Configuration Reconstruction Method of Surveillance Constellation for Geosynchronous-Target Observation

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Abstract. Geosynchronous orbit satellites hold significant strategic value, making it crucial to develop a satellite surveillance system for the geosynchronous belt and to explore the operational mechanisms and reconstruction methods for surveillance constellations. This paper constructs a surveillance constellation that leverages orbit altitude differences to achieve detailed imaging of targets within the geosynchronous belt. The design parameters and performance characteristics of the constellation are analyzed in detail. Building on this constellation model, a phase reconstruction method is introduced for specific observed targets, aiming to enhance imaging efficiency through active impulse maneuvering. A numerical example is provided to verify the feasibility of the reconstruction mission flow and the proposed reconstruction algorithm.

Keywords: GEO; Space-based Surveillance; Constellation Reconstruction.

1. Introduction

The deployment cost of high-orbit satellites is substantial, and their strategic significance is immense. High-value satellites, such as communication satellites, navigation satellites, and data relay satellites, are widely distributed [1]. High-orbit space serves as a critical bridge between near-Earth space and deep space. In particular, the geosynchronous orbit, with its scarce orbital resources, has been a focal point of international attention. Currently, the surveillance of geosynchronous orbit satellites has been effectively advanced [2].

Different from ground-based surveillance methods [3], space-based surveillance systems are not restricted by meteorological conditions, and have a wider surveillance range and higher accuracy, especially for the surveillance of geosynchronous belt satellites. Therefore, building space-based surveillance constellations is the best choice. In the existing satellite space-based surveillance system of the geosynchronous belt in the United States, the SBSS (Space-based space surveillance) system [4] is deployed in the low-orbit solar geosynchronous orbit and monitors the geosynchronous belt area by using the area gaze mode. The GSSAP (Geosynchronous space situational awareness program) system [5] is deployed near the geosynchronous orbit with a certain orbital altitude difference, and uses natural phase drift to achieve close-range imaging of geosynchronous belt satellites. In addition, based on the orbital perturbation characteristics of geosynchronous belt satellites, Lincoln Laboratory summarized the two regions with the highest density of geosynchronous belt satellites, called the "contraction point region" [6]. The proposal of this region eliminates the need for the space-based surveillance constellation of the geosynchronous belt to be set in a high orbit, and enables the medium-low orbit constellation to continuously monitor this region [7], but it cannot guarantee the stable surveillance of specific targets. Zhang et al. [8] further studied the orbital maneuvering planning technology for close observation of satellites near geosynchronous orbit, which can be used to serve the geosynchronous belt space situational awareness system at a deeper level. On the other hand, constellation reconstruction technology [9] is a necessary means to maintain the stability of the daily operation of the constellation, and can effectively enhance the reliability of the constellation in emergencies. Fang et al. [10] proposed a constellation reconstruction method based on artificial potential function, which only controls maneuvers according to the information of neighboring satellites and is suitable for the reconstruction of giant constellation. Hassan [11] introduced reinforcement learning into constellation reconstruction planning and used deep learning and near-end strategy optimization to solve the problem of reconfiguration of constellation satellites after faults.

Wang [12] proposed a double-layer optimization algorithm to solve the multi-objective optimization problem of constellation reconstruction under the condition that the target observation time is guaranteed.

Current research on constellation reconstruction primarily focuses on maintaining performance in the event of satellite failures or additions, with the main research subjects being communication constellations or terrestrial coverage constellations. Considering the observation requirements for geosynchronous belt targets, this paper designs a space-based surveillance constellation deployed near the geosynchronous orbit, utilizing phase drift to achieve detailed imaging of geosynchronous belt surveillance targets. Based on the geosynchronous belt observation scenario, the design parameters for the reconstruction optimization problem are clearly defined. A multi-objective function model is proposed, incorporating burnup, coverage, and observation duration, and optimization is carried out using the NSGA-II algorithm. Additionally, this paper presents a maneuvering control method for space-based constellation reconstruction when the observation target is shifted to a specific satellite. By reconstructing local satellites at different phases of the same orbit, the new observation target can be imaged at close range. Finally, the feasibility of the proposed method is validated through a simulation example.

