is proportional to the upper surface of the airship's envelope.
- The weight of the electric motors and the power conditioner are provided by the manufacturers [20].
- The weight of the batteries is chosen to fit the design requirements given their specific energy of 260 Wh/kg.
- The remaining components are estimated taking into account the same criteria used for airship AU-12.

Table 4 shows the weight breakdown for the propulsion system in the first iteration.

Sub-component	Mass (kg)
Installed engine	24
Solar cells	114
Collector grid network	14
Power conditioner	30
Ducted propeller	10
Duct	30
Transmission system	10
Vector system	5
Secondary batteries	70
Total propulsion system weight	**307**

Table 4. Estimated "Zero" propulsion system weight for the first iteration.

In this case no fuel weight has to be added and therefore the operational empty weight is:

$$\mathrm{OEW} = 404 + 132 + 123 + 307 = 966\ \mathrm{kg}$$

and payload 1 and 2 resulting from the first iteration are:

$$\mathrm{payload\ 1} = 1250 \cdot (1.225 - 0.19) - 966 = 328\ \mathrm{kg}$$

$$\mathrm{payload\ 2} = 938 \cdot (1.225 - 0.19) - 966 = 5\ \mathrm{kg}$$

The requirement in terms of payload is not satisfied and therefore another iteration has to be done. A bigger volume envelope for "Zero" has to be selected in order to generate more lift. In this second iteration we consider a hull length of 36 meters and a maximum envelope diameter of nine meters. The new envelope volume is 1526 m^3 and the volume of the ballonets is up to 378 m^3. The weight of the main components changes except for the gondola. The operational empty weight is obtained proceeding in a similar way as done previously. Table 5 shows the main components breakdown for the second iteration.

Component	Mass (kg)
Hull group	475
Tail group	153
Gondola	123
Propulsion system	322
Total operational empty weight	**1073**

Table 5. Estimated OEW breakdown for airship "Zero" for the second iteration.

Payload 1 and 2 resulting from the second iteration are:

$$\mathrm{payload\ 1} = 1526 \cdot (1.225 - 0.19) - 1073 = 506\ \mathrm{kg}$$

$$\mathrm{payload\ 2} = 1148 \cdot (1.225 - 0.19) - 1073 = 115\ \mathrm{kg}$$

The maximum flight level for payload 2 $\mathrm{h_{max\ payload\ 2}}$ under ISA conditions for the second iteration is:

$$\sigma = \frac{\rho_{\mathrm{air\ max\ altitude}}}{\rho_{\mathrm{air\ sl}}} = \frac{1148}{1526} = 0.75$$

$$\rightarrow \quad \mathrm{h_{max\ payload\ 2}} = 2896\ \mathrm{m}$$

The performance in terms of payload and flight altitude resulting from the second iteration is shown in Figure 7.

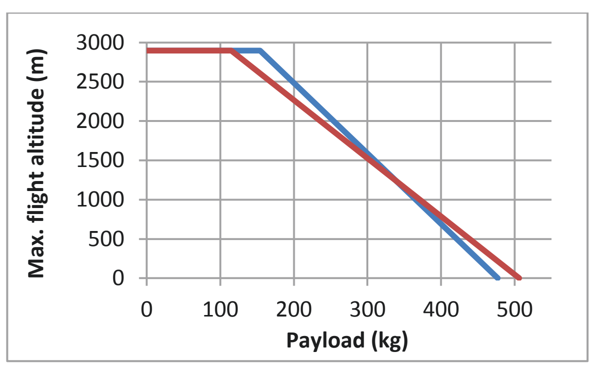

Figure 7. Performance comparison between airship AU-12 (blue) and second iteration for "Zero" (red).

The second iteration fulfills the payload and flight altitude requirements and has therefore been selected as the final configuration for airship "Zero". Table 6 summarizes its main dimensions and its motorization.

Envelope volume	1526 m^3
including air ballonets, up to	378 m^3
Length/diameter ratio	4
Max. envelope diameter	9 m
Envelope length	36 m
Solar cells weight	130 kg
Batteries weight	70 kg
Operational empty weight	1073 kg
Engine type	2 x D135RAG
Max. engine power	68.6 kW

Table 6. "Zero" airship main dimensions and motorization.

