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ON THE CAPABILITIES AND LIMITATIONS OF HIGH ALTITUDE PSEUDO-SATELLITES

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Abstract

The idea of self-sustaining air vehicles that excited engineers in the seventies has nowadays become a reality as proved by several initiatives worldwide. High altitude platforms, or Pseudo-satellites (HAPS), are unmanned vehicles that take advantage of weak stratospheric winds and solar energy to operate without interfering with current commercial aviation and with enough endurance to provide long-term services as satellites do. Target applications are communications, Earth observation, positioning and science among others. This paper reviews the major characteristics of stratospheric flight, where airplanes and airships will compete for best

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performance. The careful analysis of involved technologies and their trends allow budget models to shed light on the capabilities and limitations of each solution. Aerodynamics and aerostatics, structures and materials, propulsion, energy management, thermal control, flight management and ground infrastructures are the critical elements revisited to assess current status and expected short-term evolutions. Stratospheric airplanes require very light wing loading, which has been demonstrated to be feasible but currently limits their payload mass to few tenths of kilograms. On the other hand, airships need to be large and operationally complex but their potential to hover carrying hundreds of kilograms with reasonable power supply make them true pseudo-satellites with enormous commercial interest. This paper provides useful information on the relative importance of the technology evolutions, as well as on the selection of the proper platform for each application or set of payload requirements. The authors envisage prompt availability of both types of HAPS, aerodynamic and aerostatic, providing unprecedented services.

Keywords: high altitude platforms; pseudo-satellite; HAPS; stratospheric flight; long endurance; solar-powered

1 Introduction

Further, quicker, longer, higher. From the beginning of the aviation era, those have been persistent concerns for manufacturers, pilots, operators and users. Most of the trials to reach new achievements faced the unavoidable limits of materials, aerodynamics and propulsion systems against the air drag and the everlasting gravity force.

But progress has been spectacular so far. Materials and manufacturing processes allow airplanes to carry more payload and fuel. Supersonic flight is mature and hypersonic velocities are manageable. Air-breathing engines are now equipped with powerful compressors, enabling high altitude cruise only formerly reachable by large balloons and rocket-assisted vehicles. Electronics performance and reliability improve flight control and unmanned operation.

In parallel, solar panels increase their efficiency every day and automotive industry boosts the development of electric power plants. In this context, the idea of self-sustainable air vehicles that excited engineers in the seventies [9] has become a reality, as proved by popular Solar Impulse [110][8] and other initiatives worldwide [17][140][9].

High altitude platforms, or Pseudo-satellites (HAPS), are those aerial platforms able to emulate satellite performance at local scale. That means enough altitude for the payloads to cover an interest area without interfering with current commercial aviation, and enough endurance to provide long-term services as satellites do. Communications, Earth observation, positioning, and astronomy, among other applications, could benefit from these platforms.

Both aerostatic and aerodynamic solutions are today in-vogue in the race for stratospheric commercial conquest. Whereas the first may be very large and difficult to handle on the ground, they can carry heavier payloads than airplanes, whose values are the simpler development effort and the more mature control mechanisms. Of course there are hybrid solutions trying to keep the best of both worlds. There is also controversy on considering balloons as HAPS, since they are hardly controllable. The same occurs with manned airplanes; whereas they are capable of cruising in the stratosphere, pilot presence advises against extremely long endurance. The balloon and the manned airplanes are not considered as pseudo-satellites in the present paper due to these limitations.

This paper provides a review of the technologies involved in stratospheric flight, their readiness level and their expected evolution to compare the two approaches for HAPS: aerostatic and aerodynamic. The performance analysis on typical operational scenarios will provide useful information on the capabilities and limitation of each solution. On-design and off-design comparisons estimate the impact of the different mission and vehicle design parameters on the global performance. The paper is organised along this logic: a historical review with the main requirements allocated to HAPS; an analysis of the atmospheric environment; a motivated analysis of involved technologies with emphasis on the key issues that may limit the mission achievements, such as aerodynamics, propulsion, power management, structures and materials, thermal control, ground assets and operational constraints; a comparison between airplanes and airships in terms of performances and the sensitivities of key figures. Lessons learned are then extracted to identify bottleneck technologies, future trends and challenges.

1.1 Historical perspective

From the multitude of projects that have provided useful knowledge in the field, a short list has been selected to illustrate the type of initiatives throughout history, the solutions adopted to key issues and the major achievements.

The classic method to reach the stratosphere is through unmanned balloons. Although initially dedicated to in-situ atmospheric observations, they are currently affordable platforms for other scientific and technological disciplines such as astronomy, Earth observation and telecommunications and even planetary exploration [49]. Payload capacities move from few kilograms to several tons. Similarly, flight durations of up to several days are available. An illustrative example is the recent mission POGO+ from the Swedish Space Corporation, which demonstrated a 40-km, 7-day flight with 1728-kg on board [79]. In parallel, in 2016 the Loon Project managed to fly several balloons for 14 weeks around an area of interest in Peru, just by selecting the proper altitudes to drift on the wind in the desired directions; in 2017, the concept provided basic internet for 7 weeks to people suffering devastating floods in the same area [108].

Other limited-endurance stratospheric platforms are fast jets. Manned jets initially operated in military applications, these fast airplanes are also used today for scientific purposes. The ER-2 and the M-55 Geophysica reach more than 20 km ceiling with a mission endurance of more than 6 hours whereas the SR71 Blackbird was able to reach up to 27 km at supersonic speeds but only for 1.5 hours. In essence, the dynamic pressure given by high velocities are used to compensate low air density while powerful propulsion plants keep the cruise conditions.

Using the same principles, unmanned operations and modern technologies allow these models to reach an endurance of several days. As a matter of example, from 1998 the Northrop Grumman Global Hawk can fly 35 continuous hours in the stratosphere before running out of kerosene. Today there are more competitors with similar performances.

But despite the above, solar airplanes and airships exhibit best conditions to serve HAPS requirements as they can offer station keeping at very low operational costs given their 'unlimited' endurance. Although hybrid solutions are possible, this paper is focused on the comparison between wing-based aerodynamic and buoyancy-based aerostatic flight options. The below information is mainly taken from the review documents [26], [154] and [113] as well as web pages from manufacturers. Priority has been given to active programs and those with relevant findings through flight tests.

1.1.1 Solar airplanes

The most relevant projects developing stratospheric solar airplanes have been:

- HELIOS: The Environmental Research Aircraft and Sensor Technology (ERAST) Program was a NASA initiative started in 1994 to develop a flying wing stratospheric airplane. Two prototypes reached 21-km (Pathfinder) and 29-km (Helios) record-winning altitudes. The long wings suffered from aeroelastic instability due to turbulence, leading to a program closure in 2004 [98].
- AEV-3: this 17.2 aspect ratio, 53-kg airplane has been developed and flown by the Korean Aerospace Research Institute in 2016 after successful first and second generation models in the

former years. The AEV-3 requirement is to achieve 18-km altitude with 5-kg payload with a range of cruise velocities between 6 m/s (minimum energy) and 10 m/s [60].

- AQUILA: this internet-aimed drone promoted by Facebook (initially developed by Ascenta in UK) intends to fly at an altitude between 18-km at night and 27-km in daylight. This solution is compatible with telecom applications and reduces the need of propulsion power when energy cannot be harvested from the Sun. The platform to be used is a flying wing aircraft with 42-m wingspan and 400-kg take-off mass. The mission life in the stratosphere, to which the airplane is injected by a balloon, will be 90 days. Up to now, a tropospheric flight of 96-min has been reported by Facebook in 2016 [155].

- ZEPHYR: starting in 2000 at the Flemish Institute for Technical Research with the Pegasus project, the airplane developed by Qinetiq was finally transferred to Airbus in 2013. There is current evidence of activity in the project as several units have been sold for military applications in UK. The Zephyr-7 is the only solar-powered airplane that has demonstrated a unique mission duration of 14 days at more than 21-km flight altitude carrying a payload of 5 kg. The company plans to improve such a performance with Zephyr-S and even to develop a larger version with up to 20-kg payload capacity, to be operational around 2019. The use of Li-S batteries and light-weight structures free from harmful aeroelastic effects are considered the major key technologies on-board [149].

- CAI HONG: meaning 'Rainbow', this solar airplane has been developed by the China Academy of Aerospace Aerodynamics. In 2017, a video-recorded test proved stable flight at 20-km altitude. The airframe comprises a pair of slender fuselages that support high-mounted wings measuring 45-m in span [143]. The target payload size and mission endurance remain undisclosed.

1.1.2 Solar airships

The selected projects for stratospheric solar airship development have been:

- HISENTINEL: it is a relevant research programme developed by the US Army from 1996 to 2012. The objective was to sequentially fly under propulsion 20, 50 and 80 lb of payload in the stratosphere by lighter-than-air vehicles for at least 30 days. There were important achievements such as the deflated balloon-like launching but problems with the propulsion system and gas leakage through seams avoided tests lasting more than a few hours [122].
- SPF (Stratospheric Platform): developed by the National Aerospace Laboratory of Japan (today JAXA) from 1998, the program included several prototypes of growing size (up to a huge 245-m length model) and a hangar. In 2005, after successful tropospheric missions with a 68-m prototype, the program was cancelled due to financial restrictions. The main advances focused on the regenerative fuel cells, gas-bag management and light flexible structures (Zylon) [85].
- Korean Stratospheric Airship Program: the project to obtain a lighter-than-air stratospheric platform stared in 2000 in the Korea Aerospace Research Institute. A 50-m length model was able to fly with 100-kg payload at 5-km altitude. There is little more information from 2005, although a huge 22-ton airship was under consideration.
- HAA (High-Altitude Airship): in 2002, the US Army initiated the HAA program, with a long endurance 73-m length prototype (HALE-D) contracted to Lockheed Martin. The program was stopped in 2011 after an incident during a test flight due to the air management subsystem.

The official report [41] summarises the operations and expenses of the several USA efforts in airship development, including stratospheric ones.

- STRATOBUS: Thales Alenia Space started developing the Stratobus in 2015, aiming at a stratospheric airship with 250-kg payload able to keep its positon at 20-km altitude for one year. The Stratobus will be about 125 meters long, with an envelope made of UV-resistant woven carbon fibre, and able to stand winds of 90 km/h thanks to its two fuel cell-powered prop motors. As the program advances some of the technical solutions are varying such as the position of propulsion plants and solar panels. The investment is active, with plans for qualification flights in 2019.

1.2 Target missions

HAPS are capable of providing services that could complement, compete with or even replace those currently offered by airplanes, satellites and terrestrial networks. Most relevant services are germane to, among others areas, telecommunications, Earth observation, GNSS or scientific applications.

1.2.1 Telecommunications

HAPS are promising platforms for the improvement of existing communication systems, both in capacity and coverage [51]. For example, terrestrial networks hardly provide a reasonable quality of service and data rates to most rural and remote locations even in developed countries. Meanwhile, satellite services have been traditionally focused on broadcasting applications and government communications. New initiatives such as the massive LEO constellations also pretend to provide robust and efficient universal communications for a large amount of private users [34]. But the irruption of HAPS systems within the communication networks can provide a series of advantages at different levels when compared to satellite or terrestrial solutions, as summarized in Table 1.

Based on HAPS capabilities listed in Table 1 and inspired by the analysis of HAPS communications systems included in [51], different telecommunications services can be envisaged to be soon offered from such platforms:

- Direct-To-Home (DTH) broadband: Direct-To-Home (DTH) broadband: HAPS could be useful in unserved areas (i.e. areas with no infrastructure providing communication services) or underserved areas (i.e. areas with poor connectivity). In this case the HAPS could mimic a satellite or a terrestrial tower.
- Trunking: A large numbers of users under the footprint of a HAPS can connect to it and share a single satellite connection. Users can benefit from the good balance between coverage and signal degradation provided by the HAPS solution, avoiding the requirement to have a dedicated satellite connection for each user.
- Backhauling: HAPS can provide very high capacity backhaul links between nodes of a network (e.g. cell phone towers) and its backbone, avoiding then the deployment of costly optical fibre or terrestrial microwave links. Furthermore, they could also trunk several backhaul links and connect them to the core network via satellite.
- High Throughput Services: Although current GEO satellites are capable to generate hundreds of spot beams, each of them has a relatively large size. Should too many users in the same spot intend to stablish a connexion the beam may be overloaded and some of them will have no service. HAPS could then help to offload the beam.

- Tactical Communication: usually provided in UHF, HAPS based service is scalable, agile, reliable, affordable, defendable, rapidly deployable and requires minimum in theatre ground infrastructure [130].
- Mobile Broadband: Currently, broadband services to mobile users are usually provided by terrestrial wireless networks. If no terrestrial coverage exists, service can be provided by already existing satellites (e.g. Iridium, Inmarsat, etc.). HAPS could provide a service equivalent to the satellite, but offering higher capacity thanks to the much more favourable link budgets.
- 5G: HAPS can be part of the infrastructure needed to support 5G services, where a single platform can maintain not only a large number of connections, but a wide range of services and applications (e.g. DTH broadband, mobile broadband, trunking, backhauling, Internet-of-Things, etc.).

The deployment of such services could be notably hindered due to the limitations derived from the telecom bands assigned to HAPS by the World Radio Conference (WRC) when providing fixed services (according to Resolution 122 from WRC-07 [62] and Resolutions 145 and 150 from WRC-12 [63]). Regulation establishes several geographical limitations and conditions of operation of HAPS in all the assigned bands. Due to these reasons it is expected that during the following WRC meeting (to be held in 2019, WRC-19) appropriate regulatory actions for HAPS within existing fixed-service allocations can be taken (Resolution 809 from WRF-15 [64]).

1.2.2 Earth observation

HAPS are also a very interesting platform for Earth Observation (EO) payloads, providing useful capabilities for many services and complementing satellite and conventional aircraft (manned and unmanned) imagery.

