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DESIGN OF A HIGH-ALTITUDE SUN-POWERED AIRCRAFT

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Abstract. *The aim of this work is to present the design studies for an unmanned, Sun-powered, long-range, long-endurance, lightweight (less than 40 kg), high-altitude (above 80 thousand feet flight) research aircraft. The studies comprise the aircraft typical mission; the aerodynamic, systems, mass arrangements; and the preliminary propulsion and performance characteristics. This Unmanned Air Vehicle, or "UAV", is defined under a dedicated iterative procedure which is also briefly described in the document. Among other design challenges, special care is taken in the effects of Reynolds Number in the aircraft performance parameters, due to the requirement of extreme altitude flight. The features of the obtained configuration can be considered as good indicators of the technical feasibility of this long-endurance, Sun-powered UAV.*

Keywords: *UAV, Solar Aircraft, Aircraft Design and Performance, High-Altitude, Long-Endurance Flights*

1. INTRODUCTION

A solar aircraft or Sun-powered aircraft can be defined as an atmospheric vehicle that can move horizontally due to the power extracted from sunlight through photovoltaic cells dispersed in its external surfaces. A power chain inside the vehicle transforms the light energy received from the Sun in electrical energy, which is transformed into the mechanical energy by electrical motors, and is delivered to the surrounding gaseous mean through rotating propellers. Successful solar aircraft can be considered something new in aviation, and since the first successful attempts, occurred by 1970 and 1980 decades, the solar aircraft technology has suffered continuous development.

The power which can be extracted from the Sun by solar arrays at the aircraft surfaces is very low when compared with the power of conventional internal combustion aircraft. As a consequence, a solar aircraft must be, in terms of mass, wing loading, speeds, structures, and other design parameters, remarkably different from the conventional aircrafts. The ways to think, design and operate a solar aircraft shall be, at least in some aspects, different.

Related to this point, several important questions can be made. For example:

1. In which aspects a solar aircraft can be though by the same viewpoint than a conventional aircraft?
2. Among the aspects that solar aircraft differ from conventional aircraft, which ones are the most relevant for design and operation studies?
3. Which are the missions that solar aircraft could be useful or advantageous in the present and near future scenario?
4. Is it possible to obtain a methodology for the initial definition of solar aircraft?
5. In which point the nowadays technologies are mature to design a solar aircraft?
6. What should be the critical technologies to take into account for the specific design of a solar aircraft?

In this work, the main features of a solar aircraft are defined focusing a typical mission for such aircraft.

2. BACKGROUND

In this section seven important conceptual aspects are presented. One can notice that some of them are strongly interconnected. Nevertheless, the division between them is very useful in order to organize a list of items to be considered during the design.

One of the most important concepts of sun-powered aircraft is the propulsive chain – the energy flow inside the aircraft from the solar cell to the propeller - which is schematically shown in Fig. 1. According to Barbosa (2014) the total effectiveness of the whole chain is not more than10 to 13%. In Fig. 1, the MPPT represents the electronic device to control the amount of voltage and current from the solar panels, in order to deliver the maximum possible power output.

The second important concept is the variation of air density and viscosity of atmosphere with altitude. Indeed, since some solar aircraft can be feasible for flight levels from 60 to 110 thousand feet, above conventional aircraft levels - in general up to 30 thousand feet – special attention shall be taken with effects of high altitude atmospheric characteristics. The reduction of air density and the augmentation of viscosity with altitude tend to increase the required flight power. Both effects are a challenge to high-altitude flight and require special care during the design.

The air viscosity at high altitude leads to the third important concept: the range of Reynolds number (Re) in high altitude flight. Figure 1a presents examples of influence of Re in drag and lift coefficients (C_D and C_L respectively) for different airfoil sections. The most important aircraft surfaces affected by Re are wing and propeller blades. In order to avoid overoptimistic estimations of propeller efficiency and aircraft performance, the Re in aircraft components (mainly wing and propeller blades), along the required mission, shall be evaluated in detail.

The fourth important concept is the design of the propellers of a solar aircraft. As a solar aircraft has an extremely low power-to-area ratio, compared with a conventional aircraft, special care should be taken with propeller design. Additionally, if the solar aircraft are intended to very high altitude flights, the influence of the low Re in the blade section airfoil - and thus in propeller performance - must be considered.

The fifth concept is the Sun light incidence. The energy absorbable directly from the Sun changes along the daily hours, the geographic position in the planet, the season, and (in lower magnitude) the altitude. Energy from the Sun in Earth's orbit is about 1367 W/m^2; from which, about 73% reaches the ground, if Sun is at the Zenith (Barbosa, 2014). An example of a daily curve of solar power incidence is presented in Fig. 2.