5.4 PERFORMANCE

The speed performance of the solar airship "Zero" has been estimated considering a horizontal steady symmetric flight and assuming clear sky conditions. The speed *v* is then:

$$v = \sqrt[3]{\frac{2 \cdot N \cdot \eta_{cell} \cdot \eta_{el} \cdot \eta_{mec} \cdot \eta_p}{\rho \cdot C_{Dw}} \cdot \left(\frac{S_p}{S_{wet}}\right)}$$

where:

N is the incident (direct) normal solar flux (W/m^2), S_p the solar cells' projected area (m^2), η_{cell} the solar cells conversion efficiency, η_{el} the electrical components' (e.g. motor) efficiency, η_{mec} the mechanical efficiency, η_p the propulsive efficiency, ρ the air density, C_{Dw} the drag coefficient referred to the wetted surface area of the airship and S_{wet} is the airship's wetted surface area.

Without feeding the electric engines with the secondary batteries, the available power for propulsion is entirely obtained from the solar cells. Therefore, it is function of the solar radiation reaching the top of the airship and it is also function of the projected area of the solar cells. Solar radiation depends on the hour of the day, day of the year, latitude, longitude and altitude of the airship. The projected area of the solar cells depends on the azimuth of the airship, the solar altitude and the solar azimuth.

In order to save weight, the "Zero" airship has been designed with only the upper surface of the envelope covered by solar cells. Due to this configuration only the direct solar radiation is considered when calculating the available solar radiation at any time. For clear sky conditions the reflected radiation corresponds mainly to the radiation reflected by the ground. Consequently, the reflected radiation that is reaching the upper surface of the envelope is negligible. On the other hand, during clear days, the contribution of diffuse radiation to the total solar radiation is no greater than 10% [4]. The exact contribution of diffuse radiation is difficult to predict in advance since it depends on air humidity conditions, suspension particle content, contamination, etc. Consequently only direct solar radiation is taken into account for calculating the speed performance of the solar airship. By neglecting the reflected and diffuse solar radiation the available power obtained at any moment is slightly underestimated.

The speed performance of the "Zero" airship will be analyzed at solar noon for a latitude of 41ºN (Barcelona) and 2000 m of altitude. The four most significant solar days of the year will be considered: summer solstice, autumn equinox, winter solstice and spring equinox. Figure 8 shows the ideal daily direct solar radiation over Barcelona. The blue, red and green lines correspond respectively to the summer solstice, the spring and autumn equinoxes and the winter solstice. Any other day of the year will be represented by a line which shall be between the lines of the summer and winter solstice. The values at noon of the direct solar radiation to be considered are:

- $N_{\text{summer solstice}}$ = 1062 W/m^2
- $N_{\text{spring \& autumn equinoxes}}$ = 1020 W/m^2
- $N_{\text{winter solstice}}$ = 905 W/m^2

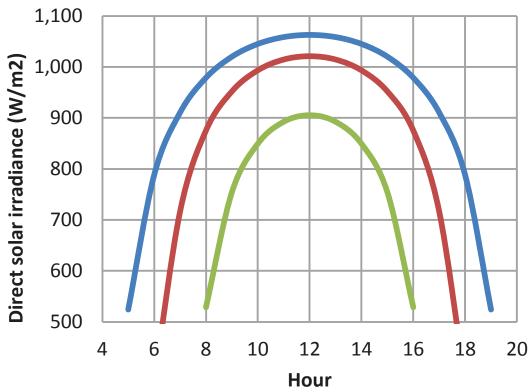

Figure 8. Direct solar irradiance in Barcelona (latitude 41ºN, altitude: 2000 m) under ideal conditions: summer solstice (blue), spring and autumn equinox (red), and winter solstice (green).

The following efficiencies and parameters are considered in order to calculate the speed:

- ρ = 1 kg/m^3 (ISA conditions)
- C_{Dw} = 0.0045 [22], [23]
- η_{cell} = 0.22 [19], [25]
- η_{el} = 0.9 [20]
- η_{mec} = 0.9 [23]
- η_p = 0.8 [23]
- S_{wet} = 822 m^2

The solar cell's projected area S_p depends on the orientation of the airship, the solar altitude and the solar azimuth. Consequently, the value of the projected area changes continuously in time and, given an arbitrary shape of the solar cells surface, its calculation is not trivial. In general the envelope's surface of a conventional airship can be very well approximated by a revolution ellipsoid [24] and, as a result, the solar cells surface is convex. For our case of horizontal airship flight with convex surface of solar cells covering the top of the airship and solar altitudes between 0º and 90º, the solar cells' projected area can be calculated using the methodology suggested by Betorz (2011) [10]. Figure 9 shows the solar cells' projected area S_p for the airship "Zero" at noon and for a latitude of 41°N, as a function of the airship azimuth (starting from southern direction).