2. Reconstruction Optimization Problem Modeling

2.1 Constellation Model of Geosynchronous Surveillance

Satellites operating in geosynchronous orbit are characterized by near-zero orbital inclination, low orbital eccentricity, and similar orbital altitudes. As a result, using a circular orbit with a slightly lower orbital altitude is highly suitable for scanning the geosynchronous belt. Additionally, configuring the sky observation payload to face away from the Earth can effectively minimize interference from the Earth's background, thereby improving imaging quality.

2.1.1 Characteristic Parameter

Considering the side swing capability of the surveillance satellite carrying loads, the half Angle of the observation field of view that can be formed is, and the motion relationship between the surveillance satellite and the observed target can be represented by a schematic diagram, as shown in **Fig 1**.

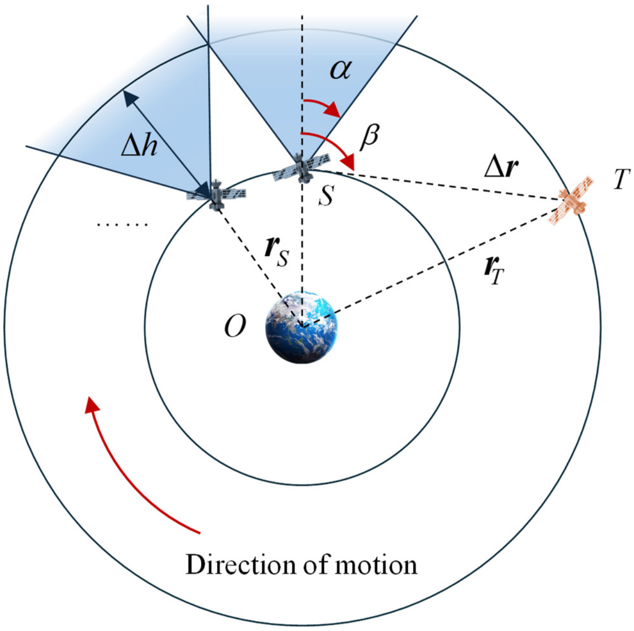

Fig 1. The motion relationship between the surveillance satellites and the observed target

Obviously, when the angle β formed by the observed target relative to the surveillance satellite diameter $\Delta\boldsymbol{r} = \boldsymbol{r}_T - \boldsymbol{r}_S$ and the surveillance satellite diameter $\boldsymbol{r}_S$ satisfies the following formula

$$\beta = \arccos\frac{\Delta\boldsymbol{r}\bullet\boldsymbol{r}_S}{\|\Delta\boldsymbol{r}\|\|\boldsymbol{r}_S\|} < \alpha \tag{1}$$

At this time, it is considered that the observed target has been successfully imaged. It can be calculated that under a certain orbital altitude difference, the orbital length that the surveillance satellite can cover the observed target is approximately

$$s = 2\Delta H\tan\alpha \tag{2}$$

The difference of mean angular velocity can be calculated according to the orbital altitude of the surveillance satellite and the observed target

$$\Delta n = n_S - n_T = \sqrt{\frac{\mu}{\|\boldsymbol{r}_S\|^3}} - \sqrt{\frac{\mu}{\|\boldsymbol{r}_T\|^3}} \tag{3}$$

where $\mu = 398600.44\mathrm{km}^3/\mathrm{s}^2$ is the gravitational constant of the Earth and $R_E = 6378.137\mathrm{km}$ is the radius of the Earth. Based on the difference of angular velocity, it can be obtained that the time of the observed target each time it is imprinted by a surveillance satellite is

$$t_{op} = \frac{s}{R_E\Delta n} \tag{4}$$

The regression period T_N of the relative motion state of the two spacecraft is

$$T_N = \frac{2\pi}{\Delta n} \tag{5}$$

If two surveillance satellites are connected to the coverage segment of the geosynchronous orbit, the minimum phase difference of the surveillance constellation is

$$\Delta\theta_{\min} = \frac{H\left(\tan\alpha_1 + \tan\alpha_2\right)}{R_E} \tag{6}$$

Among them, α_1 and α_2 are respectively the half angles of the field of view corresponding to the load carried by two adjacent surveillance satellites. In addition, the orbital altitude difference Δh between the surveillance constellation and the geosynchronous orbit satisfies the following constraints

$$\Delta h < R_{load}\cos\alpha \tag{7}$$

The significance of this formula is that Δh generally needs to be less than the effective working distance R_{load} of the load to improve the utilization of the observation field of view as comprehensively as possible.

This section introduces the constellation model for geosynchronous target surveillance, including the concept of characteristic parameters and the calculation of related performance parameters.

