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Circular revisit orbits design for responsive mission over a single target[☆]

Taibo Li [a,*], Junhua Xiang [a], Zhaokui Wang [b], Yulin Zhang [b]

[a] *College of Aerospace Science and Engineering, National University of Defense Technology, Changsha 410073, China*
[b] *School of Aerospace, Tsinghua University, Beijing 100084, China*

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ABSTRACT

The responsive orbits play a key role in addressing the mission of Operationally Responsive Space (ORS) because of their capabilities. These capabilities are usually focused on supporting specific targets as opposed to providing global coverage. One subtype of responsive orbits is repeat coverage orbit which is nearly circular in most remote sensing applications. This paper deals with a special kind of repeating ground track orbit, referred to as circular revisit orbit. Different from traditional repeat coverage orbits, a satellite on circular revisit orbit can visit a target site at both the ascending and descending stages in one revisit cycle. This typology of trajectory allows a halving of the traditional revisit time and does a favor to get useful information for responsive applications. However the previous reported numerical methods in some references often cost lots of computation or fail to obtain such orbits. To overcome this difficulty, an analytical method to determine the existence conditions of the solutions to revisit orbits is presented in this paper. To this end, the mathematical model of circular revisit orbit is established under the central gravity model and the J_2 perturbation. A constraint function of the circular revisit orbit is introduced, and the monotonicity of that function has been studied. The existent conditions and the number of such orbits are naturally worked out. Taking the launch cost into consideration, optimal design model of circular revisit orbit is established to achieve a best orbit which visits a target twice a day in the morning and in the afternoon respectively for several days. The result shows that it is effective to apply circular revisit orbits in responsive application such as reconnoiter of natural disaster.

1. Introduction

Responsiveness refers to the time between the development of a need and the subsequent solution that addresses that need. A key tenet of Operationally Responsive Space (ORS) is the ability to augment or reconstitute existing capabilities or to implement a new capability that is complimentary to fielded space assets [1,2]. Spacecraft flying in responsive orbits can be a significant asset to monitor natural disasters and to provide the necessary information to make informed decisions on the ground. For example, Russia's Resurs-P1 runs on a 475 km sun synchronous orbit with a six-day revisit period. The information obtained by it can be transmitted to a ground station in 12 h [3]. The orbits of The United States' "keyhole" series of satellites were proposed with perigees at about 315 km. These series of satellites can visit a particular area 1 or 2 times per day and conduct general and detailed survey over the target sites [4].

Traditionally, the performances of responsive imaging satellite in Low Earth Orbit (LEO) can be represented by the minimum revisit time, coverage percentage, resolution and so on [5]. Usually, low-altitude orbits may result in low coverage capability. This problem can be solved by making the orbits higher, but it will result in the loss of resolution. Increasing the number of the used satellite is another approach to solve this problem, which, however, increases the cost dramatically. Thus, it is important to optimize the responsive imaging orbits.

Literature [6] analyzed four different targets and different constellations of LEO spacecraft to understand their ability to not only support a single theater, but all four of the chosen theaters. The Nondominated Sorting Genetic Algorithm II (NSGA II) was used to design responsive orbits under the consideration of conflicting metrics including the orbital elements and launch programs of responsive vehicles [7]. In order to minimize the average revisit time (ART), the genetic algorithm was presented to find the Low-Earth fast access orbit of a single satellite and the orbits of each satellite in a constellation [8,9]. Genetic algorithms were also used to optimize the fuel consumption of constellations for responsive missions [10]. According to the ground track drift caused

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[*] Corresponding author.
E-mail address: nudt_ltb@163.com (T. Li).

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by the non-spherical nature of the Earth, a strategy for the design and maintenance of a low-Earth repeat-ground track successive-coverage orbit was presented in [11]. However, all the researches mentioned above are achieved from the numerical calculation, which costs lots of computation by ignoring some possible analytical laws in theory.

As a design tool, it is preferable to a semi-analytic or analytic algorithm with the help of special periodic orbits. For remote sensing applications, many papers have focused their attention on the study of periodic orbits. The concept of studying repeat ground track orbits as true periodic orbits in an un-averaged model was first explored in [12]. Circi et al. [13] used repeat ground track orbits for designing and control for single and multi-plane satellite constellations. The results of a general study carried out on the Periodic Multi-Sun Synchronous Orbits (PMSSOs) in [14]. Such orbits allow cycles of observation of the same region in which the solar illumination regularly varies. In terms of elliptical orbit, a polynomial equation of PMSSO is generalized in [15]. Razoumny conducted researches in satellite constellation design for periodic coverage in [16], and the symmetrical and weakly symmetric satellite constellations are analyzed and compared in [16]. The analytic solutions for latitude coverage by single satellite and N-satellite arbitrary constellation were obtained in [17]. Based on the solutions, a new approach for satellite constellation design were proposed in [17]. Furthermore, a general method for minimization of the satellite swath width required under given constraint on the maximum revisit time was presented in [18]. All the research in [16–18] conducted on the satellites swath width and the maximum revisit time of recursive orbits. However, if we assume a point is visited only if it is on the nadir of the satellite, some different conclusion can be obtained. Therefore, a special type of recursive orbit was researched in this paper for the sake of responsiveness. The minimum revisit time instead of the maximum revisit time is considered.