The sixth concept is the mass distribution. Due to the low power available, the mass-to-area ratio for a solar aircraft structures shall be remarkably lower than conventional aircrafts, as presented by Ross (2009) and Barbosa and Oliveira (2014). Additionally, the percentages of structure, systems and payload masses differ a lot from conventional aircraft (Ross, 2009, Barbosa and Oliveira, 2014).

The seventh aspect is that, if a solar aircraft is intended to long-endurance missions, or missions of wide-altitude variation, a specific Mission Analysis should be required to check the feasibility of the aircraft in execute the complete mission. A multi-day solar aircraft mission, with a large variation of altitude, is schematically shown in Fig. 3.

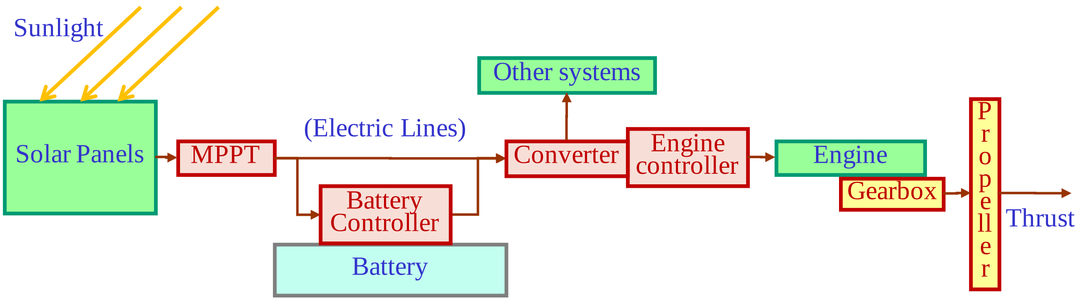

Figure 1. Sketch of the general propulsive chain in a sun-powered aircraft.

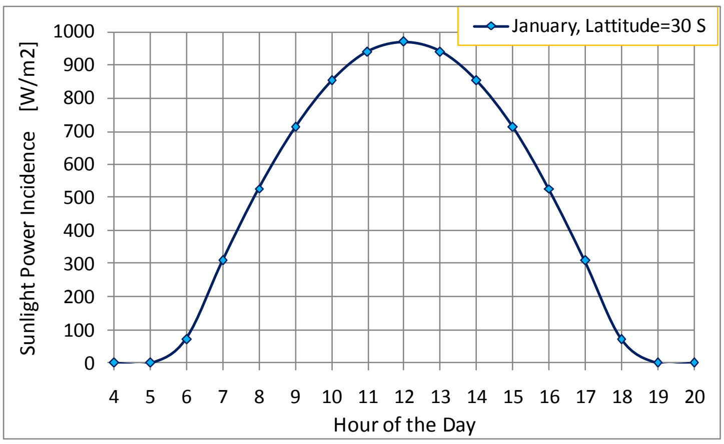

Figure 2. Example of curve of daily sunlight incidence. Note that both time of year and latitude must be defined.

3. DESIGN METHODOLOGY

The design methodology proposed comprises the following steps:

1. Target aircraft: definition of the intended mission and aircraft basic characteristics;
2. 1st aircraft definition: an iterative design process, considering the atmosphere model, the solar incidence model, the mass data and metrics, and performing aerodynamic and propeller analyses;
3. 2nd aircraft definition: aircraft adjustments during the Mission Analysis.

The methodology, illustrated in Figure 4, is detailed in the next sections.

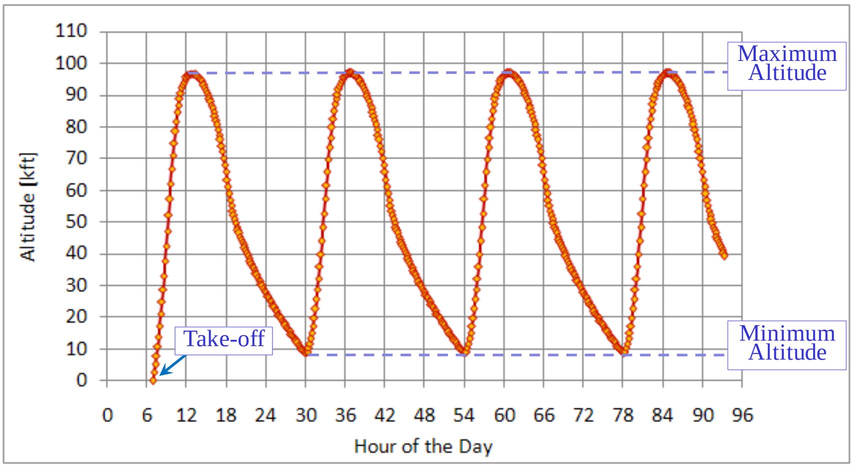

Figure 3. Schematic altitude-hour diagram of a continuous flight of a solar aircraft without batteries