2.1.2 Optimal Design Variable

Based on the content of the previous section, when planning to deploy a geosynchronous target monitoring system, the following parameters must be determined:

1. The number of satellites in the surveillance constellation.
2. Parameters of the observation load on each satellite.
3. The orbital altitude difference between the constellation's orbit and the geosynchronous orbit.
4. The phase of the surveillance satellites.

Different satellites can be assigned unique parameters, but using identical satellite types simplifies the design parameter dimensions, making the system easier to manage.

In this paper, a surveillance constellation is assumed to be in operation, and the task is to image a specific target. If the natural phase drift time required to achieve the desired phase difference is too long, the surveillance constellation can be reconstructed through impulse maneuvering, enabling rapid execution of the imaging mission for the specific target.

To address this problem, the design parameters for the optimization problem are formulated as follows:

1. The number of surveillance satellites that need to perform maneuvering.
2. The phase adjustment required for each satellite.

Given the input parameters—observed target, objective function, and maneuvering strategy—the above design variables can be optimized to reconstruct the surveillance constellation for a specific observation target. The objective functions and maneuvering strategies are explained below.

2.2 Objective Function Design

The phase angle reconstruction control of a spacecraft orbit can be characterized by two parameters: the transfer time $T_{\rm t}$ and the fuel to be consumed. The fuel consumption is usually expressed in terms of the velocity ΔV. Both $T_{\rm t}$ and ΔV will directly affect the transfer cost. If the transfer time is too long, the spacecraft will not be able to provide service for a long period of time, and if the ΔV of the transfer is too large, the spacecraft will consume more fuel, which will affect the lifetime. Therefore, the reconstruction control problem for phase angle is an optimization problem with constraints and control objectives dependent on ΔV and $T_{\rm t}$. For a given spacecraft, the phase angle control quantity Δu can be used as the cost-cost indicator of phase angle reconstruction control, i.e.

$$J_{\rm p} = m\sum_{j=1}^{S'}\left|\Delta u_j\right| \tag{8}$$

where is the control amount of phase angle in the orbital plane, and is all the normal operating spacecraft in the orbital plane.

For the uniform phase reconstruction strategy, the equalization of fuel consumption must be considered, i.e., the constellation reconstruction control mission is distributed to all spacecraft in the orbital plane as uniformly as possible, so the optimal objective function for the equalization of fuel consumption is

$$J_{\rm e} = m\sqrt{\frac{1}{S'-1}\sum_{j=1}^{S'}\left(\left|\Delta u_j\right| - \overline{\Delta u}\right)^2} \tag{9}$$

where

$$\overline{\Delta u} = \frac{1}{S'}\sum\nolimits_{j=1}^{S'}\left|\Delta u_j\right| \tag{10}$$

For observed target switching, the optimal indicator of the constellation repair capability $J_{\rm pf}$ should be changed to the constellation coverage capability toward the switching target J_c

$$J_c = \frac{n_{[t_0,t_f]}}{N_t}\cdot\frac{m_k}{m_{all}} \tag{11}$$

where N_t is the number of total observed targets, $n_{[t_0,t_f]}$ is the number of targets observed during the mission time period, m_{all} is the number of total observed spacecraft, and m_k is the number of spacecraft that observed the switching target object.

Therefore, the combined indicator that takes into account fuel consumption, fuel equalization and the coverage capability of the constellation after switching targets is

$$J_s' = \min\left(k_1 J_{\rm p} + k_2 J_{\rm e} - k_3 J_c\right) \tag{12}$$

where *k* is the weighting parameter. By weighting the weighting parameters, the multi-objective optimization can be transformed into a single objective function problem.

Using the multi-objective optimization algorithm NSGA-II, then there is no need for weighting, and three objective functions J_p, J_e and J_c are set up directly , and the optimization process will result in a Pareto front that represents the coordinate positions in three-dimensional space.

