Long Endurance Solar Airplanes– The Scaling Problems of Solar

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ABSTRACT

The ability for an aircraft to fly during a much extended period of time has became a key issue and a target of research, both in the domain of civilian aviation and unmanned aerial vehicles (UAV). The use of solar power is a solution to envisage aerial platforms that could stay theoretically endlessly in the air. In the space domain, airplanes with this endurance could be used for the exploration of other planets but also as high altitude long endurance (HALE) platforms on Earth, replacing satellites.

In year 2004, under contract with ESA, the Sky-Sailor Project started to explore the feasibility of a solar powered airplane flying continuously in the atmosphere of Mars by building and testing a demonstrator for the Earth. After almost 5 years of work, the project led not only to a first 3.2 m wingspan prototype that was presented at ASTRA 2006 and successfully tested during an autonomous flight of 27 hours but also to a solid experience and an extensive view of the problems that occur when scaling solar airplanes. This paper presents first the design methodology developed that aims at being used as well for 50 cm micro aerial vehicle (MAV) as for High Altitude Long Endurance (HALE) platforms embedding 200 kg of communication means, and then the critical points when up- and down-scaling.

INTRODUCTION AND MOTIVATION

The applications for an airplane able to stay in the air endlessly are numerous. **For planetary exploration**, on Mars for example, such a platform would be complementary to orbiters, which have a predefined path far from the surface, and rovers, which are limited by the terrain and suffer from a limited range. They could follow freely selectable paths and cover very large distances in order to achieve a lot of different tasks: near infrared spectrometry, high spatial resolution magnetometry and atmospheric sampling can be conducted over an extended area and hence provide a lot of material for variations studies. **On earth**, they could be used at high altitude for testing and evaluating satellite systems, or even serve themselves as low altitude flying satellite. Potential applications are earth observation and remote sensing, broadband communications, TV broadcasting, etc. Near ground, they could achieve border surveillance, forest fire monitoring and many other tasks.

The history of solar aviation has seen the realization of numerous very successful airplanes powered only with this abundant and free energy. In 1974, two decades after the development of the silicon photovoltaic cell, R.J. Boucher and his team designed the first solar-powered aircraft, which then performed a 20 minutes flight. The new challenge that fascinated the pioneers was then to achieve manned flight solely powered by the sun. In 1980, this was realized with the Gossamer Penguin, designed by Dr. Paul B. McCready and AeroVironment Inc. Since then, many projects started, most of them in the direction of high altitude long endurance platforms with wingspans of several tens of meters. The biggest was the 75 m wingspan Helios that reached an altitude of 30’000 m and showed incredible performances, but fell into the Pacific Ocean in 2003 due to structural failures. More recently, SoLong from AcPropulsion and then Zephyr stayed in the air for more than 24 hours [9].

Unfortunately, the theory behind the conceptual design of all these successful prototypes was either never published or only valid for a very precise case, linked to a certain size or application, and thus not applicable to other scenarios. Thus, the objectives of the Sky-Sailor project, started under contract with ESA in 2004 were to:

- Develop an efficient methodology for the conceptual design of solar airplanes that is applicable to a very large range of solar airplane, from micro aerial vehicle to large HALE platforms
- Use the methodology to design and then build a fully functional prototype of solar powered airplane
- Test the prototype to validate the design process and prove the feasibility of continuous flight over 24 hours.

CONCEPTUAL DESIGN METHODOLOGY

The design methodology, which was presented at ASTRA06 [10], is purely analytical and uses mathematical models of the various parts of the airplane. They are for example the evolution of the mass and the efficiency of a motor with respect to its power, or the mass of a lightweight wing structure one could expect to have for a certain wingspan and a certain aspect ratio. The methodology uses the weight and power balances that occur at level steady fly and that can finally be represented in a graphical manner as in Fig. 1 that summarizes the entire problem.