While space sensors can map large areas worldwide, they offer a relatively coarse resolution for certain applications and suffer operational constraints due to the fixed-timing acquisitions and weather conditions (e.g. cloud cover). On the other hand, aircraft surveys can be planned more flexibly, but they can pose difficult and costly campaign organization efforts. When continuous monitoring of an area is needed, the relatively limited persistence of existing aircrafts (even Medium Altitude Long Endurance unmanned versions) requires the deployment of multiple platforms.

A large variety of EO-based services can be identified. A good systematic classification is offered by the European Association of Remote Sensing Companies (EARSC) [36]. All these services are likely to be provided by means of HAPS when the coverage area is local or regional. However, some of them are more suitable to HAPS as those can keep flying for very long periods, up to several months, and its capability for Earth Observation is similar to other conventional aircrafts as proven from manned vehicles (Figure 1). Taking advantage of its superior endurance, [129] estimates that permanent coverage of an area over a 21-day period using a single HAPS makes it possible to reduce by a 60% the required personnel for the operation of the system or having a cost per flight hour of just a 15% that of the conventional unmanned aircrafts. The services that have been identified as highly promising for HAPS are:

security, maritime and emergency management [50]. Both passive and active sensors are under consideration, although given the low maturity of current platforms and associated services, the first are clearly the precursors.

1.2.3 GNSS, science and others

The availability of HAPS platforms opens up opportunities for the provision of navigation services, either with a stand-alone service, with additional infrastructure to complement existing systems or with services which allow improving the performance provided with such systems. HAPS could provide functionalities such as:

- Additional ranging sources to assist and improve positioning
- Network node to provide data from an external source
- Reference stations for network RTK (Real Time Kinematic) and PPP (Precise Point Positioning) types of services
- Additional sensor platform to perform radio occultation and/or GNSS reflectometry measurements.

Finally, there are many other applications for HAPS. In-situ observations of atmosphere or other scientific disciplines can benefit from the high altitude of the HAPS in different ways. As a paradigmatic example, it is an ideal platform to perform astronomical observations because most of the atmosphere lies below the telescope. The concept has already been proven as successful thanks to the 12-km altitude Stratospheric Observatory for Infrared Astronomy (SOFIA), a joint USA-German space science project active from 1996 [45]. SOFIA mounts a 2.7-m telescope inside a modified Boeing 747. Unmanned HAPS can even provide a more stable platform with extended endurance.

2 Stratospheric environment

Traditionally, the atmosphere has been decomposed in layers, each one having a characteristic vertical temperature gradient. The layer of particular interest in the case of HAPS is called stratosphere which typically is considered to start at 20 km [61] although this depends on the latitude (in the poles it starts as close as 8 km). The maximum altitude of the layer is close to 50 km. This section is intended to provide a succinct overview of the stratospheric environment focusing on: its composition, chemistry, physical properties, the wind dynamics and the solar environment, since they are the key elements that will constrain HAPS design.

2.1 Composition and chemistry

The atmospheric composition remains constant from sea level to altitude of 90-100 km [58]. As a consequence, this lower region is called the homosphere. It is characterized by a high concentration of nitrogen and oxygen molecules, being approximately 78% and 21% respectively [12] with a residual percentage for other gases such as CO_2, water or ozone (O_3). Although ozone is a minority component, its concentration in the stratosphere is high when compared to the other layers (90% of the total [115]). This is an important factor not only for the chemical and the radiative budget but also for its corrosion properties. The solar radiation with wavelengths shorter than 310 nm is absorbed by the ozone, protecting the biosphere and heating the stratosphere [11]. This ozone is generated as consequence of the photolytic decomposition of the O_2, generating atomic ozone in the process. The atomic ozone concentration increases with the altitude and during the day. In the stratosphere is not as important as in the thermosphere, in which the concentrations are 10^3 times higher than at 35 km [11].

The main stratospheric aerosol is a solution of 60-80% sulfuric acid (from 12 to 30 km). The origin of this aerosol can be found in the oxidation of carbonyl sulphide, originated from the Earth's surface [115]. The droplets diameter is around 0.2 μm with mean concentrations around 1-10/cm^3. Due to the lower temperature of the stratopause, the water vapour of the rising air is frozen out, causing a water vapour mixing ratio of only 4-5 ppm in the stratosphere [115].

2.2 Physical properties

For both airplanes and airships, one of the most influential factors in their design is the air density at the flight altitude. Following the ISA model (Figure 2), an assumed temperature, density and pressure distribution are given. The reduction of pressure and density with height follows an exponential equation for static atmospheres. As a consequence, although the temperature of the atmosphere varies less than a factor of 2, the air density and pressure at 20-km are less than 8% of that at sea level. Air viscosity is 79% of sea level reference, making kinematic viscosity be 11 times larger than that at reference. Due to these extreme low pressure levels present in the stratosphere, special considerations about the design of electrical circuits and power systems of the vehicles have to be considered. In [39] it is estimated that for 130V circuits, in contact with Helium, at an altitude of 21 km, the distance needed for an electric arc is less than 1.5 mm.

Despite this, the ISA atmosphere is only a model and the real temperature distribution depends on the latitude [93]. This temperature distribution in the stratosphere is specified in [72] as:

- Cold centres in the poles
- Warm regions in the middle latitudes
- Cold zone in the tropical zone of the tropopause
- The upper stratosphere, from 25km, presents a simple distribution: regular gradient from the poles (cold zone) to the equator (warm zone)

2.3 Wind dynamics

The power required to overcome wind induced drag forces increases with the air speed third power and that is the main reason why it is important to determine the zones in the stratosphere in which the average wind intensity is nearly the minimum. Following [138], the dynamics of the stratosphere are conveniently subdivided into two regions:

- A layer between 35 and 50 km, driven by the Semi-Annual Oscillation of the zonal winds, also called SAO. Its amplitude increases with latitude reaching values of 30 m/s [138]. This region is outside of HAPS's range.
- The region between 17 and 35 km, which is influenced by the Quasi Biennial Oscillation (QBO). There is evidence of its existence that dates back to more than 90 years ago [53]. The perturbations amplitude reaches near-constant values of 20 m/s from 22 to 30 km in the easterly phase compared to the 10 m/s in the westerly phase, diminishing for altitudes lower than 22 km [11] and decreasing with latitude.

A typical HAPS operational altitude is around 20 km. A wind speed minimum is reached at this altitude in which mean values of 10-15 m/s are quite common [30][76] although a statistic study of the wind will be necessary in the specific regions of the mission due to its geographical, seasonal and daily variability (as in Figure 3).

In the study carried out by [120] in USA, it is demonstrated that, at 20 km, the time in which the wind is more than 15 m/s is nearly 10% (grouped in blocks of several days), 1% for more than 20 m/s and reaching isolated maximum values of 30 m/s.

2.4 Solar environment

Traditionally, particular attention has been paid to the effect of the solar direct radiation on vehicles. The operational day length is an important parameter of the mission that depends on the latitude, longitude and Earth's declination (δ), as shown in Figure 4.

The direct irradiance increases with altitude. At 20 km, it is estimated to increase by 25% with respect to the value it reaches at 2 km [120] while the diffuse radiation decreases down to 5%, all considering clean sky [71]. It is clear that the total irradiance shows smaller variation with altitude than the direct irradiance, and this effect is more relevant for shorter wavelengths [33]. A model for estimating the direct solar radiation is also developed in [33] considering the altitude and the atmospheric attenuation of the solar spectrum according to the month and latitude. The Earth's orbit is slightly elliptical and as consequence, the extra-terrestrial solar irradiance varies with the Earth's true anomaly (φ), following [28]: $I_{SUN} = 1367\,(1.017 + 0.0174\cos\varphi)^{\,2}\ \mathrm{W/m^2}$. At 20-km altitude [28], the year-mean normal irradiance values are near 1300 W/m^2 compared to typical values at sea level around 800 W/m^2 for latitudes ranging from 0˚ to 40˚. Figure 5 shows the worst case along the year.

In addition to the direct solar radiation, the effect of the other radiations has been considered so as to harvest energy or model its thermal effects. Following [132], almost 30% of the total incoming radiation is reflected by the clouds (22%), atmosphere (6%) and Earth surface (2.3%). As is described in [124], the cloud albedo depends on the geographic localization in which the measure is made. The cloud concentrations are higher in Northern Europe and the Northern Atlantic (60-80% cover); the opposite is found in regions such as Australia, Central Pacific and North Africa. It also depends on the type of clouds, having in ascending order of reflectivity [124]: High types such as cirrus, cirrostratus and cirrocumulus (20%), medium clouds like altocumulus and altostratus (40-56%), low clouds as nimbostratus, stratocumulus and cumulus (60-70%) and cumulonimbus (78-90%).

3 Analysis of key technologies

3.1 Aerodynamics and aerostatics

The aerodynamics of the platform is a critical element not only for its performance, but also for the definition of the design of the control and propulsion system. Platform configuration is obviously quite different for airships and airplanes.

3.1.1 Airplane aerodynamics

In aerodynamic HAPS, cruise speed is usually quite low in order to minimise the amount of power required to keep the aircraft flying. Air density is also very low (§2.2) so, to compensate for gravity, wing must be designed making use of high-lift airfoils. High lift can result in high induced drag, which can be limited by increasing the wing aspect ratio and achieving elliptical distribution of the wing load [154]. In general, no central fuselage is needed so the most common aircraft configuration is the flying wing (e.g. Aquila [155]), sometimes including tail planes for better stability and control of the platform (e.g. Zephyr-S [149]). Wing tips and swept–back wings are also a typical strategy trying to reduce aerodynamic drag.

As a result of the low speed and low density the Reynolds number is also quite small (below 2.5×10^5 for aerodynamic speeds close to 20 m/s and chord lengths between 1 and 2 meters). Different airfoils have been specifically designed to operate at low Reynolds (e.g. E387, FX63-137, S1223) and to achieve lift coefficients that could be even higher than 1 at 0 deg angle of attack (see S1223 airfoil). Such high-lift performance can be achieved by exploiting the favourable effects of both a concave pressure recovery and aft loading.

However, high lift is not the only desirable feature for these airfoils. The aerodynamic efficiency (C_l/C_d), endurance parameter ($C_l^{1.5}/C_d$), thickness, pitching moment, stall characteristics, and sensitivity to roughness or Reynolds number are all important factors that must be studied in detail when looking for the most suitable airfoil for the aircraft [116]. Large aerodynamic efficiency is very important because it minimises the amount of drag produced when generating the required lift. However, for solar HAPS, a high endurance factor is even more important than aerodynamic efficiency, as it minimises the amount of energy required for level flight, which is always scarce in solar aircrafts, and increases flight endurance.

The aerodynamic characteristics of some popular low Reynolds airfoils are depicted in Figure 6. It can be seen that their performance is quite sensitive to Reynolds number. When it is halved from 2×10^5 to 10^5 or below, drag coefficient notably grows while $C_{l,max}$ decreases. This usually leads to poorer aerodynamic efficiency (down to 50%). This behaviour is related to some complicated flow phenomena that involve separation, transition, and reattachment, forming a bubble [4] that generates a non-linear lift curve [6] and substantial drag [154].

3.1.2 Airship aerostatics and aerodynamics

In contrast to airplanes, conventional airships generate most of their lift thanks to buoyancy instead of wings. Buoyancy is dependent on the mass of the displaced fluid, and therefore on its density, as the volume is essentially constant in airships. If the platform flies higher, lower buoyancy is generated due to the diminution of atmospheric air density and, consequently, larger platforms will be needed for the same payload.

Gas contained within the envelope of the airship (usually called lifting gas and obviously lighter than air, typically hydrogen or helium) will also change in the same way as the atmosphere because for most non-rigid and semi-rigid airships differential between internal and external pressure must be kept within a pretty narrow range [24]. There should be therefore mechanisms to allow this changes without affecting the external vehicle shape: the ballonets or the gas-bags. As the airships rise and the lifting gas needs to be accommodated in a larger volume, air is progressively released from the hull. Maximum operating height for the airship will be reached once ballonets are completely deflated or gas-bags fully inflated. Over this height, the lifting gas will start over-pressurising the container unless it is vented to the atmosphere.

The previous explanation is quite simplistic and a more in detail analysis is out of the scope of this work. However, it is important to be aware of some other factors affecting lift generation, like internal pressure (usually higher than ambient pressure that will result in higher density of lifting gas), superheat (temperature of lifting gas higher than ambient air temperature, decreasing lifting gas density), weather effects (even a small amount of rain or snow covering the envelope can notably increase the heaviness of the airship) or humidity (a higher humidity reduces the density of the ambient air and, therefore, the gross lift) [24].

Due to the huge size required to fly an airship in the stratosphere, it will show a large drag force that increases with the square of the airspeed. This resistive force dictates the required propulsive power for an airship that is proportional to the third power of the airspeed. Even a small reduction in drag can result in significant energy savings, which in turn, will lead to less battery weight, less solar panels and smaller airships for a given payload. Main contribution to the aerodynamic drag of the airship comes from the hull, which account for about two-thirds of the total drag [82][142]. Therefore, it is especially important to choose a minimum drag envelope for the stratospheric airship during the design process.

Most optimization analysis have been traditionally focused on axisymmetric bodies due to its simplicity and efficiency, aiming at determining the most convenient values of their volume and finesses ratios (length over height, usually greater than 4) [16]. In the case of stratospheric airships that optimization must consider that, typically, volumetric Reynolds for a 100-m airship is over 10^7 (the reference distance for Reynolds number in slender bodies is normally taken $V^{1/3}$ where V is the volume). As there are very few experimental investigations on these bodies at such a high Reynolds (only airships designed for tropospheric flights tested in 1931 [2]), the optimization process relies on theoretical methods for drag calculation [82] [142].

When developing those algorithms, however, it is necessary to underline the importance in the determination of the boundary layer transition point, since the length of the laminar flow region has a substantial impact on the drag coefficient. In particular, for small to medium Reynolds numbers, this fact has been clearly found in different experiments [119][2] (where high Reynolds lead to a larger turbulent flow region), see Figure 7. Notice that aerodynamic coefficients for bodies of revolution are usually calculated making use of the term $V^{2/3}$ as the reference area.