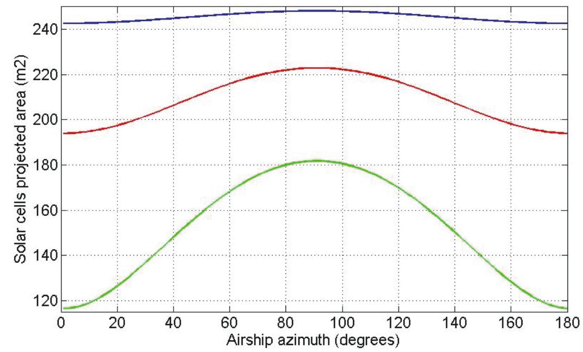

Figure 9. Solar cells' projected area for airship "Zero" (latitude 41ºN, altitude: 2000 m): summer solstice (blue), spring and autumn equinox (red), and winter solstice (green).

The blue, red and green lines correspond respectively to the summer solstice, the spring and autumn equinoxes and the winter solstice. Like for the direct solar radiation, any other day of the year will be represented by a line which shall be between the lines of the summer and winter solstice. The following considerations can be deduced from Figure 9:

- The higher the solar altitude, the higher the projected area for a given airship azimuth.
- As the solar altitude increases the variation of the projected area with the airship azimuth is less pronounced.
- The maximum solar cells' projected area for a given solar altitude is always obtained when the airship's azimuth is perpendicular to the solar azimuth.

Finally, the theoretical speed of the solar airship "Zero" at noon and for a latitude of 41°N is shown in Figure 10.

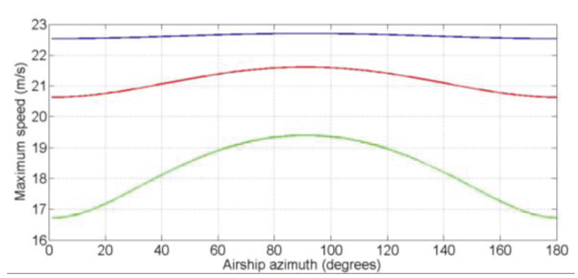

Figure 10. Maximum speed of airship "Zero" (latitude 41ºN, altitude: 2000 m): summer solstice (blue), spring and autumn equinox (red), and winter solstice (green).

The maximum attainable solar speed is 23 m/s (83 km/h) and corresponds to “Zero” flying with an azimuth of 90º at the noon of the summer solstice (blue line). On the other hand the lowest solar speed is 17 m/s (61 km/h) and corresponds to “Zero” flying with an azimuth of 0º at the noon of the winter solstice (green line). The following considerations can be deduced from Figure 10:

- The higher the solar altitude, the higher the maximum speed for a given airship azimuth.
- As the solar altitude increases the variation of the maximum speed with the airship azimuth is less pronounced. Moreover, during half of the year, in summer and spring (between the blue and red line), the maximum speed is practically independent from the airship’s azimuth.
- The maximum speed for a given solar altitude is always obtained when the airship’s azimuth is perpendicular to the solar azimuth.

5.5 EMERGENCY SPEED

In case of malfunction of the solar cells, the secondary batteries must feed the electric motors in order to guarantee a normal airship operation for at least one hour. Assuming a maximum battery discharge of 70%, the available power is:

$$70\ \mathrm{kg} \cdot 260\ \frac{\mathrm{Wh}}{\mathrm{kg}} \cdot 0{,}7 = 12740\ \mathrm{Wh}$$

This represents an available power of 12740 W for the duration of one hour or 25480 W for half an hour. Considering the same efficiency values as the ones considered in section 5.4, the emergency speed (or speed of the airship powered only by the batteries) is $\mathrm{v}_{1\ \mathrm{hour}}$ = 60 km/h for one hour or $\mathrm{v}_{30\ \mathrm{minutes}}$ =76 km/h for half an hour.

5.6 RANGE AND AUTONOMY

Like the maximum available speed, the autonomy of a solar airship depends on the day of the year, latitude and altitude of flight. According to Figure 8 and considering a minimum value for the incoming solar irradiation of 750 W/m^2 to be acceptable, the autonomy of the “Zero” with starting point in Barcelona (latitude 41ºN) and flight altitude 2000 m is 12 hours in the summer solstice and 6 hours in the winter solstice. For any other day of the year the autonomy of “Zero” will be a value between 6 and 12 hours.