Usually, the responsive satellite is proposed on nearly circular orbits and are low cost. To get a better performance with such satellites, special repeat coverage orbits called circular revisit orbits which can visit the target site at the ascending stage and at the descending stage alternately are discussed in literature [19]. Because the nadir of such satellite coincides with the target twice in a revisit cycle, it offers a low cost satellite a better observation and a higher resolution. However, the J_2 perturbation has not been taken into consideration in the previous paper [19]. Under the J_2 perturbation, not only the solutions of the circular revisit orbit but also the relation between circular revisit orbit altitude and the latitude of the target site were obtained by using a numerical approach [20]. Both of them proposed a mathematical model to define the circular revisit orbit, but they did not analyze the existent conditions of circular revisit orbits and oppose a theoretically method to get the best circular revisit orbit over a given target.

As the previous did, the study of revisit orbit in this paper is limited into circular orbits. Taking the J_2 perturbation into consideration, the mathematical model of circular revisit orbits is established in this paper. Based on the mathematical model, a constraint function related to orbit inclination is introduced to solve the circular revisit orbit. Then, the monotonicity of the constraint function has been studied, and a simple bisection algorithm is proposed to get the solution of that function. Furthermore, the existent conditions and the number of solutions have been obtained. Finally, analytical optimal solution has been achieved to minimize the minimum revisit time.

This paper is divided into five sections and the rest is organized as follows. The mathematical model of the circular revisit orbit is established in Section 2, which analyzes the revisit conditions under the central gravity model and the J_2 perturbation. Section 3 presents a method to solve the circular revisit orbit, focusing on the underlying physics and the analytical relations among the variables. An optimization model is developed in Section 4 to choose a low cost circular revisit orbit whose minimum revisit time can make the target be visited twice in the day time. In Section 5, we draw some conclusions and discuss future work.

2. Mathematical model of the revisit orbit

2.1. Basic concepts of the revisit orbit

Traditionally, satellites for responsive applications embark very simple remote sensor due to the limited cost. Considering the satellite swath width, a general method for optimizing the remote sensor required under given constraint on the maximum revisit time (MRT) was proposed in [18]. In order to visit a target without a side-sway of satellite and make full use of a satellite with a very small swath, we suppose that a satellite will visit the target site only if the target site is on the nadir of the satellite in this paper. If a satellite visits the target site at the ascending stage and at the descending stage alternately in a single cycle, we define it runs at a revisit orbit. As illustrated in Fig. 1, when the satellite is at point A, its bottom point B coincides with the target site, and due to the earth rotation, when it is at point A', its bottom point B' coincides with the target site again. Apparently, if the satellite runs at a regressive orbit, it will visit the target site at the ascending stage and descending stage alternately and repeatedly. Therefore, the revisit orbit should be regressive.

Given the longitude and latitude coordinates of a target site, three steps can be summarized to design a revisit orbit. To begin,

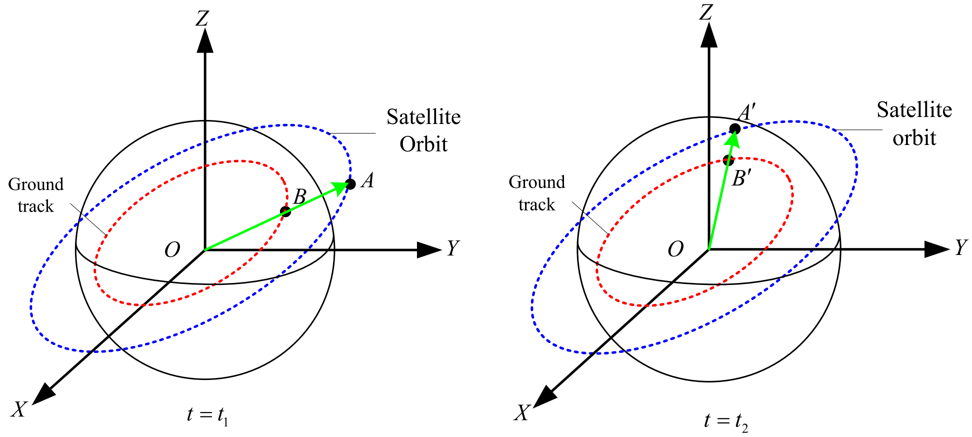

Fig. 1. A satellite which visits the target at ascending descending stages alternately.