Regarding overall aerodynamic performance some final remarks are also important. On the one hand, available experimental data confirms that airship polar curves follow the parabola law [40][141]; on the other hand, aerodynamic drag created by the fins and, mainly, the gondola is not negligible (up to 40% of total drag [141]). If possible, gondola should be installed inside the airship or at least minimizing frontal area.

Stabilisers and fins will also have an important effect on the aerodynamics of the airship. Common configurations use three or four stabilizers; all the configurations increase total drag but they also increase lift coefficient at a given angle of attack by more than double [16]. Also, hull interference will distort the flow reaching the tail planes, making it highly three-dimensional and modifying its stability parameters [40].

One of the more misunderstood effects in all of aerodynamics is added mass. When a body accelerates, decelerates or changes direction while moving in a fluid it adds work to the surrounding fluid, then it behaves as having more mass than it actually has and changing its matrix of inertia. Although this phenomenon is present for any body accelerating/decelerating through a fluid, the effect is significant only when vehicle displaces an external fluid mass similar to vehicle's mass. This is the case of an airship; its added mass will have a large influence on its dynamic behaviour and must be computed. Full potential flow methods have shown reasonable performance predicting the added mass for simple body shapes [16]; however, its calculation for complex shapes or those with little symmetry should be done making use of CFD codes [134]. The ratio of the mass of the displaced fluid volume to the actual mass of the vehicle (including internal gases), can be as high as 1.25 (Goodyear Airship *Spirit of America*) [16].

3.1.3 Hybrid airship aerodynamics

Traditional airships generate lift mainly by means of buoyancy, but they also relay on the production of certain amount of aerodynamic lift (5-10% of total lift) to account for ascent, descent and propulsion power. Hybrid airships are capable to produce a larger portion of the required lift from aerodynamic lift (up to 40%). While static lift is difficult to control due to persistence of buoyancy, dynamic lift can be varied by modifying aerodynamic speed and angle of attack. This increases its operational flexibility and allows to offload larger payloads without any loss of control [16]. On the other hand, for missions where station keeping takes most of the time, they will require a constant action of the propulsion system to keep some aerodynamic speed, making them less efficient.

3.2 Structures and Materials

3.2.1 Structures

Given that aerodynamic and aerostatic forces are directly proportional to air density, the usual size of an stratospheric aircraft has to be about 14 times larger (§2.2) to lift the same weight as a conventional one flying at sea level. And this is true provided that the size change does not increase the total mass [27]. For an airplane, the wing load results very low while the available weight per unit area for the structure is forced to be much lower. In other words, same loading with much lighter materials. And the same reasoning applies to airships, the volume of which must grow to compensate the lack of atmospheric air density. This is the main rationale why sizes and shapes need to be highly optimised for stratospheric conditions, without forgetting that a tortuous tropospheric path is unavoidable before reaching cruise level. Airplane and airship configurations and structural issues for stratospheric flight are discussed next.

Airships are made of two different types of balloons using "balloon-within-a-balloon concept", Figure 8 [150]. Typically, the external hull contains the lifting gas and the internal (so-called ballonet) contains atmospheric air as desired in order to ascend or descend; the contrary is also possible, having an internal gas-bag surrounded by air within the hull. The second option allows membranes to meet the strength and non-permeability requirements independently [78].

Conventional airships can be classified in three main groups from their structural point of view: non-rigid, rigid and semi-rigid airships.

The hull of non-rigid airships, normally equipped with ballonets (§3.1.2), not only has to provide structural strength for the system but also has to be the barrier between the outside air and the lifting gas. These two requirements are critical for hull materials as the altitude increases, as will be discussed in §3.2.2. Airship hulls are made of outstandingly high strength-to-weight ratio membranes. Rigid airships have an inner metal framework to support hull or gas-bag loading [78]. Typically, this framework consists of transverse girders forming approximately circular frames and longitudinal girders running through the length. Rigid airships size must be large enough to justify rigid frame. Last, semi-rigid airships have a rigid keel from nose to tail along the bottom surface to release membranes around stress concentration areas, being an intermediate structural solution between the former ones. This combination of keel and envelope has a better loading resistance than non-rigid hulls, but keel and envelope interaction has to be carefully designed because loading distribution is crucial in such an interface. Additionally, there are some hybrid configurations that include wing-based structures over the outer membrane, but they are nowadays still unusual.

On the other hand, stratospheric airplanes provide cruise capability thanks to a very light wing loading. Specifications of Zephyr-S [149] and Helios [98] are provided for comparison to other conventional airplanes in Table 3. The most important parameters are the wing aspect ratio and the wing loading. For stratospheric airplanes, the first one is about 3-4 times higher than typical commercial airplanes. Interestingly, the wing loading is two orders of magnitude lower. Therefore, the airframe structure has to be span loaded or weight-distributed along the wing [109]. This means that the wing may be too large to even support its own weight from a single anchor point in fuselage; this forces the use of ingenious multiple fuselage configurations and entails very delicate ground operations.

The typical configuration of these aircraft wings includes the main spar, wing ribs, skin and solar panels. This structure configuration must fulfil some characteristics like large scale, high flexibility and large aspect ratio, which results in huge deflections that may reach at tip approximately 25% of the wing semi-span [154]. Traditional linear aeroelastic theory does not model wing structure deformations properly, so more complex non-linear approaches need to be used. Helios crash in 2007 [102] is an example of structure failure. The aircraft encountered a turbulence disturbance, resulting in a high unexpected dihedral configuration. This caused a divergent pitch mode in which the design airspeed was exceeded, so the failure of the wing leading edge occurred.

3.2.2 Materials

The structural design for aerostatic and aerodynamic flight in stratosphere forces the use of the latest advances in material technology. In particular, the fabric for membranes and the fibres for light wings are critical for the successful operation of HAPS.

- Membranes

Hulls or structural strength membranes are a significant portion of the total weight of the aerostatic platforms, normally several hundred kilograms. This component must accomplish the desired characteristics of low gas permeability, high environmental resistance (UV and other radiation, ozone, temperature, etc.), high strength-to-weight ratio, fair thermal control (solar absorptivity and infrared emissivity) and excellent tear resistance. Thus, a typical hull material consists of several flexible layers specialised in environmental protection, gas retention, adherence and strength [150]. The most common hull material layer is woven fabric, either single or multilayer, but non-woven technical fabrics for aerospace applications have also been developed recently, increasing their load capabilities (Figure 9 and Table 2).

This new technique has enabled the use of composites in membranes instead of the classical textile materials, like liquid crystal polymer (Vectran), UHMWPE (Ultra High Molecular Weight Polyethylene), Zylon, Kevlar, Twaron, carbon, glass, nylon and polyester used as core fibres coated with polyamides and polyimides. These surface materials used for coating add customizable properties like low gas permeability, low temperature operating capability and radiation protection as an example [88]. Additionally, the use of laminated composite fabrics enables the introduction of internal structures, increasing the structural reinforcements and reducing weight.

Finally, joints have also improved thanks to the use of non-woven laminates. The bonding and seaming of flexible materials could be a limiting factor in these old textile structures. Thanks to their homogenous distribution of fibres, the flexible composite laminates can be bonded with seams that are actually stronger than the base material, being capable of assuming higher loads. There are several seaming techniques like sewing, adhesive bonding, heat welding, ultrasonic welding and laser enhanced bonding [88].

- Wing materials

According to the typical configuration explained above, wing materials needs to overcome loading requirements with low density materials. In the lightweight wing category, the most common materials are composites with high strength fibres, such as carbon, epoxy or Kevlar. The main beam usually has a honeycomb structure between two carbon fibre foils or a tubular spar made of carbon fibre and epoxy resin. Wing ribs are usually made of carbon fibre/epoxy and are optimised to minimize mass while preserving high strength. And finally, wing airfoil shape is provided by a thin high-tech cling film [87].

As a particular example Helios wing structural components were a tubular carbon fibre main beam, wrapped with Nomex and Kevlar to provide additional strength, and several epoxy and carbon fibre wing ribs. The wing leading edge consisted of a rigid shaped foam called Styrofoam. Finally, the wing coating is a plastic and transparent film skin to fulfil the wing airfoil [102].

3.3 Propulsion

Traditional aviation fuel is not an option for long endurance HAPS. Although the viability of some other less common alternatives has been studied [31,146], solar energy is currently the most appropriate choice to feed the propulsions system, somehow supported by batteries or fuel cells. This means that propulsion is based on one or several electric motors with their respective propellers.

When dealing with stratospheric propellers, structural considerations are similar to the ones concerning wings. As air pressure (p) is about 1/19 and blade tip Mach number (M_t) has to be somewhat lower than 1 to avoid transonic effects, the desired thrust needs to be obtained with multiple and large propellers. The product pM_t^2S, where S is the blade surface, should be similar to provide similar thrust. Typical cruise speeds in stratosphere are around 20 m/s. In this configuration, blade tip Reynolds numbers are typically below 10^6. Thereby, propeller aerodynamic problem is a low-Reynolds one, where traditional propeller design may suffer high efficiency losses [19]. Although some research work related to stratospheric propeller optimisation exists [92], there is not enough experimental data for its validation.

The large size of blades makes rotational speed be lower than usual, which may lead to a lower overall engine performance that has not been deeply studied yet.

With respect to the powerplants, brushes of conventional electric motor arcs wear out rapidly at high altitudes, so brushless DC motors made of rare-earth permanent magnets are preferred. They are lightweight and highly efficient (more than 90%), but quite sensible to overheating so its refrigeration may be an important issue, as treated later in this article.

The current state of HAPS propulsion system configurations is summarised in Table 4. Propulsion power per unit of weight is around unity for airships while this value is somewhat higher for airplanes. Gabrielli and von Kármán [42] define a specific power per unit of weight and maximum speed for all type of vehicle propulsion power comparison. Not all the maximum speeds of theses platforms are available but it is known that airplane maximum speeds are higher than airship maximum speeds. Therefore, propulsion power requirements are closer between these two types of platform when the maximum speed is also considered.

These common configurations of electric motors plus propeller are separated from the main fuselage or body, and sometimes they are installed in specific nacelles. Additionally, there exists an integrated propulsion system known as the Goldschmied propulsor [108] that has not been implemented in any airship yet. This concept consists of an embedded propulsion unit in the rear part of the body that uses the airship boundary layer to generate thrust. Theoretically, as the boundary layer is ingested inside the body it cannot be detached, allowing non-conventional shapes and reducing drag (50% according to Goldschmied's original work). Most recent research around this concept [111][117] has shown that the benefits are not as high as expected. Nevertheless, it also states that more research is needed, determining the conditions that are conductive to efficient operation.

Airships may also need thrust vectorization. This can be done in several ways: by unbalancing individual propellers when various are available, by controlling the cyclic propeller pitch like in helicopters, and by rotating the whole propulsion plant and nacelle.

3.4 On board energy management

3.4.1 Energy harvesting

The long operational time of HAPS can be only maintained by means of energy harvesting techniques. As pointed out in §3.3, electric propulsion is nowadays the preferred option for HAPS.

As already mentioned, at the operational altitude of HAPS the solar irradiance is high and unaffected by clouds. Taking advantage of the former fact together with the large surface of its wings/envelopes, solar power is the most popular energy source in these vehicles. Other alternative methods such as reception of remotely beamed energy have also been considered, both through microwaves or laser beams. However, they are not currently applied due to the high power irradiation risks [51].

There are many studies on different methods to collect solar energy. As examples of these numerous alternatives, we can find photovoltaic flat panels, thin film photovoltaic panels, solar dish concentrators, luminescent solar concentrators and advanced thermo-electric conversion systems [63][20]. The first one is the oldest and most elaborated solution, and hence the baseline for most of the aerospace designs. It includes crystalline silicon, monocrystalline or multicrystaline silicon and multijunction solar cells, the latest showing the highest efficiency among all. However, the thin film photovoltaic panels are more broadly used for HAPS mainly due to the fact that they are flexible enough to be mounted in curved surfaces. This results in a low contribution to aerodynamic drag that overcomes the disadvantages of its larger weights (almost double) and lower efficiencies compared with the conventional ones [154]. With a lower technological maturity level, the luminescent solar concentrators have obtained promising results, opening the door to its use in future projects [81].

The power produced by solar panels directly depends on the irradiance, the Sun aspect ratio, the array size and its efficiency. Thus, the available power is a function of on-design parameters such as the panel size and its technology and other off-design mission dependant parameters such as the flight latitude, date and the operational conditions of the panel (e.g. temperature, degradation, shadows, etc.). In Figure 4, the impact of the latitude and date on the daylight time is shown. During this time the system has to harvest and store all the energy for the full day, including night.

The efficiencies have been significantly increased in the last years and that is one of the reasons why the HAPS projects are now more plausible. From 1975 up to 2015, the efficiencies had almost duplicated [154]. For the sake of illustration of the evolution and future trends, the best research-cell efficiencies achieved today are (Figure 10): 20.8% in Si multicrystaline, 29.8% in single-junction GaAs cells, nearly 40% for multijuncion cells of InGaP/GaAs/InGaAs and 21% for thin-film technologies [52].

The temperature effect on solar cell efficiency should be always considered. The simulation results reported by [55] indicates that the PV-panel temperature can reach about 370 K at noon due to its high solar absorptivity. Considering that the solar cell efficiency is typically referred to 298 K, the performance differences are notorious without the correct thermal control. The cells efficiency decreases approximately 3% for a 50 K increase in temperature [22]. This efficiency is affected also by unavoidable degradation throughout its mission time due to different facts such as radiation damages, assembly defects, thermal cycling, outgassing and atomic oxygen exposure. Degradation tests in stratospheric conditions should be carried out to determine each of these effects.

Recently, methods for optimising the solar panel layout of the HAPS [84] and the use of steerable solar panels [83] have been studied as alternatives to maximize the output energy per day.