3. Phase Reconstruction Maneuvering Strategy

The first step in phase reconstruction is to determine the phase reconstruction quantity Δu. However, phase reconstruction based on observed targets cannot explicitly obtain Δu, and the problem is closer to a pseudo-rendezvous problem. It is first necessary to predict the transfer time to change a specific phase

$$\Delta t = 2N\pi\sqrt{\frac{a'^3}{\mu}} \tag{13}$$

where N is a given positive integer and a' is the half-length axis of the elliptical transfer orbit for spacecraft phase reconstruction, calculated as follows

$$a' = a\left(1 - \frac{\Delta u}{2N\pi}\right)^{2/3} \tag{14}$$

At the starting moment, if the phase drift of the observed target is not considered, the phase reconstruction is Δu_0, and the phase difference after Δt in the downstream relationship becomes

$$\Delta u = \Delta u_0 + n_T \Delta t \tag{15}$$

where Δu_0 needs to ensure that the observed target is at least outside the field of view of the surveillance satellite at the end of reconstruction, i.e., at this time, the phase difference between the surveillance satellite and the observed target $\Delta\theta_u$ satisfies

$$\Delta\theta_u > \frac{\Delta H \tan\alpha}{R_E} \tag{16}$$

The above formulas form a closed loop that can be solved analytically to obtain the phase reconstruction quantities that take into account the phase drift of the observed target Δu

$$\Delta u = \frac{\Delta u_0 + 2N\pi n_T\sqrt{a^3/\mu}}{1 + n_T\sqrt{a^3/\mu}} \tag{17}$$

Substituting the Δu obtained from the above equation into Equ.(14), the half-length axis of the transition orbit of the reconstruction maneuver can be obtained, and the maneuver planning can be realized. In addition, when the half-length axis of the reconstruction track is known, the reconstruction control average characteristic speed can be initially evaluated with the formula under impulse maneuvering

$$\Delta v = 2\left|\sqrt{\mu\left(\frac{2}{a} - \frac{1}{a'}\right)} - \sqrt{\frac{\mu}{a}}\right| \tag{18}$$

In this section, a phase reconstruction maneuvering strategy for surveillance satellites for a specific observed target is given, which takes into account the phase drift of the observed target and gives the amount of phase reconstruction based on the performance of the payload carried by the surveillance satellite.

4. Numerical Examples

According to the proposed method of reconstruction design of surveillance constellation for specific observed targets in this paper, the usability of the method is verified based on simulation examples. The list of observed targets of the current 6-star geosynchronous belt surveillance constellation is shown in **Table 1**. The surveillance constellations are distributed in uniform phases on orbits with an orbital altitude difference of 1000 km from the geosynchronous belt and with a small inclination. The demand of the observed target is set to RADUGA_4 satellite, and the surveillance satellite which is far away from this observed target in the original observed target needs to be reconstructed. Construct the reconstruction indicator functions $J_1 = J_\mathrm{p}$, $J_2 = J_\mathrm{e}$, $J_3 = J_\mathrm{c}'$. The parameters of the multi-objective optimization algorithm are set as shown in **Table 2**, and the simulation start time is November 9, 2023 at 4:00 a.m.

Table 1. List of old and new observed targets

Observed targets (old)	Observed targets (new)
INSAT-1B, SATCOM_3R RADUGA_4, OPS_3165__DSP_5 OPS_6157__DSP_4, INSAT-1A INTELSAT_4A-F1, RADUGA_2 RADUGA_5, OPS_1570__DSP_3 ATS_3, LES_8 NATO_2A, NATO_2B TITAN_3C_TRANSTAGE_R_B	RADUGA_4

Table 2. NSGA-II optimization algorithm parameters

Parameter	Maximum number of iterations $It_{\max}$	Initial population size *pop*	Crossover probability *PC*	Mutation probability *PM*
Value	100	100	0.8	0.2

