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A new algorithm for agile satellite-based acquisition operations

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ABSTRACT

Taking advantage of the high manoeuvrability and the accurate pointing of the so-called agile satellites, an algorithm which allows efficient management of the operations concerning optical acquisitions is described. Fundamentally, this algorithm can be subdivided into two parts: in the first one the algorithm operates a geometric classification of the areas of interest and a partitioning of these areas into stripes which develop along the optimal scan directions; in the second one it computes the succession of the time windows in which the acquisition operations of the areas of interest are feasible, taking into consideration the potential restrictions associated with these operations and with the geometric and stereoscopic constraints. The results and the performances of the proposed algorithm have been determined and discussed considering the case of the Periodic Sun-Synchronous Orbits.

1. Introduction

The Earth's remote sensing missions using attitude-fixed satellites are usually designed to gain repeating ground track orbits and, in the single satellite case, the minimum achievable revisit time of a given area is equal to one Earth's nodal day. To lower this limit it is possible to consider the so-called “agile satellites” (at non-fixed attitude), which, being characterised by high manoeuvrability and accurate pointing, provide better results in missions that need a fast recovery of images. Moreover, thanks to their agility, these satellites give the possibility of acquiring images over a wide area of the Earth's surface surrounding the sub-satellite point (referred to as Field of Regard – FoR). On the other hand, the advantages associated with these agile satellites are counterbalanced by an increase in complexity of the ground segment management and by the need to introduce optimisation processes to satisfy the mission objectives and avoid latencies and request losses [1]. In [2], this increase in complexity has been studied for satellites using Synthetic Aperture Radars. As far as the optimization processes in the management of mission operations are concerned, several algorithms have recently been proposed. Some important examples are reported here: a decomposition-based algorithm has been developed in [3], an algorithm for the retrieval of the maximal subset of optical images has been identified in [4], heuristic algorithms to maximise high-resolution imaging products have been developed in [5] and in [6], an algorithm to minimise the elapsing time between the data request by the User and their delivery, considering a Walker-type constellation, has been presented in [7].

Given that these “agile satellites” are thought to be exploited in remote sensing applications, from an orbital point of view the most appropriate solution is represented by the periodic orbit, which, as is known, allows cyclic observations of the entire Earth's surface in apposite time intervals. Several studies, concerning both single satellites and satellite constellations, have focused on the design of this typology of orbit. Some important examples are represented by [8,9], which illustrate the basic concept of periodic orbit and the related distribution of satellite passes at the ascending and descending nodes; [10], where the ground track spacing is analysed in relation to the latitude; [11], where the relationships presented in [10] are reconsidered to supply the angular phasing between satellites over the same orbit and between different orbital planes. Then, if together with this requirement (periodic orbit), also the possibility of carrying out observations of the Earth with appropriate solar illumination conditions is considered, Periodic SunSynchronous Orbits [12] or Periodic Multi-SunSynchronous Orbits [13] can be taken into account. If on the one hand this choice entails a reduction in the number of selectable periodic solutions, on the other hand it leads to the obtaining of remotely-sensed images characterised by a constant (Periodic SunSynchronous Orbits) or properly variable (Periodic Multi-SunSynchronous Orbits) observational local time.

In this paper an algorithm which allows an efficient management of the operations concerning optical acquisitions of agile satellites and which, thanks to its versatility, can be adapted to

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satellites with different characteristics, is described. The algorithm can be subdivided into two parts, closely linked: the Geometric Analysis and the Temporal Analysis. The Geometric Analysis consists of the geometric classification of each Area of Interest (AoI, area of the Earth's surface for which the data acquisition is required) and in the subsequent partitioning of these Area of Interests in properly designed stripes, called Acquisition Requests (ARs). The characteristic directions of the Acquisition Requests are called loxodromic lines [14] and represent the scan directions for the acquisition activities. The Temporal Analysis, which is considered once the Geometric Analysis is completed, consists of the calculation of the time windows, called Data Take Opportunities (DTOs), in which the acquisitions are feasible (for each Acquisition Request). By using a Geoserver database for the storage of geolocated data (URL: http://geoserver.org/), the above-mentioned feasibility processes (geometric and temporal) allow the consideration of the constraints deriving from the cloud coverage and from the Digital Elevation Model (DEM).

The paper is organised as follows: Section 2 describes the Geometric Analysis, Section 3 describes the Temporal Analysis, Section 4 shows examples of application, considering the case of Periodic SunSynchronous Orbits.

2. Geometric analysis

Once the geographical coordinates of an Area of Interest are assigned (by the User), the Geometric Analysis consists of the choice of the shape which has to be associated with this area and in its partitioning in rectangular sub-areas (strips). In the proposed algorithm each Area of Interest can be represented, according to the payload properties, by one of the three following types of geometry:

- polygonal area, which has to be subdivided into strips developing in the same direction (Section 2.1);
- polylinear geometry (multiple segments which do not form a closed area), which has to be subdivided into strips developing, in general, in different directions (Section 2.2);
- spot, which requires the consideration of a single strip (Section 2.3).

