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Novel mission concepts for polar coverage: An overview of recent developments and possible future applications ☆

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ABSTRACT

The paper provides a survey of novel mission concepts for continuous, hemispheric polar observation and direct-link polar telecommunications. It is well known that these services cannot be provided by traditional platforms: geostationary satellites do not cover high-latitude regions, while low- and medium-orbit Sun-synchronous spacecraft only cover a narrow swath of the Earth at each passage. Concepts that are proposed in the literature are described, including the pole-sitter concept (in which a spacecraft is stationary above the pole), spacecraft in artificial equilibrium points in the Sun–Earth system and non-Keplerian polar Molniya orbits. Additionally, novel displaced eight-shaped orbits at Lagrangian points are presented. For many of these concepts, a continuous acceleration is required and propulsion systems include solar electric propulsion, solar sail and a hybridisation of the two. Advantages and drawbacks of each mission concept are assessed, and a comparison in terms of high-latitude coverage and distance, spacecraft mass, payload and lifetime is presented. Finally, the paper will describe a number of potential applications enabled by these concepts, focusing on polar Earth observation and telecommunications.

1. Introduction

Spacecraft in geostationary orbit (GEO) have demonstrated the immense possibilities offered by the continuous coverage of a particular region. GEO platforms are nowadays the most used satellites for broadband telecommunications and weather forecasting. Unfortunately, GEO platforms can only provide their services in the equatorial and temperate zones, where elevation angles are sufficiently high. At higher latitudes, similar services are provided at present only by satellites in highly-inclined or polar, low or medium orbits. These orbits, such as Sun-synchronous orbits, allow the spacecraft to image only a narrow swath at each passage, relying on multiple passages for full coverage. For example, Landsat 7 (altitude of 705 km at 98.2°) completes just over 14 orbits per day, covering the entire Earth between 81° north and south latitude every 16 day.[3] Consequently, the temporal coverage of the entire polar region can be poor, as different areas are imaged at different times, hence missing the opportunity to have a simultaneous and continuous real-time complete view of the pole. At present, these images are post-processed to make a "composite" image, which can be used, for example, for weather forecasting and

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[3] Landsat 7 Handbook, http://landsathandbook.gsfc.nasa.gov/ [Cited 12/09/2011].

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wind vector prediction. However, the data that can be extracted is neither complete nor accurate [1].

To overcome these issues, it is desirable to have a spacecraft with a continuous view of the poles, or even better, one that is constantly above one of the poles, stationary with respect to the Earth, in the same way as a GEO spacecraft is stationary above one point on the equator. This spacecraft is known in literature as "pole-sitter". The first study of this concept appears to have been made by Driver [2] in 1980, although the author claims that the original idea belongs to the mathematician and writer Kurd Lasswitz. In the following years, the idea was then extended by other authors, introducing new mission concepts, either by releasing the strict constraint of the positioning of the spacecraft, or by introducing new forms of propulsion (solar sailing [3], or hybrid propulsion [4]) or a combination of both [5,6], to increase the mission lifetime, decrease the launch mass, or increase the visibility conditions of the polar regions, in terms of coverage and resolution.

The paper is organised as follows. The first section is a brief overview of low-thrust propulsion technologies. The second and most extended section of the paper attempts to provide a comprehensive overview of mission concepts for high latitude and polar Earth observation and telecommunications. It will not only focus on the pole-sitters, in the strict sense, but also on other concepts, in particular to those exploiting non-Keplerian orbits and the circular restricted three-body problem (CR3BP). The paper will critically describe the concepts presented starting from 1980 onwards, comparing feasibility and performance in terms of polar coverage performance, thrust required, and spacecraft mass for a given payload size and lifetime. Molniya orbits [7] will also be included, for two reasons: the first is that they have been historically used for high-latitude telecommunications; second is that they have recently been extended with a novel concept [8]. The overview also includes some recent results obtained concerning natural and solar sail-displaced orbits in the CR3BP. Finally, the paper briefly introduces some possible mission applications that can be enabled by continuous polar observation, including observation, polar meteorology and telecommunications.