3.4.2 Energy storage

A key feature of HAPS is their capability to achieve a continuous flight during more than one day. Due to the absence of solar energy during part of the day, a notable energy storage capability will be required in order to keep the platform flying for several hours (depending on the season and latitude). The specific energy (gravimetric energy and volumetric energy densities) and peak power density are the main determinants in the consideration of the most suitable energy storage system [1]. The use of higher energy density systems makes it possible to reduce the total weight required for the storage of the energy needed for night operation, while peak power is needed for high torque and acceleration. Although the number of existing technologies for energy storage is quite large and includes some “exotic” options like flywheels or supercapacitors [54], only two of them are technologically feasible to be considered on current developments: batteries and regenerative fuel-cells, which have been selected for platforms like the Airbus Zephyr 8 and Thales Stratobus respectively.

Rechargeable or secondary batteries store electricity in the form of chemical energy and produce electricity through an electrochemical reaction process. Electrodes and electrolytes within the battery can be made from different materials, then they will exhibit different properties. The most common technologies are: lead-acid (LA), nickel-based (Ni-Fe, Ni-Zn, Ni-Cd, Ni-MH, Ni-H_2), zinc-halogen-based (Zn-Cl_2, Zn-Br_2), metal-air-based (Fe-Air, Al-Air, Zn-Air), sodium-beta (Na-S, Na-$NiCl_2$), high-temperature lithium (Li-Al-FeS, Li-Al-FeS_2), and ambient temperature lithium [lithium-polymer (Li-poly), lithium-ion (Li-ion)] [54].

Thanks to the development experienced by portable consumer electronics and the automotive industry during the last decade, Nickel based batteries have been progressively displaced by the more capable lithium-based ones (mainly Li-poly and Li-ion but also the modern Li-Sulphur). They offer high energy density, high specific energy and power and light weight; furthermore, lithium batteries have no memory effect and no harmful effects unlike mercury or lead. On the other hand, they are costlier than other technologies, need protection for safe operation and thermal runaway (*e.g.* B787 battery fire [99]) and a cell balancing system to ensure consistent battery performance at the same voltage and charge level [128]. A brief review of the capabilities of different battery technologies can be found in Table 5.

Regenerative fuel cells are efficient power sources offering much higher energy densities and energy efficiencies than any other current rechargeable system. A fuel cell is an 'electrochemical' device that transforms the chemical energy of a fuel (hydrogen, methanol, etc.) and an oxidant (air or pure oxygen) in the presence of a catalyst into water, heat and electricity [106]. Storage tanks should be provided for fuel and oxidant (the use of hydrogen and oxygen gases respectively is necessary to achieve a reasonable power density in fuel-cell system [43]) as well as for the products resulting from the combustion (water). Under the regenerative concept, energy in excess generated from the solar cells during the day is used to disassociate water molecules into oxygen and hydrogen gases, which are stored and made available to be used again in the fuel cell to generate electricity and water during night.

There are several types of fuel cells under development, each having advantages and limitations, an exhaustive review, including cost analysis, can be found in [118]. The two most promising fuel cell types for aviation are the proton exchange membrane fuel cell (PEMFC) and the solid oxide fuel cell (SOFC). While PEMFCs offer high power density, fast start-up time, high efficiency, low operating temperature, and easy and safe handling, when several cells are placed together they produce a significant amount of heat that is difficult to dissipate resulting in the need for liquid cooling to the higher potential specific power [1,118]. On the other hand, SOFC operates at much higher temperature, however significantly more airflow moves through the stack which provides heat removal, eliminating the need and corresponding weight of a liquid cooling system [1].

Helios prototype airplane from NASA became the first solar-powered airplane that used fuel cells and the currently under development Stratobus HAPS airship (Thales) is also intended to use regenerative fuel cells. Fuel cell performances have also been included in Table 5 for comparison to other energy storage technologies.

3.5 Thermal control

One of the main thermal characteristics of the stratosphere is the predominance of radiative processes over the convective ones [148]. As consequence of the air density, the convection at 20 km is reduced by 2/3 of its value at 2 km. Therefore the temperature difference between the day and the night, depending on the radiative properties of the material, can reach values higher than 120 K [147]. Night temperatures as low as -80 ºC has been considered for different designs as a real possibility [123] and typically they reach values of -50 ºC [71].

For airship, two phenomena are important, superheat and supercool, and both increase with altitude. During day time, the solar radiation together with the weak convective heat loss cause the denominated superheat, the gas inside the hull has higher temperatures than the outside air (reaching up to 30 K of difference [145]). On the other hand, the long wave radiation emission of the airship hull can cause supercool during the night, in which the inside gas reaches a lower temperature than the outside one. The supercool presents less magnitude than the superhot reaching values as much as 5 K [145]. Due to the difference of the external heat fluxes at the airship surface, there is a significant temperature difference between the lower and upper envelope.

The temperature at noon is determined mainly due to solar radiation [145]. Regarding the heat balance, direct solar radiation term contributes as much as 80%, proving the vital importance that the correct modelling of its effects has in the design phase. Other radiative terms as albedo, diffuse or longwave radiation also contribute and their effects are predominant during the night. Moreover, the convection is still an important heat transfer mechanism and has to be considered for ambient pressures as low as 14 Pa [59] being more important in the case of airplanes.

It is desirable to reduce to a minimum the difference between night/day temperatures. In airships. low absorptivity paints/materials are best fitted for hulls. On the other hand, The increase of infrared emissivity will also reduce the day-night difference [29]. Thus, low absorptivity and low ratio of absorptivity to emissivity are the main goals. However, the solar panels present high solar absorption, that together with low efficiency may cause heating problems around. Different methods have been studied so as to reduce the effect of the heat generated by the solar panels. The consideration of MLI provides good results as simulated and tested in [66]. Other methods such as thermal insulation coatings, materials and heat sinks are described in [89].

The propulsion system also requires to be thermally controlled. Indeed, this has been the focus of recent investigations considering brushless motors [69]. They try to optimise heat evacuation, which implies a better overall performance. Stratosphere temperatures may lead to think, a priori, that the refrigeration process is done in a more efficient manner. Nevertheless, it is quite the opposite. Convective heat flux q is calculated as $q = h(T_{sur} - T_f)$, where h,T_{sur} and T_f are the convective heat transfer coefficient, the surface temperature and the fluid temperature. h is proportional to the non-dimensional Nusselt number (*Nu*), which is a relationship between convective and conductive heat transfers. *Nu* is usually determined using experimental correlations based on Reynolds (*Re*) and Prandlt numbers (*Pr*) according to $Nu = aRe^{b}Pr^{c}$ [145], where a, b and c are different constant values depending on surface geometry. *Pr* does not vary too much with height but *Re* is a function of the varying kinematic viscosity. Figure 11 shows the variation of the convective heat flux ratio for a flat plate and a sphere, q/q_0, where q_0 is the sea level heat flux. This analysis proves that refrigeration is poorer in stratospheric conditions.

The similarity between space thermal conditions with those in the stratosphere seems to advise the realization of the test and design in a similar way. Following the ECSS [37], thermal test in low pressure conditions should be carried out for electronic, electrical and RF equipment, antennas, battery, motor, thermal and optical equipment and solar arrays with special attention to the number of cycles and thermal conditions depending on the mission profile. The lubrication in partial vacuum is complex; gear boxes and brushes of conventional motors wear rapidly and the use of direct drive brushless motors is usually preferred.

3.6 Flight management

3.6.1 Flight dynamics

As in the case of other flight vehicles, the control of HAPS relies heavily on a proper modelling of their flight dynamics. This field has many ramifications and an intrinsic complexity that is neatly appreciated in the block diagram (Figure 12) drawn by Etkin [114] almost sixty years ago.

A first step in understanding the intricate time evolution of aircraft is achieved by splitting up its motion into two groups: one concerned with trajectory or performance analysis and the other with stability and control analysis [114]. In the first case the vehicle is regarded as a point, in general with a time varying mass, whereas in the second the interest is focused on its attitude relative to some coordinate system. Of course, this separation is an approximation that is only justified as far as the coupling between the translational and rotational dynamics is weak, which is the case for conventional vehicle configurations. If not, it is necessary to work out simultaneously all the dynamics of the vehicle.

Point mass models are useful to investigate the local and global properties of the flight path, that is to say, the point and integral performances [90]. They allow us to determine the control values to obtain optimum flight conditions, for example, defining the navigation law to obtain the maximum endurance†. This approach has been extensively used in the investigation of

† The word control is used here in a global sense. It refers not only to governing the "movable" devices of the vehicle (conventional control) but it also includes the procedures to obtain the vehicle desired trajectory as a point (guidance and navigation).

airplane performances [103][80] and also for determining the optimal trajectories for stratospheric airships [73][121].

In contrast to 3-DOF (Degrees of freedom) former models, stability and control analysis considers the whole dynamics of the vehicle. In a first stage the body is assumed to be rigid, hence characterized by a 6-DOF system. Further enhancements over this situation allow the incorporation of deviations from rigidity like those due to internal rotatory parts, deformable constituents, fluid sloshing, etc.

The stability of the aircraft relative to a particular steady motion, typically a trimmed flight, is usually tackled by linearizing the original 6-DOF equations of motion with respect to that reference condition, i.e., by a small disturbance theory. In contrast to other problems of Analytical Mechanics, this task is not straightforward and leads to the introduction of the stability and control derivatives in order to compute the linearized expression of the aerodynamic forces and moments [114]. This approach is indeed a simplification of the non-linear original equations. In many circumstances, however, it has shown to be a formidable tool to understand the vehicle stability characteristics and to design its control systems both for airplanes [114][103] and airships [127][77].

Specifically, the linearized equations of motion for the vehicle attitude variables allow the modeling of the aircraft response under different circumstances (e.g., free, forced, etc.) and its closed-loop control systems (e.g., stability augmentation systems, autopilots, etc.). In many aircraft configurations these equations can be further decoupled giving rise to separated longitudinal and lateral-directional dynamics. Within this small disturbance model the characteristics of the free response (stick-fixed) is of paramount importance, since its eigenvalues give rise to the stability modes. In the case of the airplane these are phugoid and short-period modes (longitudinal), and roll-subsidence, spiral, and dutch-roll modes (lateral-directional) [103]. For airships they are urge, heave-pitch subsidence, and oscillatory pitch-incidence modes (longitudinal), and yaw subsidence, sideslip subsidence, and oscillatory roll pendulum modes (lateral-directional) [24].

One of the key roles of the stability modes rely on their connection with the handling qualities of the aircraft that, following [56], could be defined as "the characteristics of the dynamics behavior of the aircraft that allow precise control with low pilot workload". Whereas this aspect has been extensively studied in the case of airplanes [114][56], it has been seldom tackled for airships [48] nor some related topics like, for example, pilot-induced oscillations (PIOs).

To carry out the presented framework it is necessary to establish the particular 6-DOF equations of motion. They are derived in many references for airplanes [114][103] and are less extended, although known many years ago [133], in the case of the airships [75]. An exhaustive literature review of airship dynamics has been provided in [77]. the construction found in [25] and [24] is of particular interest, where the author runs similar methods to determine the equations of motion for an airplane and an airship.

Symbolically, the dynamics of the aircraft as a 6-DOF system can be described similarly as in, for example, [48] [126], providing the non-linear differential equations system

$$\mathbb{M}\begin{pmatrix} \dot{\boldsymbol{v}} \\ \dot{\boldsymbol{\omega}} \end{pmatrix} = \mathbb{f} + \mathbb{a} + \mathbb{s} + \mathbb{g} + \mathbb{b} + \mathbb{p} + \mathbb{c}, \quad (1)$$

which must be supplemented with other kinematical relationships and the proper initial conditions to determine the whole state vector of the vehicle. The vectors $\boldsymbol{v}$ and $\boldsymbol{\omega}$ are the linear and angular velocities of the body referred to a certain reference frame, in general non-inertial. The mass matrix, including the added mass and matrix of inertia, is denoted as $\mathbb{M}$. The right hand side of Eqs (1) contains the main different forces/torques exerted on the aircraft. From the left to the right: inertial, aerodynamic, atmospheric, gravitational, buoyant, propulsive, and control terms. In the construction of some of these forces/torques it is very important to distinguish between the aerodynamic velocity of the vehicle, i.e., with respect to the surrounding atmosphere, from the linear velocity $\boldsymbol{v}$.

Although Eqs. (1) are valid for airplane and airship platforms, there are remarked differences in the terms entering in them. For example, for conventional airplanes the added mass and matrix of inertia, and buoyancy terms can be safety neglected, whereas they are fundamental for airship dynamics [24]. In contrast, for these vehicles the lift, entering in the aerodynamic forces, plays a minor role. Nevertheless, let us point out that these two airframes can be viewed as representing extreme positions in the configuration of the flight vehicle, whereas other intermediate, or unconventional configurations are possible [68], like for example the hybrid airships [78], which combine the properties of heavier-than air vehicles (airplanes) and lighter-than-air-ones (airships). For these, all the terms in Eqs. (1) are generally relevant [3].

It may not be out of place to recall here that our model is for a 6-DOF system and has to be supplemented in many cases with additional internal degrees of freedom that are relevant in the dynamics of HAPs like, for example, the ballonet sloshing [77][139] for airships or the structural flexibility [77][3] for both kind of aircrafts.

3.6.2 Flight control

The control of the aircraft is achieved through different devices. The most popular is based on the generation of an incremental lift force on some lifting surface of the aircraft [35][101]. The classical control surfaces are the elevator (pitch control), the rudder (yaw control), and the ailerons (roll control). Depending on the particular design, however, some control surfaces cannot be implemented. For example, aerodynamic roll control is usually not considered for airships [24][77] and some airplanes like, for example, UAVs can combine two control surfaces into a single surface [86]. They work in the same manner both for airplanes and airships; although due to the differences in the operating velocities the control surfaces for airships have larger sizes in order to obtain enough control effectiveness.

These aerodynamic controls are useless when there is no relative velocity between the aircraft and the atmosphere. This situation is not possible for airplanes, but can happen for airships, because of their inherent advantage of hovering. In these circumstances the control is achieved by thrust vectoring and differential thrust control [24][18]. In a different context the same kind of thrust control has also been used in some airplanes, to provide yaw control like, for example, in NASA Helios prototype.

