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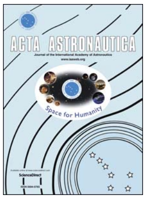

Polar constellations design for discontinuous coverage

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ABSTRACT

A novel constellation design method is developed for discontinuous coverage of the globe and polar caps. It integrates and extends the applicability of the coverage regions and mitigates the limitations of the existing techniques based on streets-of-coverage (SOC) theory. In particular, the visibility conditions of the targets are mapped in the (Ω, u)-domain to identify the number of satellites per plane and the distance between successive orbits, whereas the planes are arranged around the equator exploiting satellites both in ascending and descending phase. The proposed approach is applied to design potential space segments in polar LEO supporting the existing maritime surveillance services over the globe and on the future polar routes. Results show they require a smaller total number of satellites with respect to the SOC-based configurations for revisit times less than one hour and wide range of swaths. In details, it is observed a reduction between 6% and 22% for global coverage and between 24% and 33% for the coverage of polar caps.

1. Introduction

Telecommunications and navigation were the first applications, which drove to the development of satellite constellations for continuous coverage. In support to this need, the first design models were developed in the 1960s: Streets of Coverage (SOC) and Walker's method. A street of coverage (e.g. [1,2]) is generated by combination of all fields-of-view of the satellites in a same orbital plane, which are then added to achieve global or zonal (i.e. latitude belt) coverage. Walker's constellations rely on satellites in inclined circular orbits with their nodal crossing points equally spaced around the equator [3–5]. They were regarded as the ones requiring the smallest number of satellites able to provide continuous global coverage.

More complex constellation configurations were proposed using elliptical orbits, which are characterized by peculiar ground tracks [6,7] and require fewer satellites. Such constellations typically imply higher altitudes, which pose challenges for real world applications. More recently, Flower Constellations have been also proposed, which are not constrained to circular orbits and whose design is approached in rotating reference frames [8,9]. These constellations can support global, regional or spot areas services.

In the last decade, a number of applications have been arising which, contrary to the past, do not require continuous observation. As an example, in the field of telecommunications great momentum has been reached by the Automated Identification System (AIS), the coastal maritime safety and vessel traffic system developed by the International Maritime Organization and the International Telecommunications Union (ITU) [10]. Conceived as a ship-to-shore and a ship-to-ship telecom system to mitigate collision risk within 40 nmi (74 km) from the coast, it is now under investigation as an open sea infrastructure with AIS receivers also installed on satellites [11,12]. Required offshore revisit time (ship location update) ranges from few tens-of-minutes to few hours.

Earth remote sensing has also taken advantage from a constellation approach, as documented by the development of electro-optical (e.g. Disaster Monitoring Constellation, RapidEye) and synthetic aperture radar (e.g. COSMO/SkyMed) constellations. If on the one hand, continuous Earth monitoring at high resolution is impossible, time varying phenomena (including disaster management) studies gain benefits from discontinuous monitoring within a predefined revisit time.

Furthermore, global warming, among the detrimental effects, is going to impact international shipping in the near term, thanks to polar routes which tend to be opened much longer than in the past [13]. On the long term, new routes at higher latitudes are under study to reduce delivery times and fuel consumption [14]. Safe navigation and support to search and rescue activities are critical applications, which can be tackled by synergic exploitation of telecommunications and remote sensing constellations with discontinuous coverage. Literature on the analysis and design of discontinuous coverage constellation is still extremely limited. Ulybyshev [15–18] presents a design method to achieve

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discontinuous coverage over a selected (wide) area on ground, limited in both longitude and latitude. The method is based on satellites with a wide sensor swath, able to observe the whole target area. In addition, Graziano et al. [19,20] develop a method for global, discontinuous coverage by opportunely combing the fields-of-view of different satellites. Interestingly enough, the two methods tackle the problem from opposite perspectives: from ground to space and from space to ground, respectively.

In this paper, a new design method is presented for constellations able to provide discontinuous coverage for either the globe or polar caps. It integrates and extends concept proposed by Ulybyshev and Graziano et al. taking advantages of positive aspects of both methods. First, the proposed approach is derived. Then, it is applied for global and polar coverage.

2. Satellite constellation design for discontinuous coverage

2.1. Overview of existing models

This section describes the two procedures dealing with the design of satellite constellations for discontinuous coverage. Both of them assume circular orbits at the same altitude and inclination and nadir-pointing sensors.

The main feature of the method in [15] is that the coverage properties are represented as two-dimensional maps in (Ω, u)-domain, where Ω is the right ascension of the ascending node and u is the argument of latitude. In such domain, (a) the target visibility conditions for the satellite are described by an *oval* of boundary points [18], called *coverage regions* or *polygons* [15], (b) the satellite trajectories are straight lines along u-axis, (c) the constellation is represented by a grid whose vertexes identify the instantaneous satellites positions. There is a visibility interval of the target if the lines representing the satellite trajectories intersect the coverage region, and the continuous coverage is guaranteed if a grid vertex is included in the coverage region at any time. In [15] the discontinuous coverage design is carried out considering an enlarged coverage region, extended along u-axis of ωt_{rev}, where ω is orbital velocity and t_{rev} is the revisit time.