The range of the “Zero” airship has been studied for the year 2008 using the introduced technique of the guaranteed covered area. One GCA has been computed for each month of the year 2008, considering the following flight characteristics:

- Airship: “Zero”
- Energy source: Solar power
- Starting point: Barcelona
- Flight altitude: 2000 m
- Flight duration: 3 hours
- Starting time: 11:30 (UTC)
- Day: 15th of each month
- Month: Ranging from 01 to 12
- Payload: 200 Kg

Figure 11 shows the GCAs calculated for February 15th, May 15th, August 15th and November 15th of 2008. The trajectory corresponding to a flight with constant airship azimuth of 0º is illustrated in red in the GCA charts. Figure 12 shows the range (in km) as function of the azimuth of the airship (in degrees) for February 15th and May 15th of 2008. As expected, the wind conditions encountered along the trajectories have a great impact on the shape of the GCA.

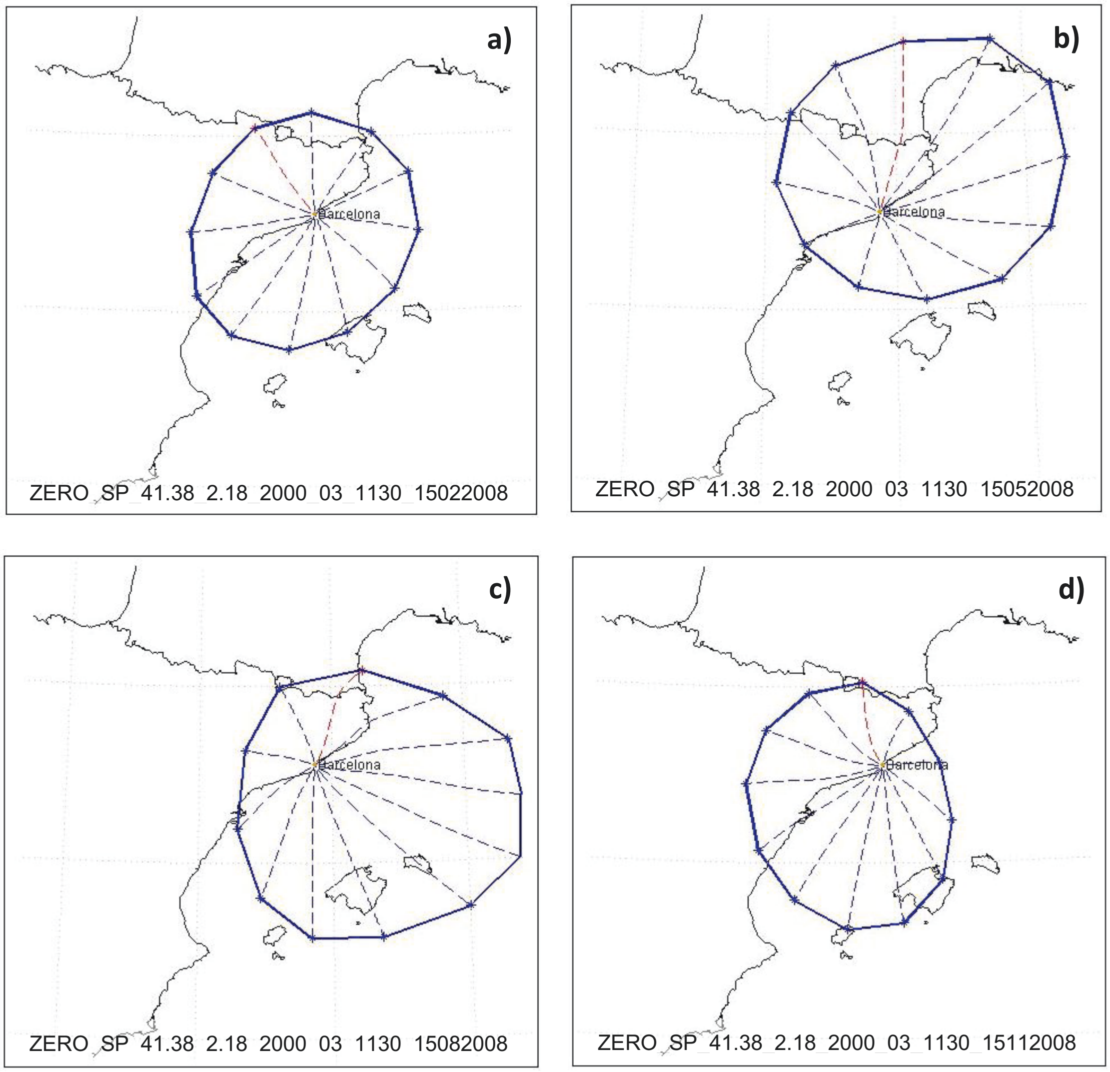

Figure 11. Guaranteed covered area (GCA) calculated for: a) February 15th, b) May 15th, c) August 15th, and d) November 15th of 2008. Trajectories with constant airship azimuth of 0° are shown in red.