Other control mechanisms are exclusive of airships, since they are related with the control of the buoyancy force. Typical examples are the ballonets and the ballast [18][95]. Because there is usually more than one ballonet, their balance can control the pitch angle which in turn modifies the amount of lift generated by the airship. It enables flight with a non-neutral buoyancy condition when the airship moves. Even some researchers have proposed their use as a means of propelling the airship, i.e., a buoyancy-driven airship [144].

The control devices are actuated by a human pilot, automatic flight control system (AFCS), or a combination of both. Roughly speaking [35], automatic flight control aims at improving the inherent dynamics of the aircraft (stability augmentation) and piloting it accordingly to a specified flight program, e.g., following a pre-fixed trajectory (autopilot). The flight envelope of HAPs is usually larger than that of ordinary airplanes, since they have to evolve from the surface to the stratosphere, experiencing a great variety of atmospheric and wind conditions. Besides, the special characteristics of these vehicles make them operate close to their limits due to their flexible structures, light materials, daily energy balance necessary to feed payloads and propulsion system, etc.

Those stringent conditions are found both in airplanes and airships [70][151] and couple the flight dynamics with the elastic modes, the energy system, the wind conditions, etc. Hence, the complexities in the design of the AFCS for these aircrafts. In fact, as in other underactuated mechanical systems like rotorcraft unmanned aircraft systems (RUAS), some cases require to go beyond the linear control framework as is shown in Figure 13 [67].

There have been many investigations where some of these techniques have been implemented. For example, airship control laws design based on a PID (proportional-integral-derivative), a linear H_∞ optimal control law, and backstepping method are presented in [97][96][152]; and, for airplanes, some designs considering PIDs [32], adaptive control [14], and

LQR/LQG (linear-quadratic-regulator/linear-quadratic-Gaussian) [21] have also shown their suitability.

One of the key roles of those control laws in terms of enhancing the vehicle's performance is optimizing trajectories with wind conditions, for example, for station-keeping trajectories. These trajectories may also look for efficiency in the propulsion system in order to fit to the daily power balance. In this scenery the possible strategies are multiple and, depending on the considered type of HAP, they can run from a simple conceptual "sprint and drift" approach to a more elaborated methods like, for example, the use of open-loop trajectories of segment-wise steady flight, as shown in Figure 14.

3.7 Ground infrastructures

A major concern when considering airship operations is the availability of ground infrastructures. Moreover, in the case of extremely long, light and fragile fixed wing airplanes hangar requirements can also be constraining, although the vertical clearance minimum is not so demanding.

Stratospheric airships are estimated to measure 100-m long or more. If conventional shapes are used that means more than 40-m height. Provided that a 10/15% operational margin has to be considered, the hangar for aerostatic HAPS is also huge. However, there are several constructions worldwide that demonstrate the feasibility of such kinds of buildings. Most of them come from the airship golden age, either under restoration (e.g. the 60-m high Hangar One for USS Macon in USA, 1932) or re-cycled to serve new initiatives in civil aviation in the last part of 20th century (e.g. the 52-m high RAF Cardington in UK, 1915). New hangars have been more recently created to hold huge cargo projects (e.g. the 106-m high hangar for Cargolifter at Brand-Briesen Airfield in Germany, 1996, today an indoor resort area) [105].

Although very flexible due to their long endurance, stratospheric missions will require some kind of deployment to allow maintenance or emergency landings. A convenient option is to develop inflatable structures such as the ones used nowadays by several aircraft manufacturers [13]. These flexible hangars can be moved in a few weeks and do not need very demanding easements.

In the case of airships, bearing in mind the scarce availability of Helium, a purification mechanism is necessary during the maintenance campaigns (e.g. every yearly landing). The most popular techniques are absorption, cryogenics and membrane-based methods [137]. Although not the most rapid or efficient, membrane methods enable simple Helium purification circuits. The filtering is feasible when the source is not very contaminated, preventing membrane fouling; fortunately, that is the case of airship worn-out Helium. Some useful membrane technologies for Helium recovery are discussed in [125].

4 Design facts of airplane and airship HAPS

4.1 HAPS modelling

In order to develop simple budgets for mass and power that enable comparison between airships and airplanes in stratospheric flight, the many models found in literature [104][78][153] can be simplified in a common process as depicted in Figure 15. Those more complex models normally include optimization algorithms that trade-off parameters among the subsystems to maximize interesting figures of merit. However, the model in this paper is thought to maintain its validity in both airplane and airship designs and hence serve as preliminary inter-system comparison.

Starting with typical mission requirements for HAPS and the knowledge of atmospheric variables, the main inputs of the model are the mass and power consumption of the payload. From there, mass and shape of the full vehicle is estimated to allow aerodynamic and aerostatic force estimations. These forces can be directly related to the propulsion requirements and hence the dimensioning of motors and propellers is possible. The total energy balance is achieved by integrating the power requirements, both from payload, propulsion and other subsystems, along the whole solar day-night cycle. This results in a deduction of the solar panels and batteries or fuel cells on board.

However, an update phase is always necessary, provided that the mass of the vehicle is very much affected by energy storage and harvesting systems, and their size can only be calculated once all the forces, including the propulsive force, are known. Similarly, the propulsion power is very dependent on the mass and shape of the vehicle. Besides, the size of panels must match the room available in the airplane or airship, being the first the most sensitive to this restriction. In the process of Figure 15, the double-way dependence is solved with a feedback line that updates the total mass from the power and energy subsystem masses. In the analysis provided in this paper, solutions implemented through a basic Newton-Raphson method seldom posed convergence problems provided that initial estimations are always sufficiently close to the goal. When iterations diverge, flight is impossible as subsystem power is not enough the hold its own weight at the given velocity (too high or too heavy or both).

As intended, the proposed model is valid both for airplanes and airships. For the first, the wing loading is estimated as input in the airframe shape and size stage, so extra payload or subsystem mass involve larger wing surface. For the airships, the surface density of hull membrane plays the same role, this time as fixed input. Extra equipment mass implies more volume and hence hull mass. The wing aspect and hull fineness ratios are taken from similar systems and used to complete the size estimations. In both cases the enlarged size requires the repetition of aerodynamic, propulsion and power calculations to complete the loop, preparing following iterations. In order to ease the comparison, both airplanes and airships are supposed to be equipped with secondary batteries as power storage elements. The use of regenerative fuel cells may provide a certain advantage to airships as they can carry larger systems.

4.2 Airplane-airship off-design comparison

The reference points for model validations are the two largest European projects for airplane and airship HAPS: Airbus Zephyr-S and the Thales-Alenia Stratobus. For the different model blocks, the reference parameters used are the ones discussed in each of the sections of §3.

The airspeed is critical to assess the vehicle performance. When it is too low, airplanes require extraordinary lift coefficients or unaffordable lifting surfaces. When it is too high, drag compensation in airships may require too powerful propulsion plants. In summary, an exact station-keeping will only be possible with airplanes if winds are present and with airships if winds are calmed. In this last case airplanes can manoeuvre to hover certain position by circling at safe airspeed. There is no equivalent solution for airships when winds exceed their full-throttle airspeed. Having in mind the typical winds in stratosphere (§2.3) and to enable direct comparison between the two concepts, the airspeed references for airplanes (30 m/s) and airships (20 m/s) are kept different, matching the typical design points of those types of vehicles. The impact of flying out of the design point is shown in Figure 17. A mostly parabolic law covers the full range of velocities for airships whereas for airplanes this is a good approximation for quick airspeeds, where parasitic drag dominates. When airplanes try to fly slower that base velocity, required thrust is enormous and stall may occur.

The available solar power is also a key issue for mission planning. When in high latitudes, winter conditions reduce not only the daylight hours but also the solar incident angles and hence the energy income. In these case, the only option to provide station-keeping during night is to reduce the payload as per Figure 17, where the estimated payload of the two references Stratobus and Zephyr-S are shown for different latitudes (and hence illumination conditions as given in §2.4). Logically, the smaller margin of airplanes limits them from operation in latitudes as high as 45 deg in worst conditions.

4.3 Airplane-airship on-design comparison

In a very simplified approach, for a given payload, flight altitude and cruise speed, the development and operational costs are a direct function of the size of the vehicle. Solar panels, batteries, motors and propellers, materials and many other subsystems and ground support equipment are dependent on the vehicle size. In general, the larger the vehicle the more complex and expensive it is.

Figure 18 and above show the dependence of typical size parameters such as airplane wingspan and airship length with relevant mission requirements. First conclusion is that airplanes are much larger than airships for payloads above 100 kg or so. When payload mass decreases or flight altitude lowers airplanes are more competitive (always at reference airspeeds), although wingspans longer than 75-m have not been demonstrated to be feasible up to date. This reduces the payload capacity of airplanes to a few tenth of kilograms. For airships, 100-m length or more is required even to keep aloft with no payload.

An important deduction from Figure 19 is related to the slope of the curves. The benefit-to-cost ratio of increasing the size of the vehicles is about 7.5 kg per extra meter length at reference altitude, almost constant in the range of interest. For example, a 120-m airship increased as low as 6-m (5%) would carry 45-kg more payload (+30%). The opposite effect is visible for airplanes; every extra payload kilogram brings about a sensitive increase in vehicle size, up to unrealisable limits. The conclusion is that airship HAPS are much more scalable towards powerful payloads than airplanes. The effect of illumination conditions due to mission latitudes (Figure 17) can be compensated with aircraft size; as commented, airplanes encounter structural limits before airships.

The operational ceiling for airships is achieved in a smooth manner (Figure 19). Assuming no wind effects, the higher they fly the less payload capacity. However, that is not the case for airplanes, where the altitude limitation is given by the coupling of aerodynamic effects and propeller thrust; the payload mass is a small fraction of the airplane mass and hence it does not play an important role in this performance figure.

The technology analysis in §3 has evidenced how, while the structural and propulsion subsystems have had a gradual evolution over the last years, energy management has provided disruptive solutions that effectively contribute to HAPS feasibility. Figure 20 and Figure 21 show the dependency of vehicle size with the specific capacity of batteries and solar panel efficiency.

In the first case, airplanes are quite immune to changes in panel efficiencies from the current status. This is because thin-film panels are very light and, although less panel surface is necessary, wing surface cannot be reduced due to its lifting role. Only in cases where wing surface is driven by panel requirements the quality evolution could be important, but these cases are normally avoided by changing the reference cruise velocity.

Regarding the energy density of batteries, airplanes are greatly affected as a relevant percentage of the vehicle mass is due to the energy storage need. Even though, a 40-m wingspan airplane may increase 15% payload mass if battery energy density improves 10%, and according to history is not unrealistic to expect in an evolution period of about one year. The effect in airships is not as conspicuous in Figure 20, as lines are quite close to each other. However, the low slope of the curves makes the impact even larger than in the former case. For a given size, the 10% energy density increase is a saving in subsystem mass equal to about 13% of a 250-kg payload, or 20% of a 150-kg one.

5 Operational considerations

To make the commercial exploitation of any flight vehicle feasible there must be a regulatory framework supporting its activities. HAPS are not an exception.

Although this issue has many ramifications of technical, legal and economical nature, the conceptual scheme developed in [65] can provide some insight when considering the same problem for Large Hybrid Air Vehicles. In fact, it runs parallel to the difficulties raised by the

International Civil Aviation Organization (ICAO) when defining the fundamentals of the necessary rules for operating Unmanned Aircraft Systems (UAS or UAVs) in [135]. It can be summarized by adapting [65] and [135] to formulate the following three main questions:

- Operations: How will HAPs operate in the existing airspace environment?
- Aircraft and Systems: Where will this aircraft type fit into current certifications structure?
- Personnel: How will remote flight crews be trained and licensed?

Regrettably, at best, these questions have partial answers even for ordinary UAS. Indeed, many efforts have been made to regulate the use of UAS in such a way that their operation guarantees the same level of confidence as manned flight vehicles.

Many countries and states unions like the United States of America, the European Union, the United Kingdom, etc. have developed their own legislation considering different aspects like Registration and Labelling; Flight Authorization Information; Operator Qualifications, etc. A survey of the regulations adopted in thirteen countries and the European Union is given in [74]. One of the main concerns is how to integrate these vehicles into a non-segregated airspace, making their operations compatible with those of regular manned aircraft, i.e., from the perspective of ATM control. Those operations are not possible today and will require further developments and research as has been recognized, for example, in [23] by the European Aviation Safety Agency (EASA).

The situation relative to airworthiness from the point of view of the airframe is more favourable, since UAS and ordinary aircrafts share many of their commonalities [135]. That is not the case for airships, even the piloted ones. There have been a few regulations from FAA

(USA), CAA (UK), JAR (EU), etc., but with notorious differences as surveyed in [44] and [107]. A remarkable regulatory framework is the Transport Airship Requirements document [131], developed by Aviation Authorities Luftfahrt-Bundesamt of Germany and Rijksluchtvaartdienst of The Netherlands in 2000 and now depending on EASA. This document contains the most detailed set of airworthiness requirements for large airships as stated in [107] and has been employed in current FAA Airships-Regulations & Policies.

This scene becomes more cumbersome when taking into account that the operations are performed in the stratosphere. In this case there is very little practical experience about how to transpose our ordinary UAS and airship's regulatory knowledge to the particular conditions of that atmospheric layer. There are some documented cases [38], but much more real flight test data is required to establish ready to use stratospheric airworthiness requirements.

In addition to these technical difficulties we must also mention that there are unsolved legal problems. They are associated with the fact that HAPS missions are operating in the interface between airspace, subject to national ATM system and ICAO rules, and outer space, an area named in this context Protozone. It poses several drawbacks related with the sovereignty, access to space, threats and risks, etc. that must be analysed as was done by the Global Space Governance study commissioned by the 2014 Montreal Declaration in [46].

At any rate, as it has been the case for other technological developments, when HAPS had shown their maturity to operate offering advantageous commercial services, the regulatory framework will be adapted to make possible the development of this aerospace sector.