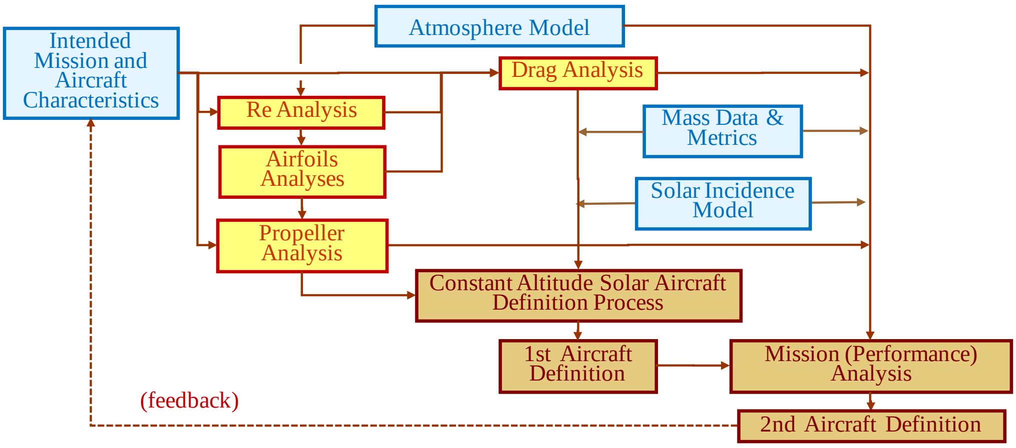

Figure 4. Solar aircraft definition methodology

3.1 Target aircraft

Sun-powered aircrafts can open some new possibilities of missions that are not achievable by conventional aircraft. For example, for missions in which long endurance periods are required, and speeds are not a constraint, a solar aircraft can be effective. Due to the strong mass constraints of solar aircraft, payloads should be defined as light as possible.

Based on these considerations, a long-endurance, light-payload mission is defined for the aircraft presented in this work. The initial requirements are:

1. Aircraft shall be unmanned, and electrically powered;
2. Aircraft should be capable of flying more than 48 hours with a 1 kg payload;
3. Total aircraft mass should not exceed 40 kg;
4. Structure and systems, making use of existing technology, should not present overoptimistic features;
5. Flights should be performed from equator to latitudes of 30 degrees south, during the Summer;
6. The minimum amount of batteries shall be employed; energy should be stored in terms of gain of altitude during sunny phases of flight as much as possible.

The above requirements suffice as input data to be used in the next step.

3.2 First aircraft definition through the iterative design process

From the requirements presented in the previous section, the aircraft parameters are defined from the 'Constant Altitude Solar Aircraft Design Method' (CASAD). This process, illustrated in Fig. 5, is an iterative procedure presented in Barbosa (2014). From an arbitrary initial point, the aircraft characteristics are recalculated, until a convergence is obtained. Several parameters (flight altitude, airspeed, payload mass, sunlight level, physical constraints and laws) are initially defined and are kept constant during the iterative process. The main control parameters for the iterations are the aircraft mass and wing area.

The main input and output from CASAD are presented in Table 1, and the evolution of aircraft mass and wing area during the iterative process is presented in Fig. 6.

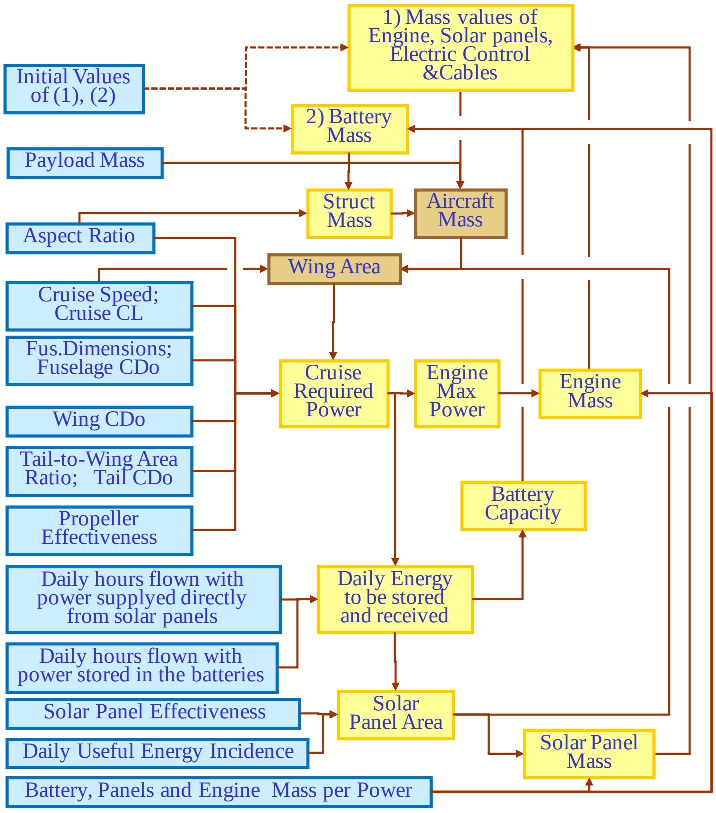

Figure 5. Constant Altitude Solar Aircraft Definition (CASAD) iterative process

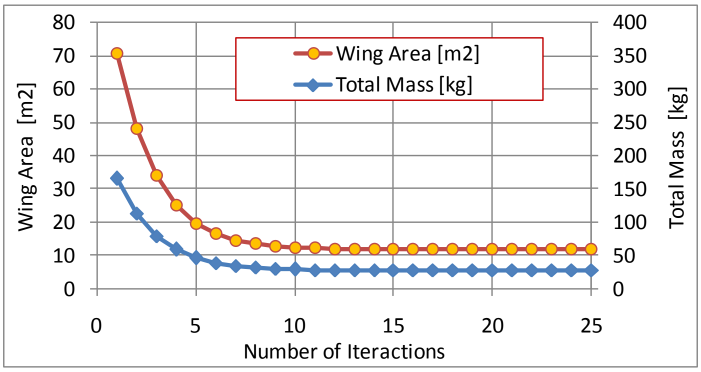

Figure 6. Visualization of parameters convergence during CASAD process

The aircraft characteristics obtained from this process should suffice for a constant altitude mission; but as the aircraft of this study is aimed to a mission involving large altitude variation, a second analysis is needed. So, the aircraft obtained from CASAD is the starting point for the next main step, the Mission Analysis.

3.3 Second aircraft definition though the'Mission Analysis'

The Mission Analysis is a simulation of the aircraft - preliminarily defined – performing its intended mission. In this simulation, the quasi-static approach is considered, and the most important transient effects are taken into account, as:

- The large altitude variation (for example, from sea level up to heights above 60 thousand feet);
- The large variation of available sunlight energy (for example, from zero before 6 AM up to about 1000 Watts/m^2 with the Sun at its zenith, and again to zero at 6 PM).

The schematic profile for a multi-day flight mission of a solar aircraft with no or low support from batteries is shown in Figure 3. During climb phase the aircraft acquires sunlight energy, and stores it by means of gain of altitude and speed; and during the absence of enough power to provide climb or level flight, the aircraft starts to descent. The target of the Mission Analysis is to obtain an aircraft capable to be kept airborne up to the moment that the sunlight, at next day, allows the aircraft to climb again. The main data for the analysis are, besides the ones considered for CASAD:

- Drag coefficients of the aircraft components (manly wing and tail) versus Re;
- Propeller power and thrust coefficients versus advance ratio, and Re;
- Sunlight power incidence curve – as the one presented in Fig. 2 – for the place and time of year in consideration;
- Variations of the atmospheric characteristics – density and viscosity – with altitude.

Table 1. Input and output related to the CASAD process

Main Input Data	
Latitude and Date of flight	30°S, 20Dec
Daily solar energy intensity [kW.h/m^2]	8.55
Flight hs powered directly from solar array	11.
Flight hs powered with support of batteries	0.
Payload mass [kg]	1.7
Flight altitude [km]	14.0
Equivalent airspeed EAS [km/h]	22.
Wing Oswald efficiency factor	0.95
Wing drag coefficient(1) C_{DO}	0.025
Empennages drag coefficient(1) C_{DO}	0.030
Fuselage equivalent drag area C_D.S [m^2]	0.09
Interference factor for aircraft drag	0.10
Empennages-to-wing area ratio	0.22
Solar array-to-wing area ratio	0.85
Solar cells effectiveness	0.069
Electric transmission system effectiveness	0.9
Max engine power / cruise power	1.5
Motor + propeller effectiveness	0.51
Wing-to-aircraft structural mass ratio	0.75
Engine mass/power ratio [kg/kW]	1.2
Solar Array mass/area ratio [Kg/m^2]	0.7
Aircraft cruise lift coefficient(2) C_L	0.8 / 1.0
Wing aspect ratio(2) A	10 / 16.

Main Output Values		
Aspect ratio A	10	16
Aircraft lift coefficient C_L	0.8	1.0
Wing area [m^2]	14.8	11.9
Wing span [m]	12.2	13.8
Wing chord [m]	1.22	0.86
Solar array area [m^2]	12.6	10.1
Aircraft mass M [kg]	27.6	27.8
Aircraft drag coefficient C_{DO}	0.063	0.064
Payload mass [kg]	1.7	1.7
Systems mass (3) [kg]	19.7	17.9
Structural mass [kg]	6.2	8.1
Payload mass [kg]	1.7	1.7
Engine cruise output [watts]	594	486
Engine maximum power [hp]	1.2	1.0
Wing loading M/S [kg/m2]	1.9	2.3
Air kinematic viscosity(4) ν [m^2/s]	6.3E-05	
Air specific mass(4) rho [kg/m^3]	0.227	
Reynolds Number(4) for length 1m	2.2E+05	
True Airspeed(4) TAS [km/h]	51.1	

(1) At cruise flight altitude conditions
(2) Two lift coefficients and two wing aspect ratios are considered for sensitiveness purposes
(3) 'Systems' comprises engines and propellers, solar arrays, controls, sensors and wiring
(4) Intermediate analysis values, related to flight altitude conditions.

It can be noticed that Mission Analysis requires data with deeper level of detail and complexity than CASAD process; it must be also noted that airfoils and propellers shall be suitably designed for the Re range into consideration.

Based on the configuration already obtained from the CASAD procedure, a set of 50 cases have been established for the Mission Analysis: Wing loading M/S of 2.0, 1.8, 1.6, 1.4, 1.2 kg/m^2; wing aspect ratio A of 10, 12, 14, 16, 18; and aircraft lift coefficient C_L of 0.8 and 1.0. The main outputs from the cases are the maximum and minimum altitudes achieved, as shown in Figure 3. Minimum altitudes with values greater than zero indicate that the aircraft can achieve continuous flight. Despite this, in order to get an altitude margin (related to the avoidance of ground irregularities, cloudy and gusty conditions and air traffic), a criterion of minimum altitude higher than 9 thousand feet is established. The maximum and minimum altitudes achieved during the mission cases simulated are shown in Figure 8.

From the output values obtained, the configuration with M/S=1.4 kg/m^2 and A=16 has been selected as the 'design point', since it presented the minimum heights of 9.2 and 11.1 thousand feet for C_L=0.8 and 1.0 respectively. The other characteristics of the aircraft and the time history of the simulated aircraft mission are presented in the next section.

4. RESULTS

4.1 Aircraft characteristcs

The aircraft, whose parameters are obtained from the CASAD process and Mission Analysis, is shown in Fig. 9. The main characteristics obtained for this selected aircraft are as follows:

- Span=18.5m, Wing Area=21m^2, Solar Area=19m^2, Wing aspect ratio=16.

- Level required power: 0.1 to 1.6 hp, maximum engine power=3.3 hp (2.46 kW).
- Cruise True Airspeed TAS =17 to 149 km/h, with Lift Coefficient C_L=1,0.
- Continuous flight at November to February, Latitude 30^o South, daily flight distance: 1450 km.
- Maximum aircraft flight weight =30 kg, Wing Loading M/S=1.4 kg/m^2.
- Mass Breakdown: Payload: 1.0 kg, batteries: 1.0 kg, structure: 9.5 kg, solar array: 13.5 kg.
- Drag coefficients range (effect of variation of Re with altitude): C_{DO}= 0.014 to 0.060, C_D= 0.028 to 0.039.

Other relevant characteristics are:

- Launched by very-low speed trolley, or by assistance of team members, running together;
- Four engine-propeller assemblies; propellers fold automatically during the glide segments of the flight;
- Wing is divided in three segments to allow easier transportation;
- Aircraft mission will need a ground station support to check atmosphere (avoidance of bad meteorological conditions or cloudy sky regions, during low-altitude flight phases);
- Systems and structure shall be qualified for temperatures down to -60^o Celsius.