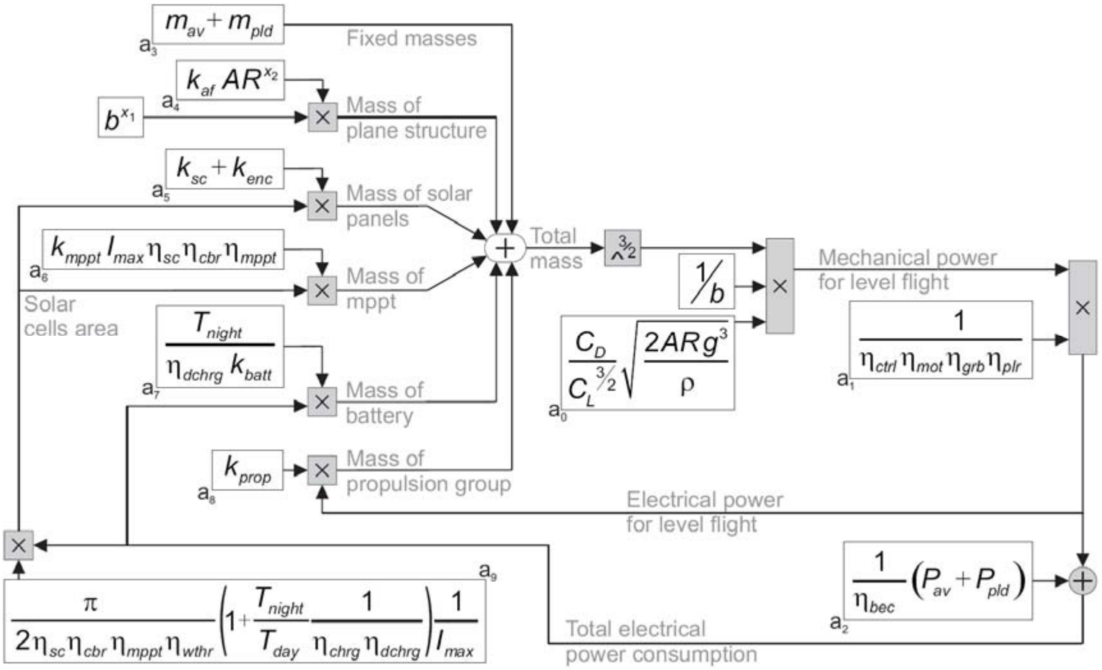

Fig. 1. Schematic representation of the design methodology

From all the parameters present in this figure, we can distinguish three categories. The first one contains the wingspan *b* and the aspect ratio *AR* that are the layout variables. The second category contains parameters linked to the mission like the air density, the payload power and mass, as well as the duration of day and night. All the other are in the third category that contains the technological parameters, for example the gravimetric energy density of a batterie k_{batt}.

The process to solve the loop analytically is quite simple. Considering the point where the masses of all elements are summed up in Fig. 1 and using the substitution variables a_i, we can write:

$$m=m_{struct}+m_{bat}+m_{solar}+m_{mppt}+m_{prop}+m_{elec}+m_{payload} \tag{1}$$

$$m-\underbrace{a_0a_1(a_7+a_8+a_9(a_5+a_6))}_{a10}\frac{1}{b}m^{\frac{3}{2}}=\underbrace{a_2(a_7+a_9(a_5+a_6))+a_3}_{a11}+a_4b^{x_1} \tag{2}$$

$$m-\underbrace{a_{10}\frac{1}{b}}_{a12}m^{\frac{3}{2}}=\underbrace{a_{11}+a_4b^{x_1}}_{a13} \tag{3}$$

The last equation has only a positive non-complex solution for *m*, which makes physical sense, if:

$$a_{12}^2a_{13}\le\frac{4}{27} \tag{4}$$

APPLICATION TO THE SKY-SAILOR

In order to see how it can be concretely applied, we will present here the example of the Sky-Sailor airplane. The objective here is to design an UAV that can embed a small payload of 50 g consuming 0.5 W, but that can achieve continuous flight at constant altitude over 24 hours using only solar energy. The mission and technological parameters that were used are presented in more detail in [11],. Using these parameters and trying various airplane shapes, i.e wingspan from 0 to 6 m and different aspect ratios, equation 4 determines if the solution is feasible, in which case equation 3 is solved to find the airplane gross mass (figure 3). The mass is then the starting point to compute the power for level flight and the the size of all other elements. In the present case, the airplane needs to have a wingspan of at least 2.2 m, but after 4.5 m, there is no solution anymore. The reason is that the wing structure becomes too heavy due to the model we considered where the weight is proportional to the cube of the wingspan.