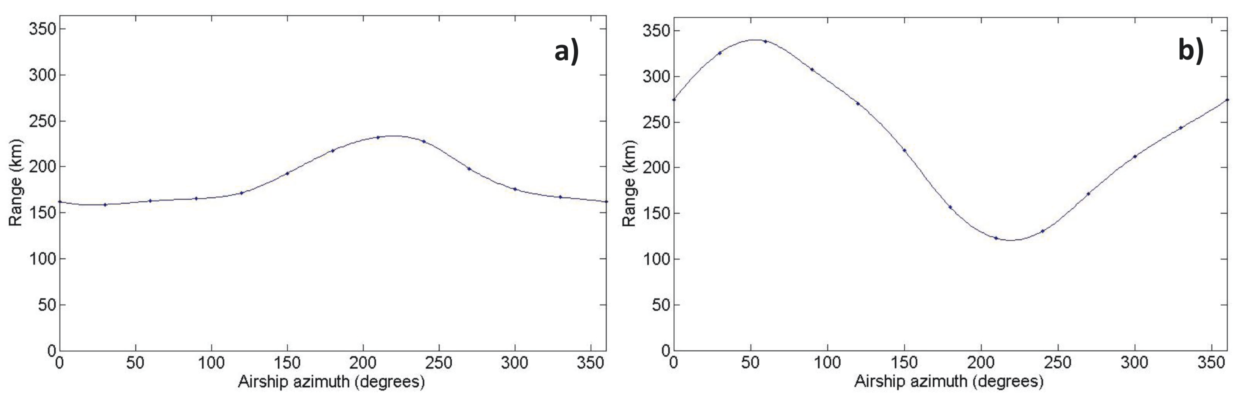

Figure 12. Range as function of the airship's azimuth for: a) February 15th, and b) May 15th of 2008.

Table 7 shows the mean range for each of the computed GCAs. As expected the mean range is higher during the summer and spring months due to the greater available solar power.

Flight	GCA mean range (km)
January 15th	189
February 15th	186
March 15th	219
April 15th	229
May 15th	231
June 15th	236
July 15th	227
August 15th	245
September 15th	216
October 15th	195
November 15th	187
December 15th	180

Table 7. GCAs' mean range for "Zero" for a flight from Barcelona for the 15th day of each month of the year 2008.

6. CONCLUSIONS

This paper has shown that recreational airship solar flight is feasible with current technology. The dramatic improvement of numeric weather forecast models over the past 60 years may overcome one of the disadvantages of airship flight: its relatively low speed which makes airships more dependent on wind conditions. By knowing the weather conditions for the flight in advance, on the one hand potential dangerous wind situations can be avoided and on the other hand faster flight trajectories can be implemented in case of favorable wind conditions. The concept of geostrophic flight has been introduced as a tool to forecast the trajectory of a solar-powered airship. The key element for trajectory determination is the availability of accurate short term weather forecast data, which is available using regional weather forecast models like NAM or MM5. The inherent big volume and large envelope surface of airships make them ideal candidates for solar flight. Indeed, the still low efficiencies of solar cells require a distribution of solar cells spread over a large surface, which is available on the upper side of the airship's envelope. A further advantage is that a possible loss of solar power is not critical since the solar airship can remain aloft even with no means of propulsion.

A conceptual design of "Zero", a recreational solar airship, has been made using already existing technology. Results show that in terms of payload and speed the performance of "Zero" is similar to the reference airship AU-12, with the additional advantage of producing zero contaminant gases during flight. The guaranteed covered area (GCA) has been modelled for a 3-hour flight starting from Barcelona, performed for every month of the year 2008. It is shown that the GCA mean range for the months between October and February is about 190 km, whereas the mean range between March and September rises to 230 km, concluding to a seasonal dependency of the GCA. As expected, during summer and spring the range of the airship is larger due to the greater available solar power. Because of the dependency of the GCA with the day of the year and location of the starting point, in the opinion of the author, nowadays the possible implementation of the solar geostrophic airship flight is restricted to the field of recreational aviation. However, the rapid improvement of solar cell technology and the steady increase of the accuracy of numerical weather forecast models can make the 21st century solar airship flight safe and reliable for further potential applications.

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