6 Conclusions

After several serious attempts worldwide in the last decades, high altitude pseudo-satellites (HAPS) are close to becoming operational. Aerodynamic versions will be first, following the wake of Airbus/Zephyr-S, cruising the stratosphere for long periods of time and carrying small instruments for precursor applications. Aerostatic counterparts will come afterwards, following the developments of Thales/Stratobus, with large payloads to provide unprecedented imagery or communications services.

The critical technologies such as flexible or extremely light structures have reached the appropriate level of maturity. In parallel, the improvement in solar panel efficiency and the reduction of the energy density of secondary batteries, enable to close the on board energy budget, which makes flight endurance only limited by the wearing of components. Regenerative fuel cells also present a promising evolution to be applied to flying vehicles, which even improves the mass and power availability on board. Efficient stratospheric propulsion poses problems due to the size of the propellers but motors and controllers are already mature. Thermal and environmental protections are already tested in long balloon missions.

However, there are still important challenges. Stratospheric airplanes must deal with aero-elastic effects in extremely high aspect ratio wings with very low loading. Their flight control intelligence must be prepared not only for the most efficient stratospheric flight but also for the turbulent and windy ascent and descent paths. This fact is currently limiting airplanes to payloads of few tenths of kilograms. On the other hand, airship developers face the problem of manufacturing and handling huge elements, which require immense infrastructures and non-negligible operational issues. Nevertheless, the operational services they can provide are numerous due to their payload mass and power availability, in the order of hundreds of kilograms and several kilowatts.

Meanwhile, regulators, space and aeronautic agencies, service providers, researchers and end users seem to be prepared for the definitive operational conquest of the stratosphere.

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Tables

Table 1: HAPS capabilities compared to terrestrial and satellite systems for telecommunications

Issue	High Altitude Platform
Deployment	Faster deployment than space-based platforms and requires less initial build-out than terrestrial networks to provide sufficient coverage for commercial service. Very fast response to emergency situations (occasional use).
Upgrading	Access to platform/payload after deployment enables service upgradability similar to terrestrial networks, enhancing flexibility and adaptability.
Link budget	Shorter distance to HAPS makes link budget much more benign when compared to satellite links. Moreover, smaller antenna coverage area allows high focus on areas of interest getting higher capacity density (x100) than GEO satellites.
Signal processing	Lack of Doppler shift due to the platform motion (HAPS are quasi-stationary)
Ground terminals	Use of current terrestrial terminals can be valid for services like Terrestrial Trunked Radio (TETRA) or mobile communications (LTE). Simpler and/or smaller terminals than those required for satellite links can be used for equivalent data rates.
Antenna pointing and directivity	Although high-throughput connections require antenna pointing and directional beam (like current GEO), TETRA and LTE services are based on omnidirectional links.
Latency	Very low, equivalent to terrestrial networks. Round-trip time ~0.26 ms versus ~30 ms for LEO and ~250 ms for GEO.
Geographical coverage	Hundreds of kilometres per platform (~200-km radius), between terrestrial (few kilometres) and space GEO (up to 33% of the Earth surface).

Table 2: Fibre properties comparison. Adapted from [88]

Fibre type	Density (g/cm^3)	Tensile Strength (GPa)	Specific strength ($GPa \cdot cm^3/g$)
Zylon	1.55	5.8	3.74
UHMWPE	0.97	3.4	3.51
Vectran	1.4	3.1	2.21

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Table 3: Zephyr-S and Helios physical specifications

Characteristics	Stratospheric		Conventional	
	Zephyr-S	Helios	DG-1000 Glyder	Boeing 737-900
Payload (kg)	5	330	160	~30000
Wingspan (m)	25	75	20	34
Mean wing chord (m)	1.12	2.44	0.9	3.57
Aspect ratio	22.3	31	22.8	9.5
Wing area (m^2)	28	183	17.5	125
Gross weight (kg)	65	930	750	84000
Wing load (kg/m^2)	2.32	5.08	43	675

Table 4: Propulsion system configuration

Platform	Electric power (kW)	Weight (kg)	Specific power (W/kg)
HiSentinel80	~1	~500	2
HALE-D	2	1360	1.47
Zephyr S	0.9	65	13.8
Cai Hong	2	400	5
Aquila	2	400	5
HELIOS	15	1300	11.53

Table 5: Major parameters of energy storage solutions for HAPS

	Gasoline Engine	Rechargeable batteries					Regenerative Fuel Cells	
		NiCd	Ni-MH	Li-Po	Li-Ion	Li-S	PEMFC	SOFC
Energy density (Wh/kg)	12800	40-60	30-80	130-200	160	250-350	300 - 2000	300 - 2000
Operating temperature (°C)	-50/60	-20/60	-20/60	-20/60	-40/60		50/100	700/1000
Efficiency‡ (%)	15-25	80	70	99.9	99.8	99.8	40-45	60
Life cycles	N/A	500	500-1000	>1000	1200	>100	N/A	N/A

‡ From energy input to electrical output

ON THE CAPABILITIES AND LIMITATIONS OF HIGH ALTITUDE PSEUDO-SATELLITES

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Figures

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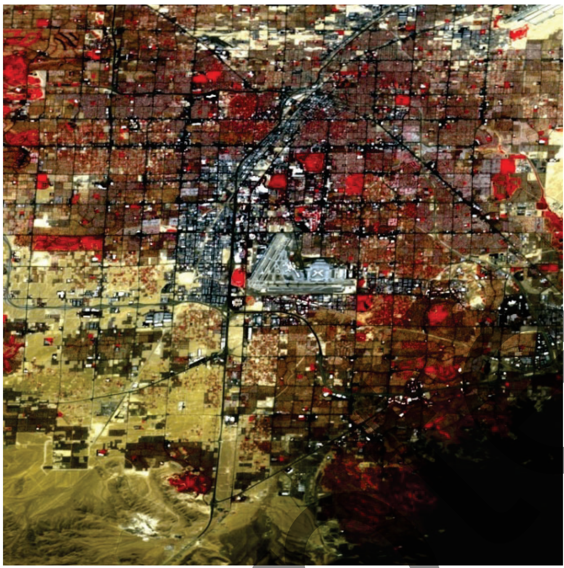

Figure 1: False colour image over Las Vegas taken from stratospheric ER-2 to test infrared space sensor HyspIRI [**Error! Reference source not found.**]. Red indicates well-irrigated vegetation.

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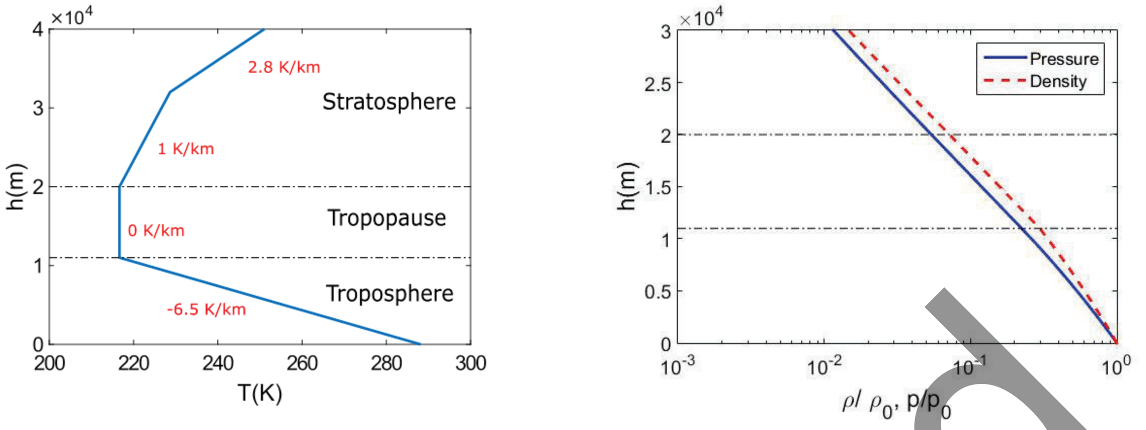

Figure 2: Temperature, density and pressure distribution following the ISA atmosphere [**Error! Reference source not found.**] in function of geopotential altitude (ρ_0 = 1.225 kg/m^3, p_0 =101325 Pa)

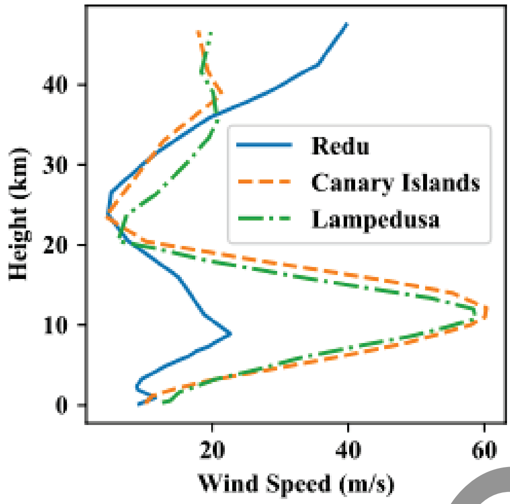

Figure 3 Typical winter height profile for Canary Islands/Spain (27˚N,15˚W), Lampedusa/Italy (35˚N, 12ºE), and Redu/Belgium (50˚N,5˚E)

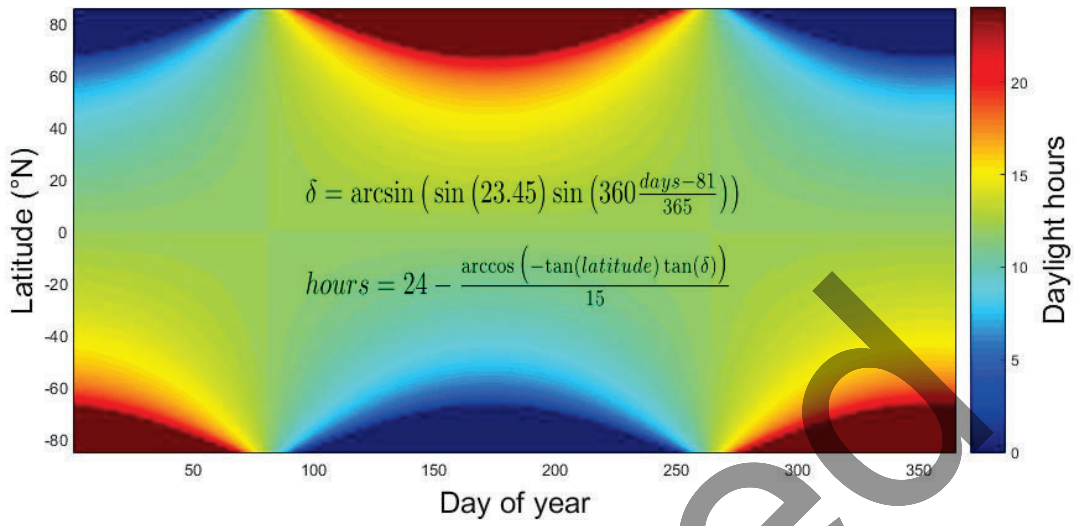

Figure 4: Day hours calculated using the Sunrise equation and simple geometry considerations

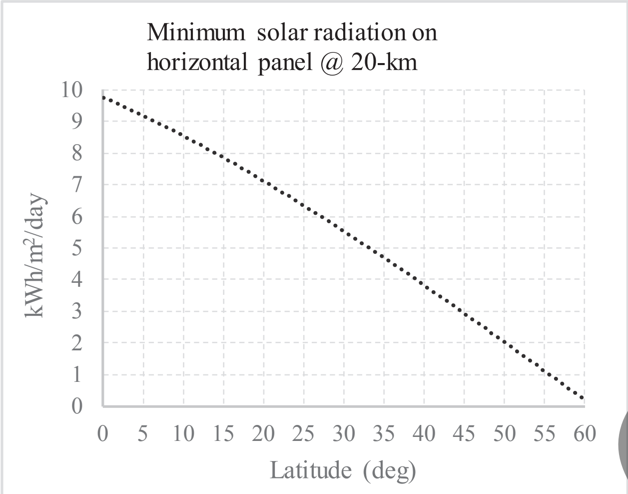

Figure 5: Dependence of minimum solar radiation on horizontal panels at 20-km altitude with latitude [**Error! Reference source not found.**]

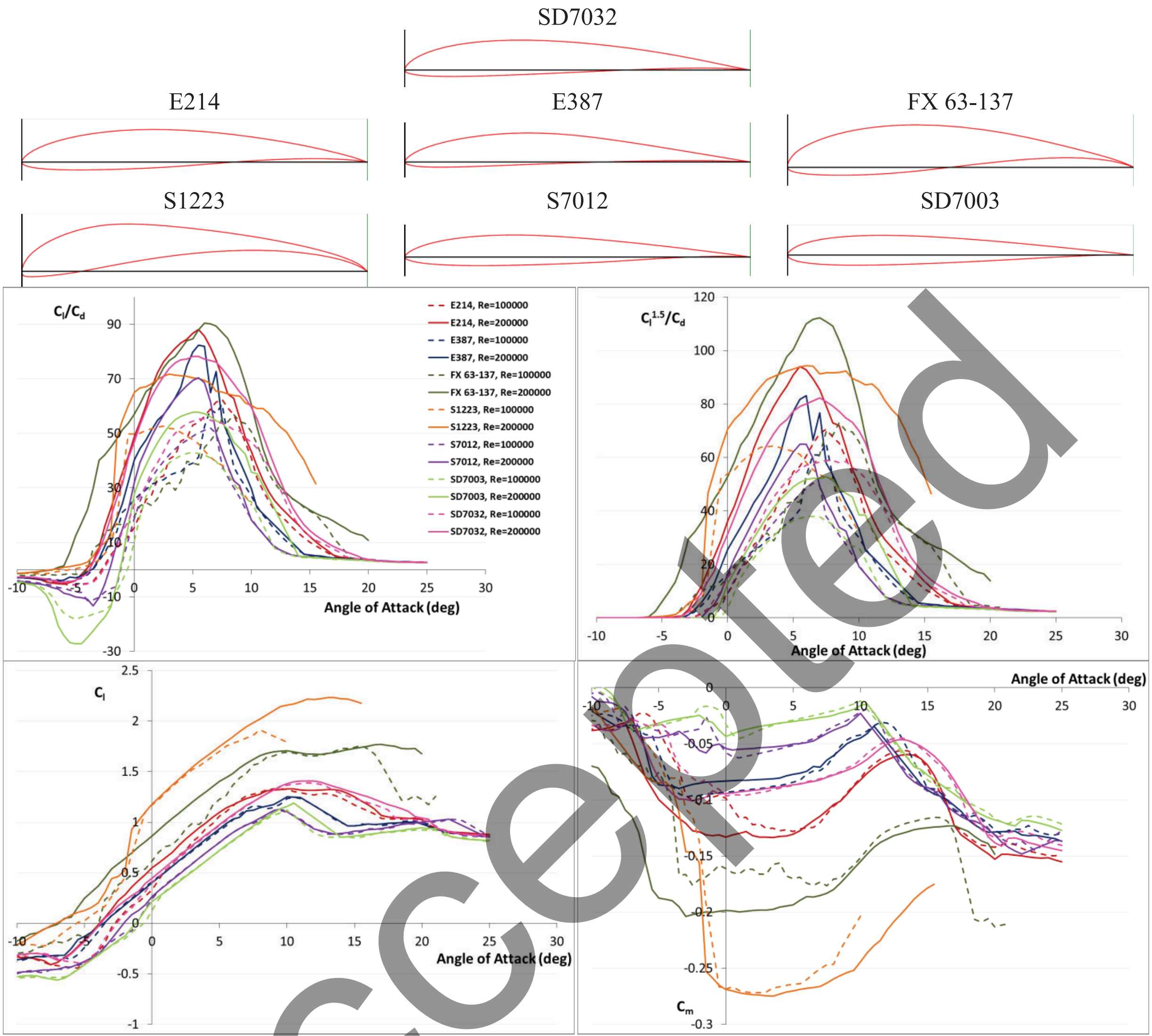

Figure 6: Shapes and aerodynamic characteristics of some popular low Reynolds airfoils (as calculated by XFLR5); from left to right, and top to bottom: aerodynamic efficiency, endurance, lift coefficient and moment coefficient