The partitioning of the Area of Interests is carried out following appropriate characteristic directions, referred to as loxodromic directions (or loxodromes). These directions represent the lines along which the payload will has to perform the scanning of the region. These loxodromes are identified by an angle Λ, measured from the North axis (N), clockwise ($0 \le \Lambda < 360°$). As an example, Fig. 1 shows the basic elements of the Geometric Analysis for a polygonal Area of Interest, where a bi-dimensional reference frame, called Loxo-Frame, with origin in the centre of an Acquisition Request (AR), X-axis along its loxodromic line (Λ) and Y-axis right-handed perpendicular, is introduced.

The determination of the loxodromic directions is carried out according to the geometry of the Area of Interest, to the ground track pattern of the satellite and to the features of the payload (agility and scan velocity). While the closed areas and the spots are characterised by a single loxodrome, the polylinear geometries require the introduction of a set of loxodromes.

2.1. Polygonal area of interests

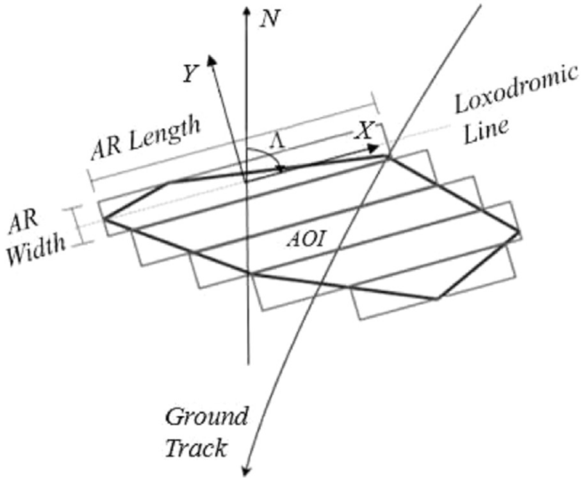

Fig. 1. Geometric analysis elements.

In the case of polygonal Area of Interest, the partitioning is based on the determination of an optimal angle (Λ, identifying the inclination of the Acquisition Requests) which is able, at the same time, of minimising the number of strips and of maximising the time interval to retrieve data from the Area of Interest (Data Take Opportunities). To gain this result, two functions, both variable from 0 (best case) to 1 (worst case), which consider the above-mentioned goals, have been implemented and properly weighted [15]:

- First function: $f_1(\Lambda)$, to minimise the distance between the loxodromic line and the points that delimit the Area of Interest (vertices of the polygon):

$$f_1(\Lambda) = \frac{D(\Lambda) - D(\Lambda_{MIN})}{D(\Lambda_{MAX}) - D(\Lambda_{MIN})} \tag{1}$$

In Eq. (1) the function $D(\Lambda)$ is defined as $D(\Lambda) = [\frac{\sum_{i=1}^{N} d_i^2(\Lambda)}{\sum_{i=1}^{N} p_i^2(\Lambda)}]$ while Λ_{MIN} and Λ_{MAX} represent, respectively, the loxodromes for which $D(\Lambda)$ is minimum and maximum. In this formulation d_i is the distance between the loxodromic line passing through the centre of the Area of Interest (average of the coordinates of the vertices of the polygon) and the i-th boundary point of the Area of Interest (i-th vertex of the polygon, with i=1…N), while p_i is the distance between the perpendicular to the loxodromic line passing through the centre of the Area of Interest and the i-th boundary point. The best case is $D(\Lambda) = D(\Lambda_{MIN})$ and $f_1 = 0$. This condition allows the coverage of the Area of Interest with the smallest number of Acquisition Requests and therefore with the smallest number of scans.

Fig. 2 shows the distances d_i and p_i between a boundary point p_i and, respectively, the loxodromic line (Λ) and its perpendicular line (Λ_P); λ_i and μ_i are, respectively, the latitude and the longitude of point p_i, while λ_C and μ_C are the latitude and the longitude of the centre C of the Area of Interest.

- Second function: $f_2(\Lambda)$, to maximise the observation time of the Area of Interest:

$$f_2(\Lambda) = \left| e^{-[\tan(\Lambda) - \tan(\Lambda_{GT})]^2} - 1 \right| \tag{2}$$

In Eq. (2) a particular loxodrome Λ_{GT} coincident with the tangent to the satellite ground track passing through the centre of the Area of Interest is introduced. Considering Λ=Λ_{GT} leads to $f_2 = 0$. This direction is associated with the longest observation intervals of the Acquisition Requests (Data Take Opportunities). Under the hypothesis of circular orbit, the angle Λ_{GT} can be expressed as a function of the orbit inclination (i), of the satellite mean motion (n) and of the latitude of sub-satellite point (λ_S) [16]: