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On the challenge of a century lifespan satellite

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ABSTRACT

This paper provides a review of the main issues affecting satellite survivability, including a discussion on the technologies to mitigate the risks and to enhance system reliability. The feasibility of a 100-year lifespan space mission is taken as the guiding thread for the discussion. Such a mission, defined with a few preliminary requirements, could be used to deliver messages to our descendants regardless of the on-ground contingencies. After the analysis of the main threats for long endurance in space, including radiation, debris and micrometeoroids, atmospheric drag and thermal environment, the available solutions are investigated. A trade-off study analyses orbital profiles from the point of view of radiation, thermal stability and decay rate, providing best locations to maximize lifespan. Special attention is also paid to on-board power, in terms of energy harvesting and accumulation, highlighting the limitations of current assets, i.e. solar panels and batteries, and revealing possible future solutions. Furthermore, the review includes electronics, non-volatile memories and communication elements, which need extra hardening against radiation and thermal cycling if extra-long endurance is required. As a result of the analysis, a century-lifetime mission is depicted by putting together all the reviewed concepts. The satellite, equipped with reliability enhanced elements and system-level solutions such as smart hibernation policies, could provide limited but still useful performance after a 100-year flight.

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1. Introduction

Lifespan is a requirement of space missions with an obvious but complex impact on the cost and the revenue [55]. As hands-on maintenance of space systems is almost impossible, lifespan is driven by the reliability of the elements and their architectural integration to achieve the final objective. From a practical point of view, reliable systems are more expensive in terms of materials, components, manufacturing and testing, but provide more robust business models [54], lower insurance prices and more time to recover the investment.

The present paper reviews the feasibility drivers of a mission with an enhanced lifespan of 100 years. If successful, the satellite could be able to transport a data load into the future and deliver it to our descendants, regardless the existence of the companies or individuals that created the mission.

This extended lifespan poses stringent requirements on all the subsystems on-board and on ground [56]. However, since there are running proves working for the last four decades [30], Earth observation satellites like Landsat for 30 years [35,16], other exceeding many times their expected lifetime [68] and new communication satellites declaring nominal figures of around 20-year lifetime [11], the challenge seems to be achievable in the near future.

The review below is focused on the space segment, because the proposed long-lasting mission should be autonomous enough to survive without specific contact from ground. Conventional missions are built on a space–ground interaction scheme. The unique characteristic of the new concept is the fact that the ground segment built for the satellite is not essential for the success of the mission. Thus, during the first months/years, a ground facility can be used to monitor the satellite and to complete the data upload. However, at some point in time, the satellite must make its way on its own, in a deep hibernation flight, until the time of data download is reached. At that point, the satellite should be prepared to communicate to a generic ground segment, requiring a minimum level of hardware and protocol knowledge. These points also deserve an analysis from the endurance point of view. Thus, the study includes analysis and trade-off's of orbital profiles, radiation hardening, thermal protection, energy harvesting and accumulation, data storage and communications. All of these are combined with reliability enhanced mechanisms such as homogeneous and heterogeneous redundancy and system-level solutions such as smart hibernation policies.

The analysis of the available technologies and the proposed solutions permit the development of the first satellite concepts for this revolutionary achievement, which would push the terms lifespan and autonomy further than what is envisaged today.

Table 1
Reference budgets used along the paper for the discussion on lifespan extension.

	Trip stage	Hello stage	Duty stage	Total
Av. power (W)	2	1/30	10	
Bandwidth (kbps)	9.6	1.2	2048	
Operation time per contact (min)	10	1	10	
Contact frequency	4/year	1/h	3/day	
Stage duration	100 years	10 days	32 days	
Operation time (h)	67	2	25	117
Total energy (W h)	133	24	267	424

Although the economic issues are not within the scope of this work, all the decisions suggested during the concept definition look for affordable solutions, presently available or expected in the very near future. As a consequence of that, precursor satellites meeting the centennial lifespan could be launched in a few years from now.

The space environment strongly influences the performance and lifespan of any space system. This is a major issue for satellite developers, especially in this case where the expected operational lifespan is as long as 100 years. Vacuum, exposure to extreme temperatures, debris, meteoroids or radiation configure a very hostile environment threatening satellite survivability [38,64]. Thus, a good understanding of the space environment and its impact on individual elements or components on-board is needed in order to define the constraints and to choose the best technological solutions from the endurance point of view.

Electronics, communications and power system malfunctions are typical causes of mission termination [66]. With respect to the on-board digital storage and data processing, which are also prone to radiation effects [63], it is necessary to fix some top level requirements in order to focus the discussion on representative applications. In this paper, the target mission would be required to carry 24 GB of information and to be able to download those data in the last phase of the mission. Besides, in order to meet the lifespan requirement, a dedicated power management policy needs to be established. Thus, the satellite should be hibernating most of the time, with all but a small waking-up device disconnected. This will limit capabilities that are present in normal satellites such as battery charging, data processing, ground communications, attitude stabilization and others along most of the mission. The satellite would be able to wake up from time to time to check data integrity and, if required, to perform some data update. In this sense, the Rosetta comet-hunter mission [24,23] is a definitive proof of the technique to achieve long missions using hibernation periods. Finally, after the 100-year trip, the satellite should provide its full functionality during a limited time.

In order to allow some preliminary estimations on the system feasibility, some budgetary issues need to be taken into account. Thus, three operational stages could be considered, so-called Trip, Hello and Duty. The first stage is 100-year long, with quarterly short contacts with ground; the second is a period of maximum 1 month in which the satellite tries to catch the attention of a ground receiver using an emitting beacon; the third is the effective time during which the payload is downloaded, pass after pass, to one or more ground facilities. Taking into account typical power consumptions of conventional transmitters and the timing of the contacts, Table 1 provides reasonable power and communications budgets for all the stages of a reference mission. These figures will help with the discussion for the rest of the paper.

2. Analysis of lifespan killers

2.1. Upper atmosphere

Although the satellite environment can be considered as a vacuum for many applications, this is not the case when dealing with low Earth orbits, especially if lifetime is a concern. The atmosphere limit is not clearly defined but it is possible to find gas molecules, primarily oxygen in the range of 80–90 km to 500 km height, and hydrogen and helium beyond 500 km [42]. The interaction between these