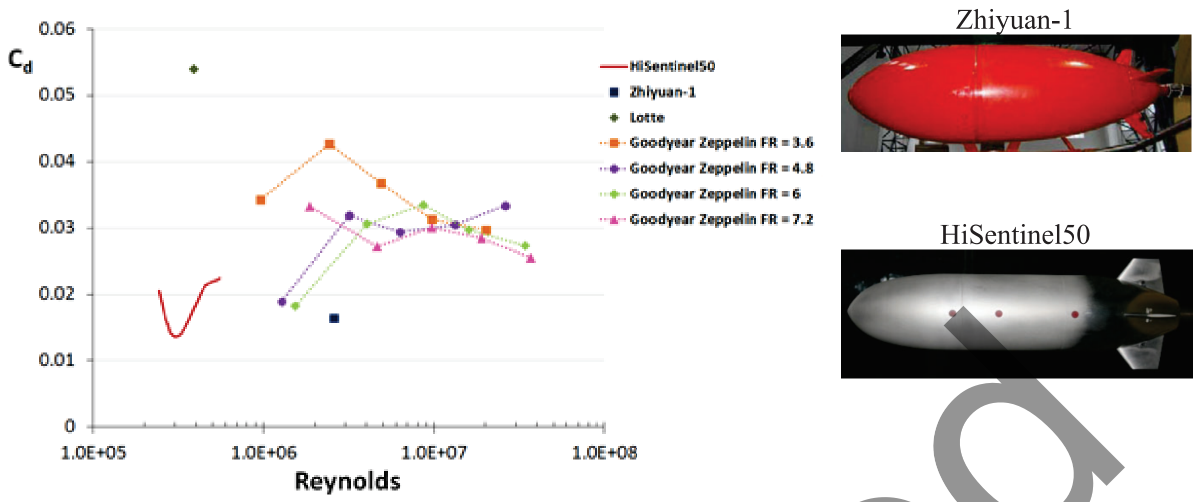

Figure 7: Experimental wind tunnel measurement of volumetric drag coefficients for different earlier airship designs (Goodyear Zeppelin of different finesses ratios [**Error! Reference source not found.Error! Reference source not found.**]) and some modern stratospheric ones: HiSentinel50 [**Error! Reference source not found.**], Zhiyuan-1 [**Error! Reference source not found.**] and Lotte [**Error! Reference source not found.**]. Models with hull and fins

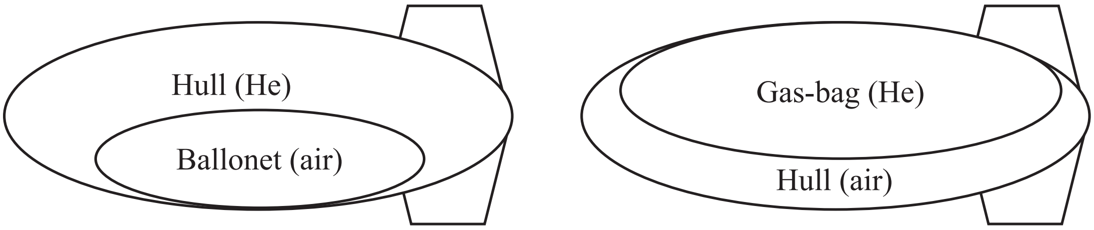

Figure 8: Balloon-within-a-balloon concepts

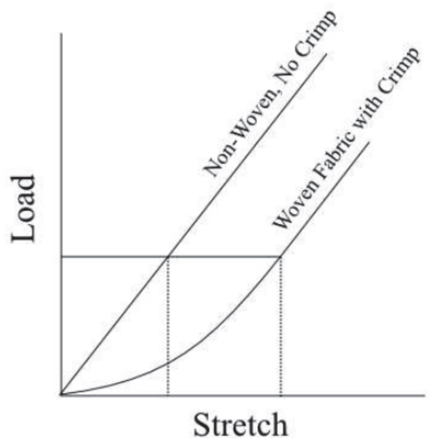

Figure 9: Comparative Load-Stretch of materials with and without crimp [**Error! Reference source not found.**]

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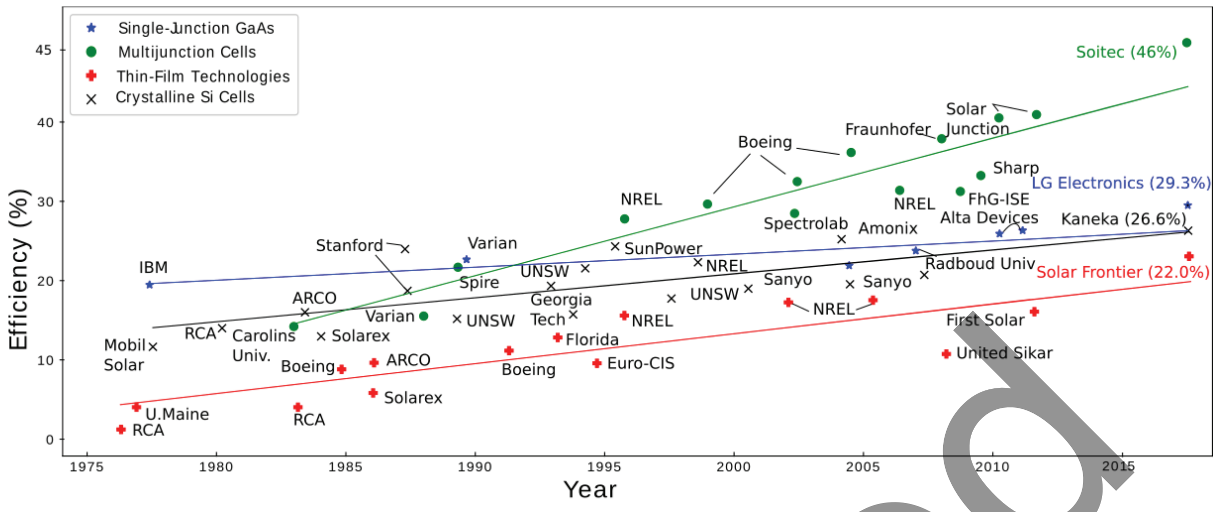

Figure 10 . The efficiency evolution of solar cells, updated from [**Error! Reference source not found.**]

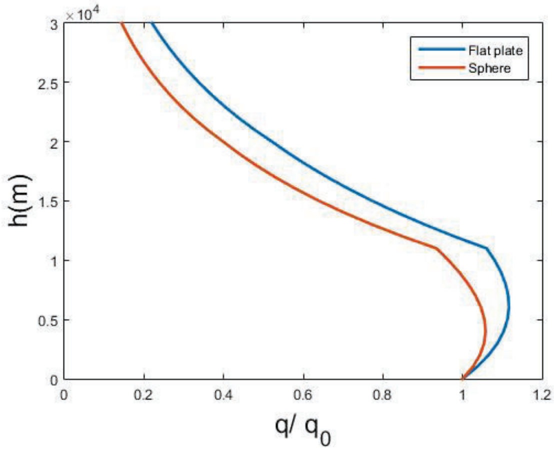

Figure 11: Heat flux ratio variation with height (parameters taken from [**Error! Reference source not found.**])

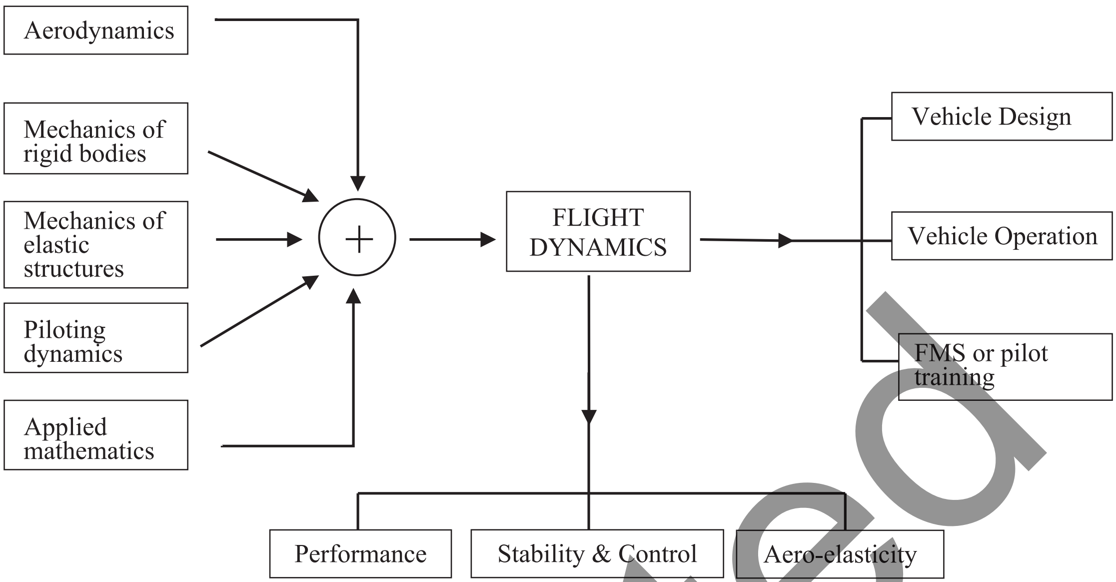

Figure 12: Flight Dynamics block structure after Etkin [**Error! Reference source not found.**]

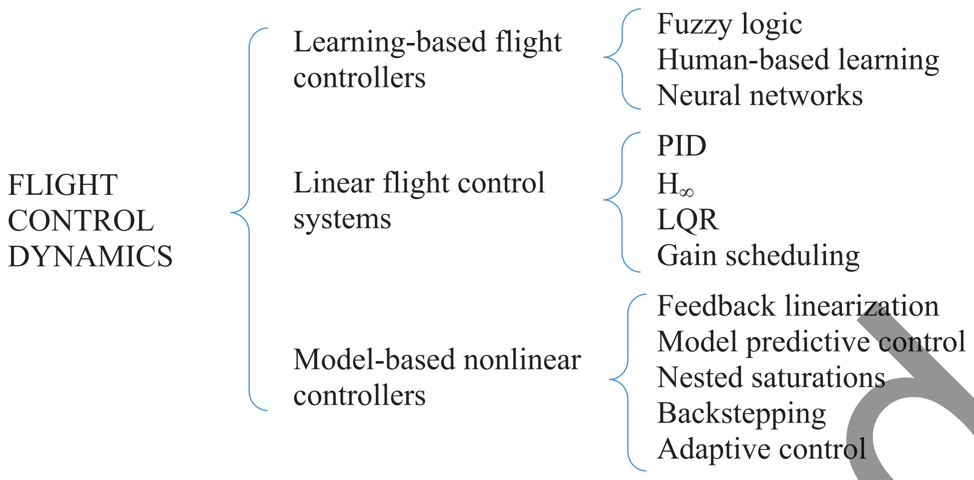

Figure 13: Flight control systems taxonomy after Kendoul [**Error! Reference source not found.**]

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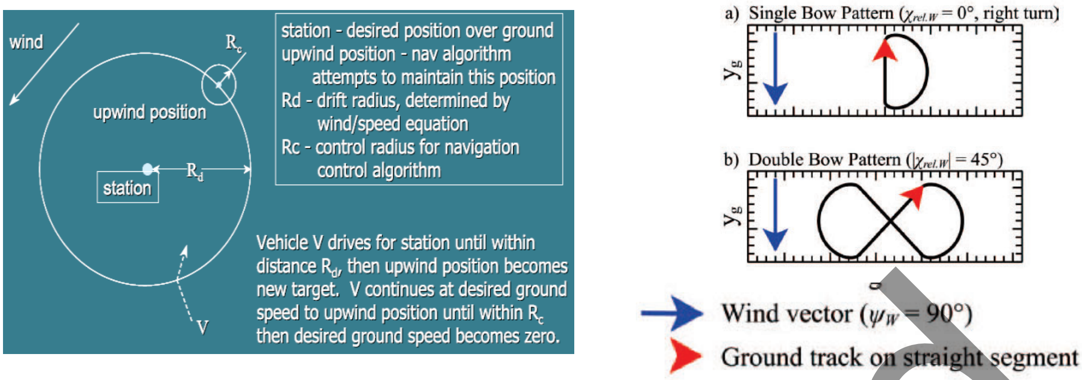