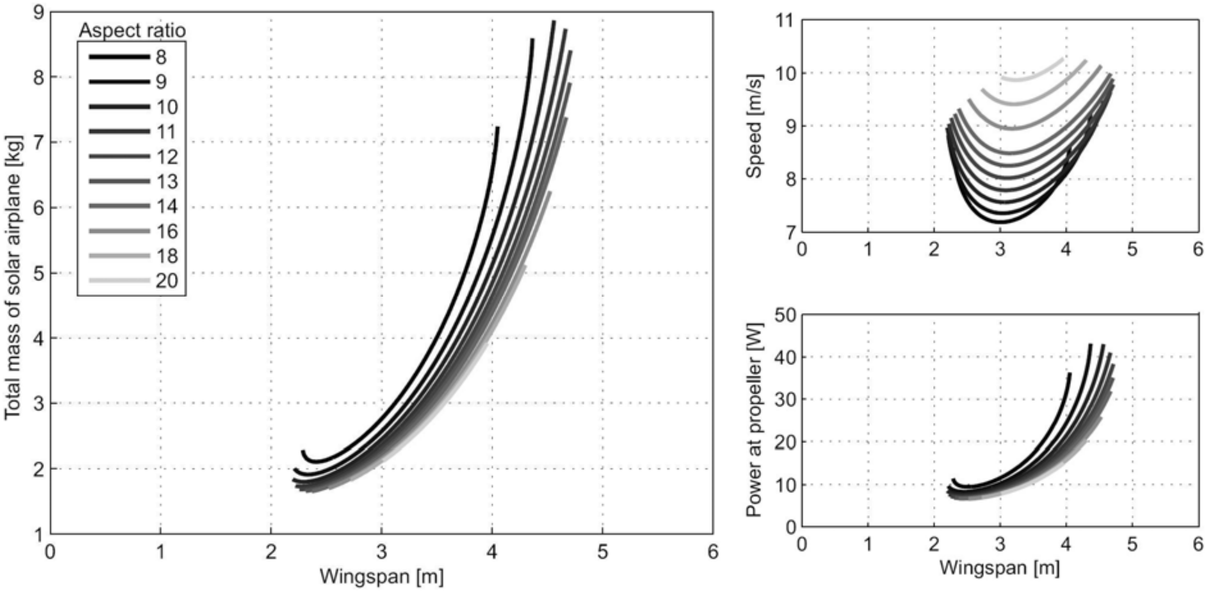

Fig. 2. Possible configurations presenting the total mass as a function of the wingspan b and aspect ratio AR

THE SKY-SAILOR PROTOTYPE

After having selected a final wingspan of 3.2 m and an aspect ratio of 13, using the figures above, a prototype of the airplane called Sky-Sailor was entirely built. It is covered by 216 RWE-32 solar cells that deliver a maximum of 90 W under AM1.5 irradiance conditions, whereas the airplane requires only 14 to 16 W electrical for level flight, thank to an excellent aerodynamic and a very efficient combination of the motor, the gearbox and the propeller. A lightweight and low-power autopilot was also developed specifically for this airplane. It ensures the navigation and control and also communicates all flight data to the ground control station. Virtual instruments and a 3D representation of the airplane on the map allow an efficient monitoring of the experiments.

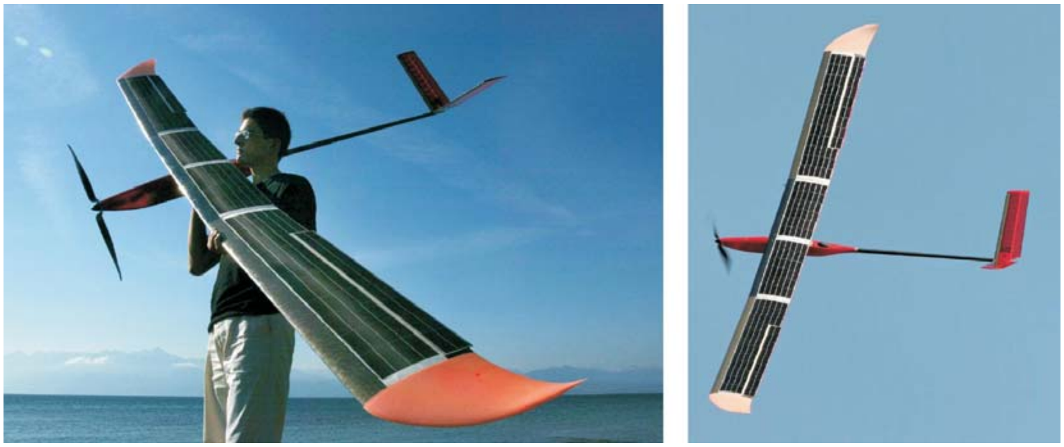

Fig. 3. The Sky-Sailor solar powered airplane prototype

After 4 years of developments and improvements, a solar flight of 27 h 05 mn was achieved on the 21st of June 2008, proving thus the feasibility of continuous flight, without using thermal wind or storing energy into altitude, and with a very limited wingspan. The airplane covered a distance of 874 km and retrieved more energy from the solar panels than it used for the motor and the autopilot system. Hence, the battery was completely charged at the end of the experiment, potentially ready for a next 24 h period.

SCALING

After the successful experiments with the Sky-Sailor prototype, one research direction was to study how the feasibility of continuous solar flight evolves with the size of the airplane. In the design methodology presented above, the mathematical models of the different parts were studied on a very wide range and are thus valid on many orders of magnitude. That is precisely why, considering the analytical character of our conceptual design method, it is possible to observe what are the pros and cons of down- or up-scaling. We will hereafter briefly mention the most important.

When **scaling down**, problems come first from the bad efficiencies of the motor, gearbox and propeller. Figure 4 shows the results of our study on around 2000 electric motors from 1 mW to 10 kW power. It shows clearly that the weight is well proportional to the power, depending of the technology used. However, the efficiency represented on figure 5 drops very fast for motors with a power below 1 W. For very low power, it seems that piezoelectric actuators could play an important role as their efficiency, poor compared to traditional electromagnetic motors at big dimensions turns to be higher in comparison at low dimensions [15]. However their command requires a high voltage which induces more complex and heavier control electronics.

On the side of aerodynamics, the lift to drag ratio of the main wing also decreases because of the low Reynolds number. The propeller also sees its efficiency reduced at smaller dimensions. The weight of solar cells, scaling only with the square of the wingspan because of the constant thickness, becomes also a heavier part in the mass distribution, and the smaller curvature radius of airfoils makes their integration more difficult without breaking them.

