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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 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.

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 [8,110] and other initiatives worldwide [9,17,140].

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

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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 h whereas the SR71 Blackbird was able to reach up to 27 km at supersonic speeds but only for 1.5 h. 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