Figure 14: Some station-keeping trajectories strategies (left for airships [**Error! Reference source not found.**]; right for airplanes [**Error! Reference source not found.**])

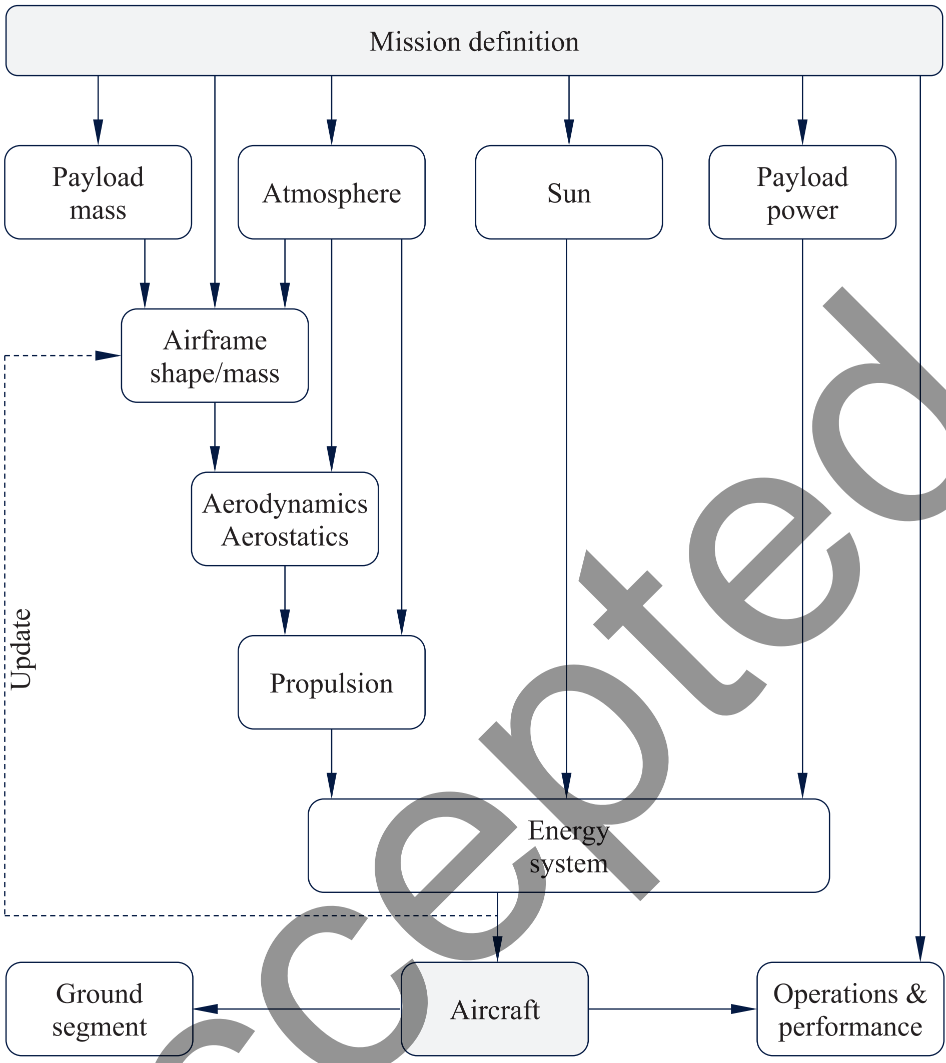

Figure 15: Dataflow for aircraft budget model

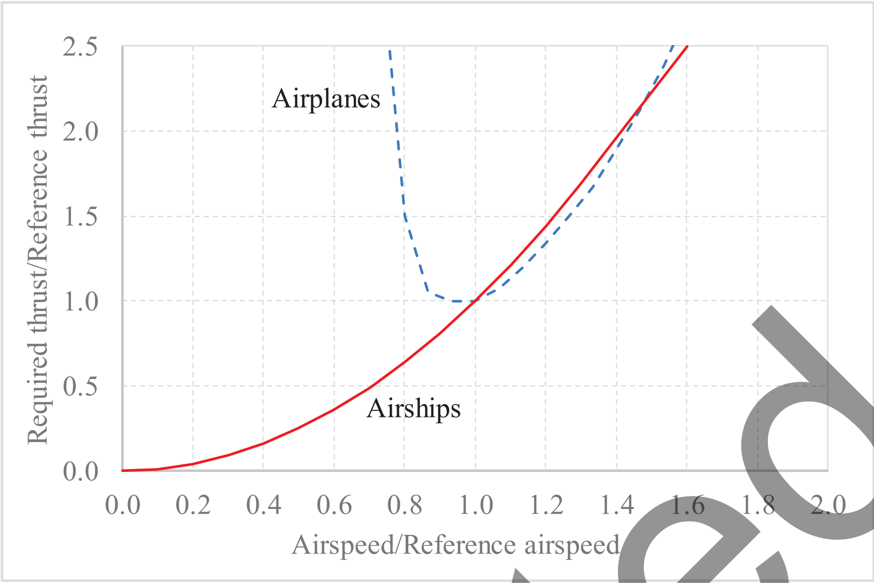

Figure 16: Off-design aircraft performance comparison for different cruise airspeeds (dashed line: airplanes; solid line: airships)

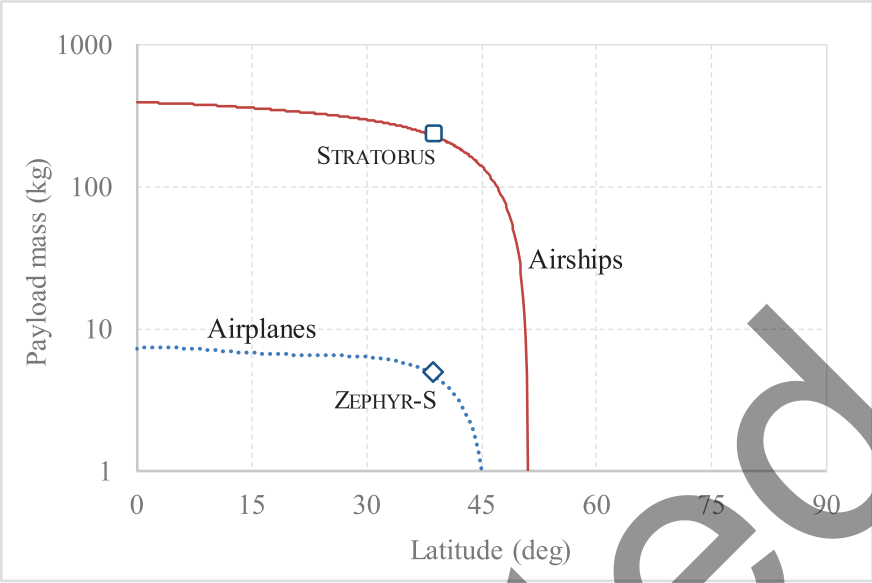

Figure 17: Off-design payload capacity for different flight latitudes (dashed line: airplanes; solid line: airships)

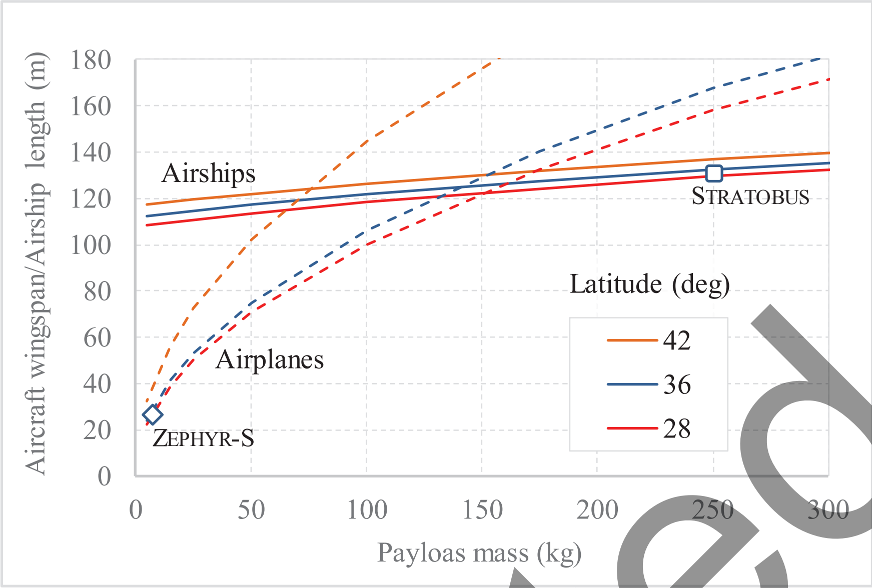

Figure 18: Aircraft size required for different operational latitudes (dashed lines: airplanes; solid lines: airships)

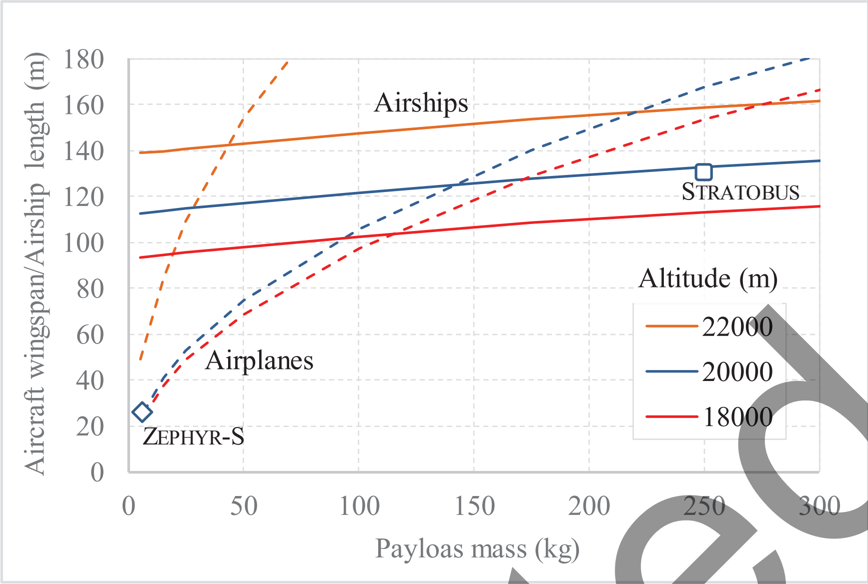

Figure 19: Aircraft size required for different payloads and flight levels (dashed lines: airplanes; solid lines: airships)

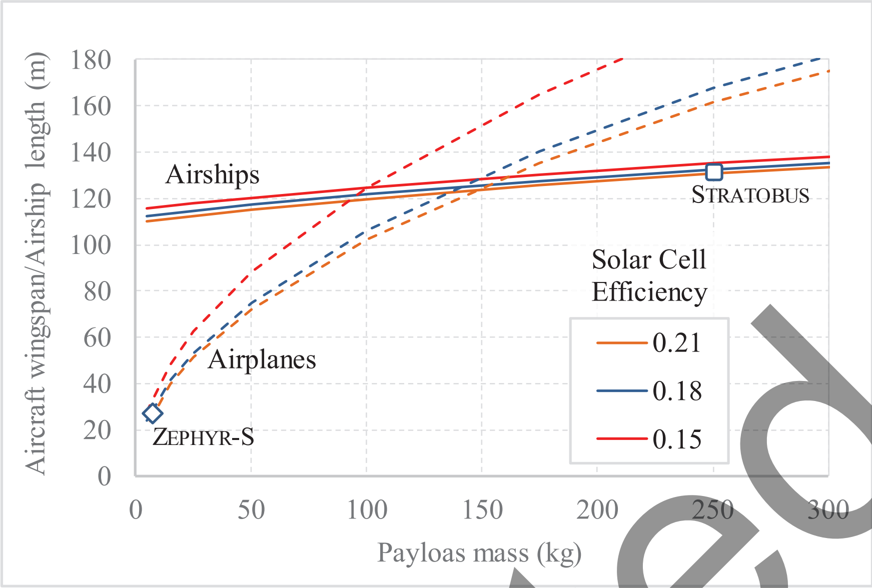

Figure 20: Aircraft size required for different solar cell technologies (dashed lines: airplanes; solid lines: airships)

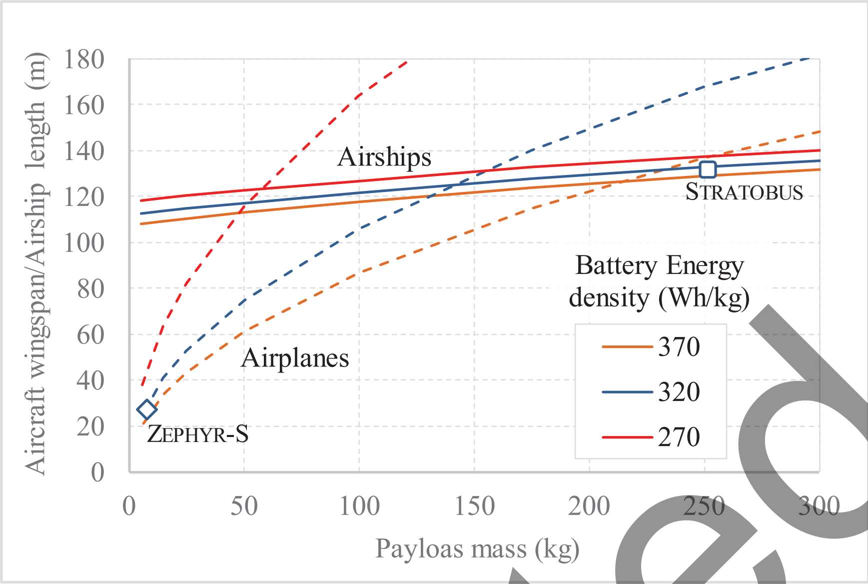

Figure 21: Aircraft size required for different battery energy densities (dashed lines: airplanes; solid lines: airships)