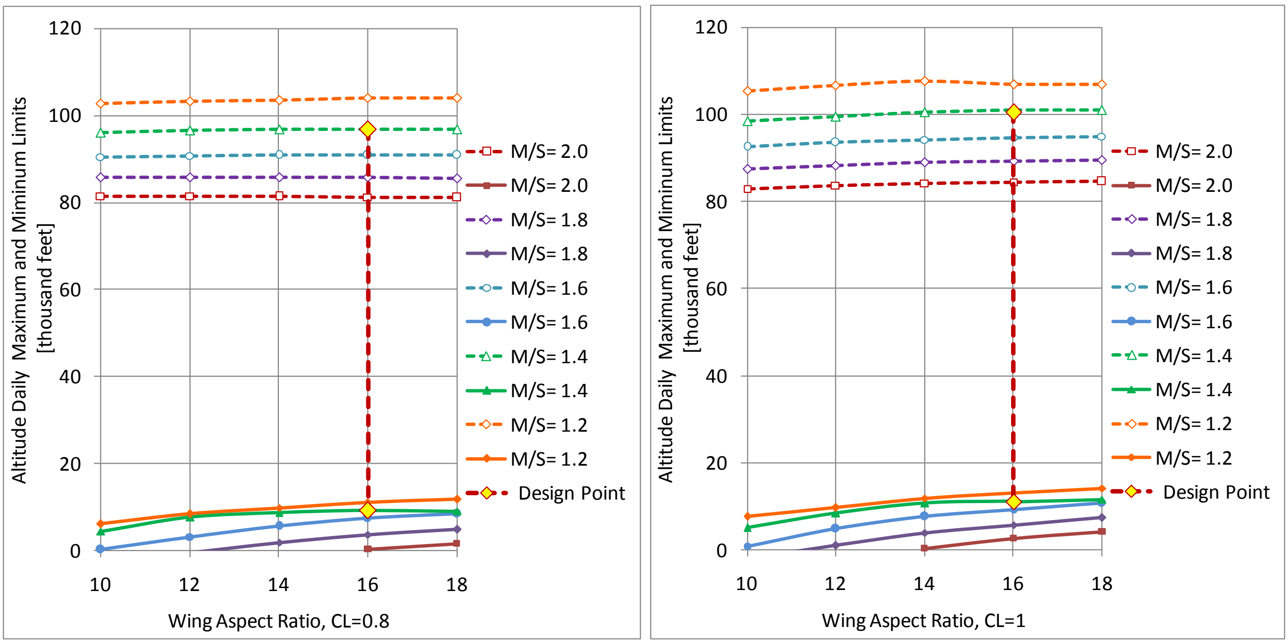

Figure 8. Sensitiveness parameter study from Mission Analysis evaluations, and the design point chosen

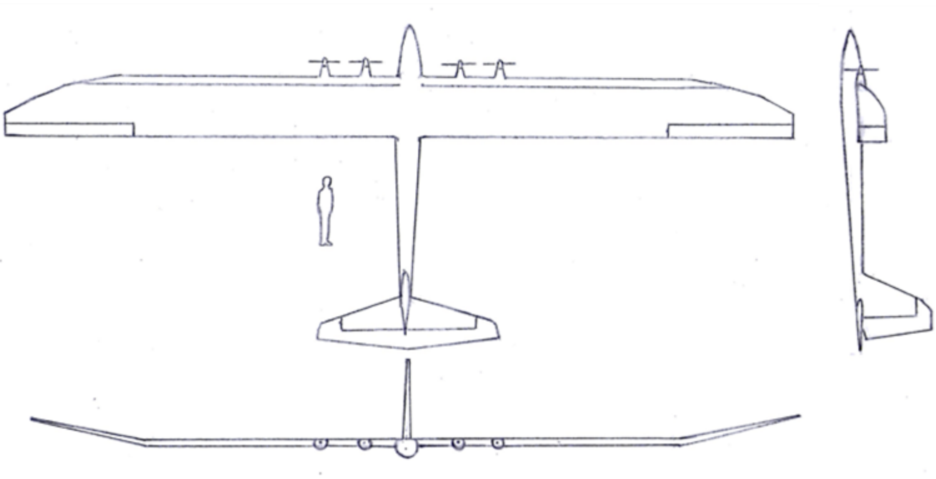

Figure 9. Aircraft General Arrangement

4.2 Flight parameters of the simulated mission for the selected configuration

Figures 10 to 13 present the time histories of several parameters during the flight mission, obtained from the Mission Analysis for the configuration which corresponds to the Design Point, shown in Figure 8. Figure 13 also presents the variation of propeller effectiveness in function of the advance ratio, during the flight mission.

Figure 14 presents the envelope of the aircraft continuously flyable region, in terms of months of year and latitudes. This envelope is the result of evaluations using Mission Analysis for several Sun irradiance profiles. It can be noticed that – theoretically and depending on the month of the year -a large region of the planet could be continuously flown, with the aircraft configuration defined. Even a non-stop-flight around the word could be theoretically possible.

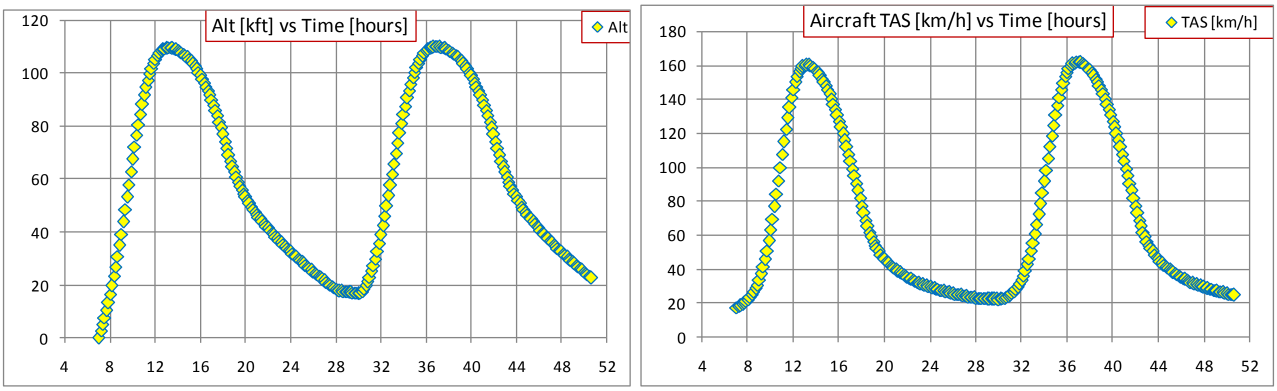

Figure 10. Aircraft altitude and true airspeed TAS, versus time

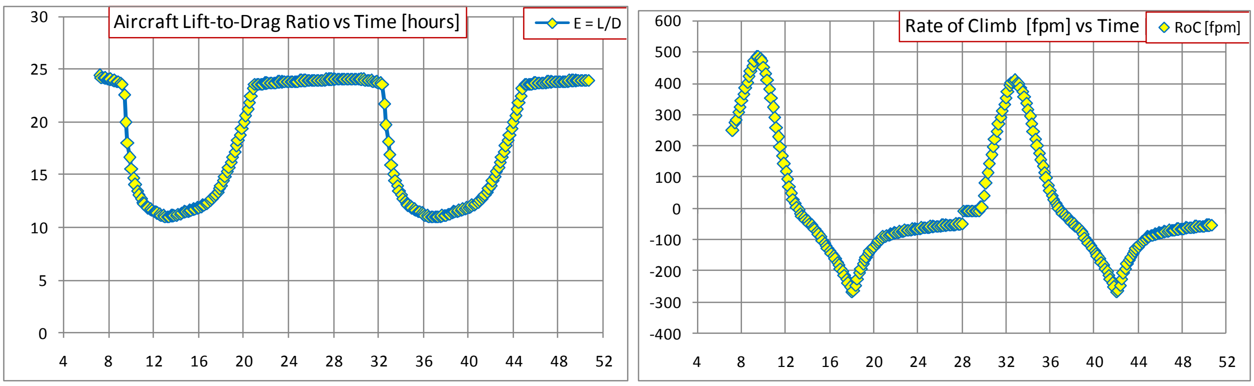

Figure 11. Lift-to-drag ratio and rate of climb, versus time.

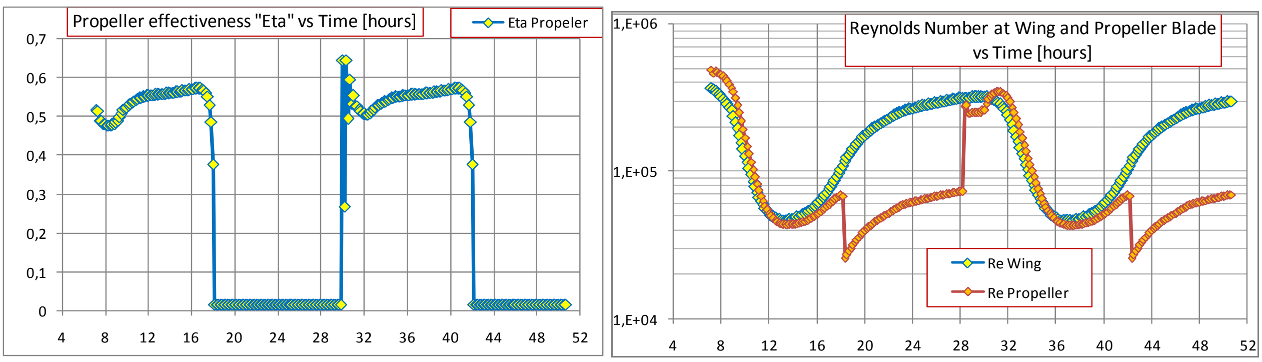

Figure 12. Propeller effectiveness 'Eta' and Reynolds number at wing and propeller blade, versus time.

5. CONCLUSIONS

In this work, a solution for a specific type of solar aircraft has been obtained to meet a specific mission requirement. The configuration presented is an example of the utilization of the design methodology developed.