The coverage polygons can be built following the analysis described in [21] and successively modified to meet the temporal requirement as indicated in [15]. Their geometric shape and size depend on the satellite altitude (h), on the orbit inclination (i), on the sensor swath width (Θ), on the target latitude (ϕ) and on the revisit time (t_{rev}), whereas the target longitude (λ) simply shifts the polygon along the Ω direction. The coverage region can be a convex or non-convex single region (*single connected coverage polygon*) or two detached polygons (*double connected coverage polygons*) consisting in an *ascending lobe* and a *descending lobe*.

The constellation design approach presented in [15] assumes a discrete set of inner and boundary points representative of the target area. Each point is associated to a coverage region in the (Ω, u)-domain, thus the constellation design process for covering the whole target area is carried out considering the polygons intersection (union) when *full* (*partial*) coverage is required. Finally, if the resultant *map* exists and if it is a simple connected convex polygon, the symmetric constellation is identified thanks to a numerical procedure that first computes the largest parallelogram inscribable into the map and, then, identifies the grid in the (Ω, u)-domain, guaranteeing at least one parallelogram vertex in the map at any time. The spacing between the grid vertexes along u-direction defines the number of satellites per plane (S), whereas the distance along Ω-direction between the two parallel sides identifies the number of orbital planes (P), symmetrically displaced around the equator. Finally the slope of the parallelogram leads to the phasing angle between satellites in successive orbital planes.

The method in [19] is conceived for global discontinuous coverage. Three different strategies are proposed, based on streets-of-coverage in the orbital planes or between the orbital planes, leading to both symmetric and asymmetric satellite patterns. The mathematical models are elaborated on the grounds of the projections of the combined sensors fields-of-view on parallels at different latitudes [22]. Results [19] have shown that the strategy relying on horizontal strips of coverage is the most effective in terms of total number of satellites. Assuming that the ascending node spacing between successive orbital planes is 2Θ and a null inter-plane satellite phasing angle, the fields-of-views of satellites in adjacent orbital planes form a continuous horizontal line of coverage, sweeping half globe with satellites moving northward (ascending phase) and half-globe with satellites moving southward (descending phase). Hence, the orbital planes are distributed asymmetrically around the equator. Each point of the Earth is observed in a maximum time interval depending on the number of satellites per plane (S_B), which is properly selected accordingly to t_{rev} and to the orbital period T as [19]

$$S_B = \lceil T/t_{rev} \rceil \tag{1}$$

It is worth noting that since half-globe is covered by satellites in the same phase, the Earth rotation leads to regions first observed by ascending (descending) satellites and then re-observed within t_{rev} by descending (ascending) satellites. Such condition impacts on the definition of the number of orbital planes [19].

As mentioned before, the two methods carry out the constellation design with opposite perspectives. The method in [15] starts with the discretization of the target area and then performs the constellation design guaranteeing at least one satellite in the visibility cone of each target. It is only applicable when the coverage map exists and it is a single convex polygon, which strongly limits the latitude extent of the target area within 2Θ. On the contrary, the method in [19] assumes a given satellite coverage cone and selects the constellation parameters to achieve discontinuous global coverage. It suffers the typical limitation of the streets-of-coverage approach: the constellation parameters are defined assuming that the portion of the satellite coverage circle outside the street-of-coverage does not contribute to target coverage.

2.2. Polar constellations for discontinuous coverage: a new design approach

A new design approach for discontinuous coverage is presented, exploiting both the coverage regions concept [15] and the asymmetric distribution of orbital planes around the equator [19]. It extends the applicability of the method in [15] to double connected polygons and to the global coverage and overcomes the intrinsic limitations of the streets-of-coverage approach [19].

The proposed method assumes satellites in circular polar orbits so that the visibility conditions are represented in (Ω, u)-domain as double connected coverage polygons or as single connected strips covering the whole Ω range. In fact, for circular inclined orbits, the coverage regions are non-convex and convex single connected for the target latitudes $i\text{-}\Theta \le \phi \le i+\Theta$ and they are double connected for $\phi < i\text{-}\Theta$ (Fig. 1a). The non-convex single polygons are obtained by the intersection between the satellite trajectories and target visibility circle in the configuration shown in Fig. 2a and c. At westernmost Ω values, the satellites cross the visibility circle (dashed black circle) in descending-only phase (red orbit portion). When the ascending nodes move eastward, the satellites cross the visibility circle in both ascending (blue orbit