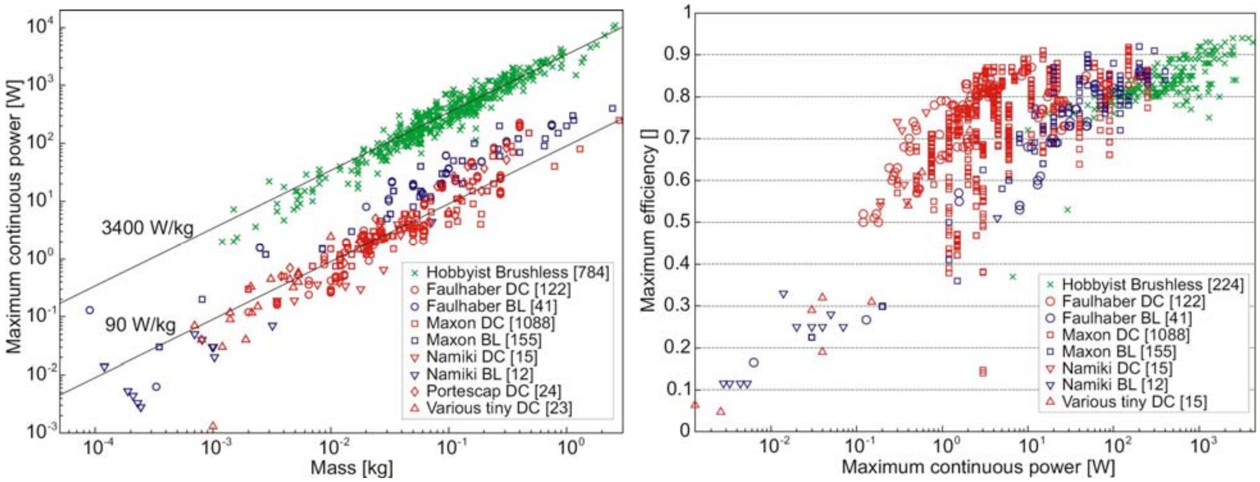

Fig. 4 & 5. Evolution of mass and efficiency with respect to the power of around 2000 electric motors

If the micro aerial vehicle is aimed at being autonomous, the development of a navigation and control system becomes very critical for small scale, especially from the sensor side. It is no more possible to embed GPS or IMU, the smallest of these two devices weighing currently around 10 g including antenna for the GPS. Hence, the expectations concerning the control capabilities have to be reduced. This limitation force the engineers to develop lightweight way to sense the environment, taking inspiration from the nature such as optical flow that can be used to avoid walls [16].

Concerning the actuators of the control surfaces, servo motors are generally used for UAVs, but at the MAV size, it is more difficult to find lightweight and still reliable products. Alternative solutions are the use of magnet-in-a-coil actuators [16] such as those used on the MC2 microflyer or shape memory alloys [7].

At the opposite, **scaling up** is very benefic for many things, especially for the aerodynamics and the efficiencies of the propulsion group such as the motor, its controller and the gearbox. Unfortunately, the single part that doesn't scale up in a positive manner is the airframe. As a matter of fact, interpolation on 515 manned and remotely piloted model sailplanes showed that the weight of a wing structure is proportional to the cube of the wingspan. This cubic tendency was also demonstrated by the biologist Henk Tennekes who presented, in his book ”The simple science of flight” [14] very interesting correlations including insects, birds and airplanes. He summarized the relations in a loglog diagram named ”The Great Flight Diagram” where, following his own words, ”everything that can fly” is represented. The result is impressive: 12 orders of magnitude in weight, 4 orders of magnitude in wing loading and 2 orders of magnitude in cruising speed. From the common fruit fly, Drosophilia Melanogaster, to the boeing 747, all the flying objects follow this cubic tendency with $W \approx b^3$ what is equal to $W/S \approx W^{1/3}$.

Figure 6 presents this Great Flight Diagram superposed with 83 solar airplanes flown to date. Using our design methodology, we can demonstrate mathematically that the ideal airframe weight prediction model, in order to make solar flight possible at large wingspan, should be square with the wingspan instead of cubic. Concretely, it explains why for large wingspan solar airplanes, new ultra light construction methods have to be found, which also lead to a greater fragility.

CONCLUSION

This paper presented the conceptual design methodology developed within the framework of the Sky-Sailor project. Based on empirical mathematical models, it was validated by the realization of a high performance prototype showing characteristics that were very close the prediction. This airplane named Sky-Sailor recently proved the feasibility of continuous flight using only solar energy with duration of more than 27 hours in the air.

But additionally, the analytical character of the methodology and the large validity range of the models allows observing how the feasibility of solar flight evolves with scaling, identifying what parts become more problematic. We observed that at small size, the efficiencies and the aerodynamics are still preventing us of building micro aerial vehicles of some centimeters able to fly with solar energy only. At the opposite, we clearly demonstrated that a very critical issue when scaling up solar airplanes is the wing structure. In fact, whereas one can prove mathematically that its weight should ideally go with the square of the wingspan, it goes in fact with the cube. That explains the extreme lightweight construction technique required for high wingspan solar airplanes.

However, being now able to clearly identify where the problems are will allow the scientist to orient and focus their research and development efforts in the correct direction. In the next years, solar airplanes will without any doubt play a major role in planetary exploration and space missions.