2. Propulsion system technology

Many of the concepts presented in the following require a continuous acceleration, to keep the spacecraft at a stationary point (e.g. constantly above the pole) or along a non-Keplerian orbit, counterbalancing other forces. We provide here a brief overview of the two propulsion systems that will be exploited: solar electric propulsion (SEP) and solar sailing.

Solar electric propulsion is a mature technology that provides a spacecraft with a relatively low thrust (of the order of a fraction of a Newton per thruster [9]), by accelerating propellant to very high speed. Despite the relatively high specific impulse of modern thrusters [9] (of the order of 3000–8000 s), the thrusting time and hence the mission duration is always limited by the mass of propellant on-board: the lifetime L is directly related to the propellant mass fraction m_{prop}/m_0, the required acceleration a (assumed constant), and the specific impulse I_{sp} through the scaling law:

$$L = -\ln\left(1 - \frac{m_{prop}}{m_0}\right)\frac{I_{sp} g_0}{a} \quad (1)$$

where $g_0 = 9.81\ m/s^2$.

In the attempt to increase mission lifetime, many concepts propose to adopt a solar sail: this device can provide a continuous thrust without the use of any propellant mass. The idea, dated back to the beginning of 20th century and investigated in detail [10] since then, is in principle simple: gaining momentum by reflecting the photons from the Sun.

In the case of a flat, perfect sail, the acceleration is directed normal to the sail and away from the Sun, and its magnitude is [10]:

$$a_s = \beta \frac{\mu}{r^2} \cos^2 \alpha$$

where μ is the gravitational parameter of the Sun, r the Sun-spacecraft distance, and β is the lightness number, a function of the sail loading $\sigma = m/A$ of the spacecraft (mass over sail area):

$$\beta = \sigma^* / \sigma$$

and $\sigma^* = 1.53\ g/m^2$ is a constant for the Sun. The cone angle of the sail $\alpha \in [0,90^\circ]$ measures the angle between the sail normal and the Sun direction. When the sail is flat towards the Sun at 1 AU ($\alpha = 0^\circ$), then the acceleration produced by the sail is known as the characteristic acceleration (a_0). The conversion between β, σ and a_0 at 1 AU is represented in Fig. 1. Any of these three parameters are an indicator of the technology needed for the spacecraft: the larger the lightness is, the lower the sail loading is. This is achieved either using a larger sail area, or by reducing the system or sail mass. Values of β up to 0.05 can be assumed for a near-term system. Recently flown solar sail demonstrators, however, had considerably lower lightness numbers: JAXA's IKAROS [11] has a 20-m-diagonal square sail and weighs 350 kg ($\beta = 0.001$), while NASA's NanoSail-D2 [12] is 4 kg for 10 m^2 ($\beta = 0.003$).

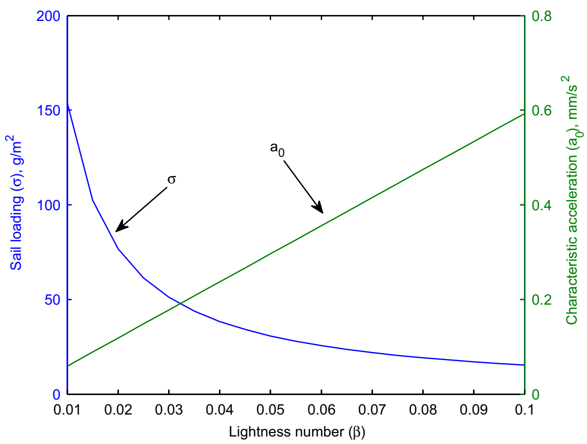

Fig. 1. Conversion between lightness number (β), sail loading (σ) and characteristic acceleration (a_0) at 1 AU.