It can be noticed that some very important aircraft characteristics – wing loading, power-to-mass ratio - are very low compared to conventional aircraft. This aspect seems to be the compromise associated to a long-range solar aircraft. Anyway, with a dedicated and focused design, a long-endurance, long-range unmanned solar aircraft may be feasible.

Considering the daily flight distances shown in at figure 14, and assuming still air, it would be possible to think a non-stop, round-the World theoretical flight mission, with a total flight time of about 31 days.

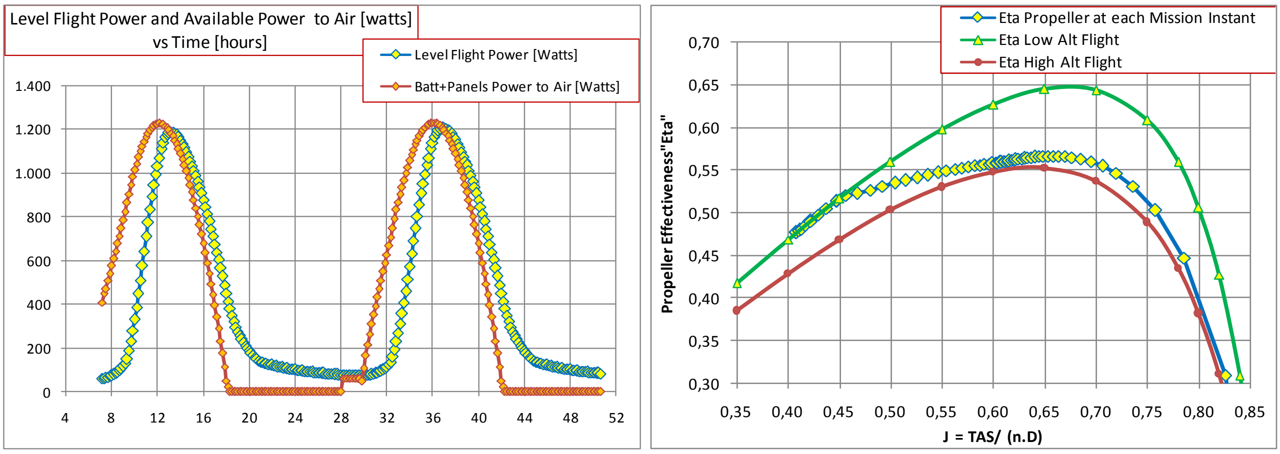

Figure 13. Level flight power and available power to air versus time; and propeller effectiveness during flight.

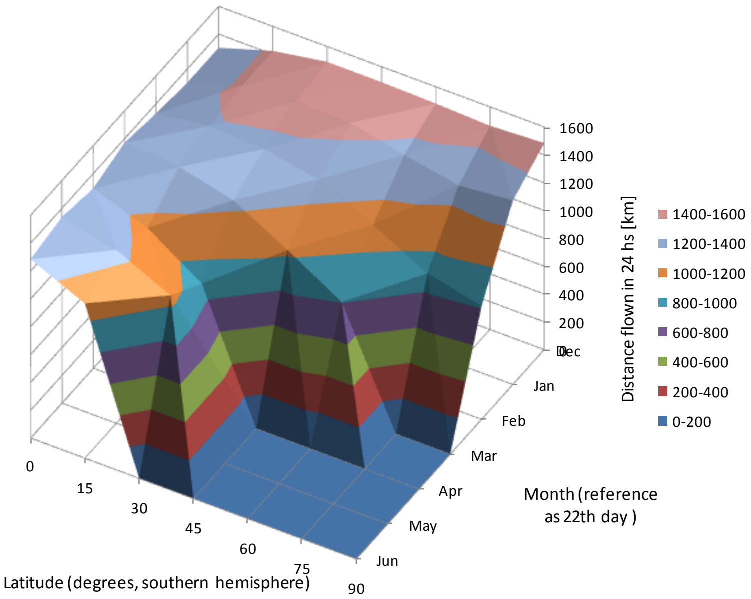

Figure 14. Daily distance flown in function of south latitude and month

6. REFERENCES

Barbosa, L.M.F., 2014. *Development of a Conceptual Design Methodology Focused on Solar Aircrafts*. MSc Dissertation, PPGMEC UFMG, Brazil.

Barbosa, L.M.F., Oliveira, P.H.I.A., 2014. *Weight Analysis for Low-Speed and Sun-Powered Aircraft*. SAE paper 2014-36-0508, Brazil.

Ross, H.,2009. *Fly around the World with a Solar Powered Airplane*. EWADE Conference, Sevilha, Spain.

Noth, A., Siegwart, R., Engel, W., 2007. *Design of Solar Powered Airplanes for Continuous Flight*. ETH, Zurich Switzerland.

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