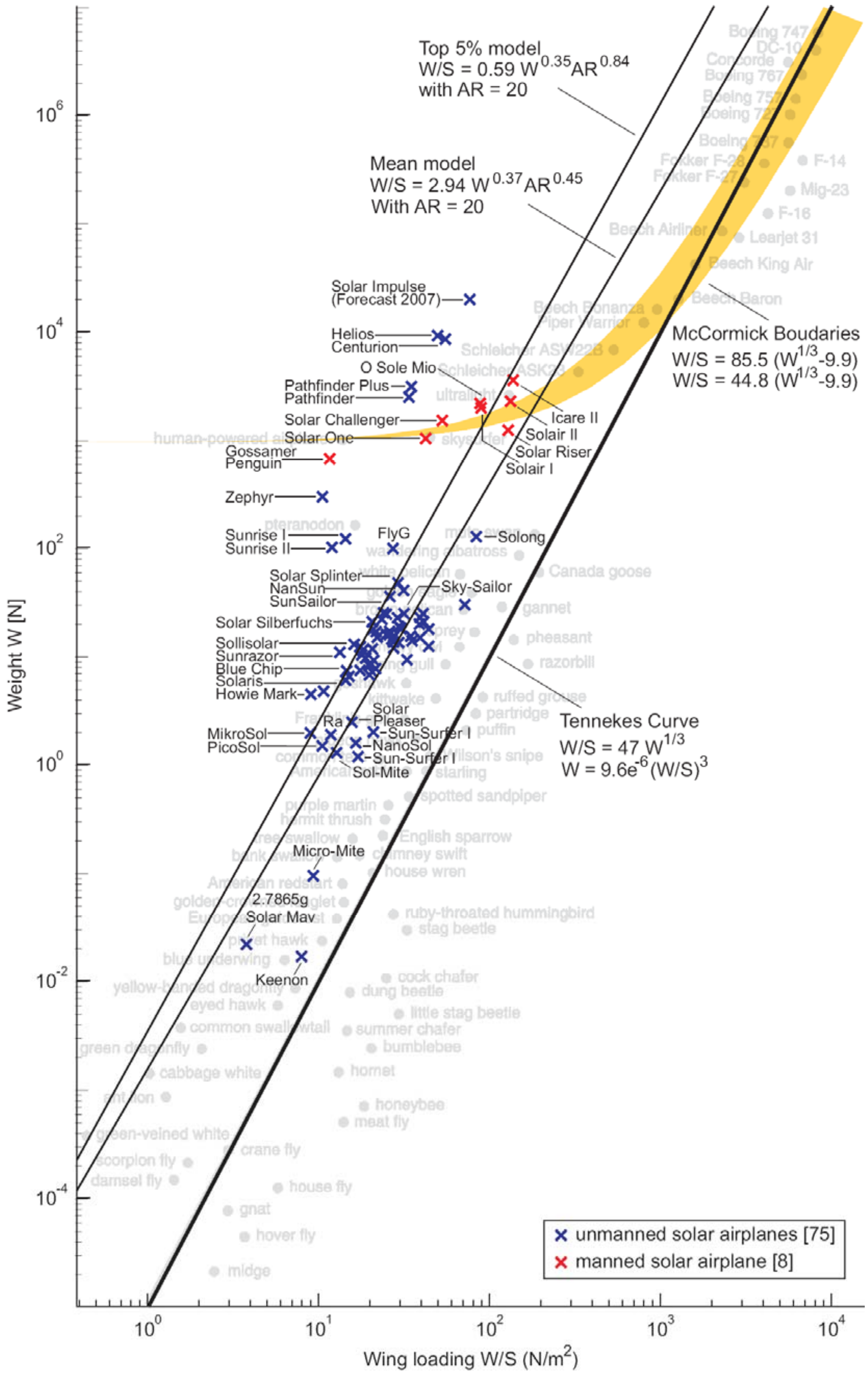

Fig. 6 The Great Solar Flight Diagram, augmented version of Tennekes Great Flight Diagram with 83 solar airplanes flown from 1974 to 2008

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