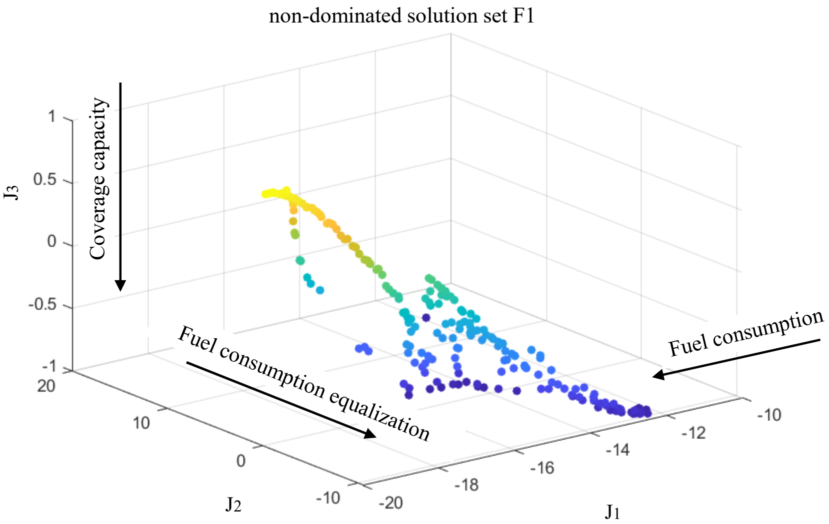

Fig 2. Reconstruction optimization pareto frontier

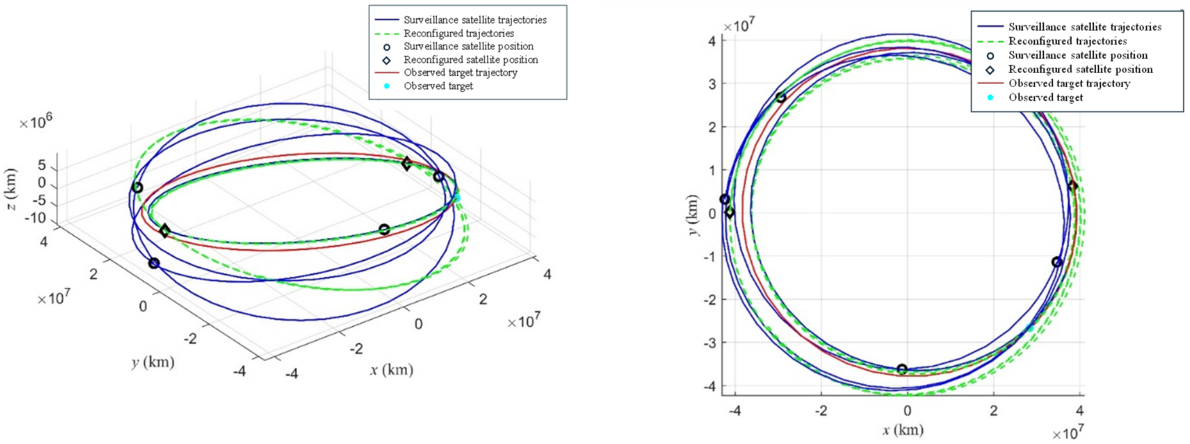

Fig 3. Spatial trajectory maps before and after reconstruction of constellations

The Pareto frontier solution is obtained as shown in **Fig 2**. When the optimization objective is 3, the coordinates corresponding to each solution will also change to 3D form. The configurations of the observation constellation before and after reconstruction are shown in **Fig 3**. The reconstruction star is mainly in a more favorable spatial orbital position for the observed target by means of phasing. The reconstruction maneuvers are mainly in-plane and the phasing is performed by adjusting the orbital half-length axis.

It can be seen that a total of 2 satellites performed the reconstruction maneuver, and the phase variation curves of the two satellites during the reconstruction process are shown in **Fig 4**.

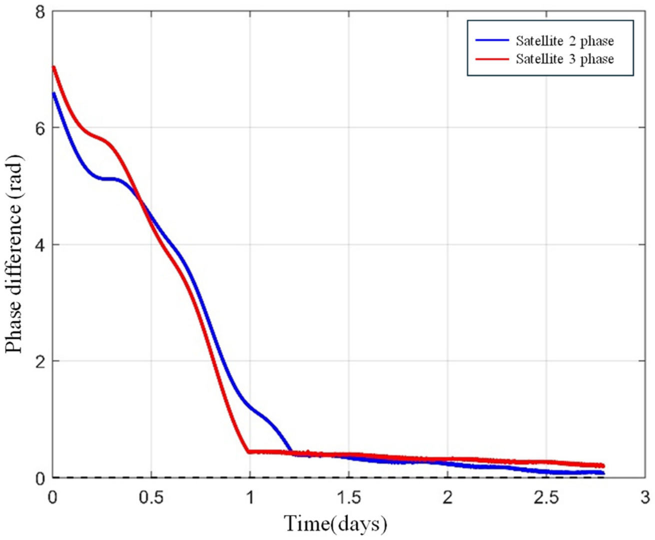

Fig 4. Phase change curves during reconstruction

Table 3. Objective function optimization results

Objective function	J_1	J_2	J_3
Value	-15°	-0.23	-0.83

From Table 3, it can be seen that the total control of phase angle is 15°, corresponding to J_1, which is associated with the size of fuel consumption; the fuel consumption equalization index is close to 0, corresponding to J_2; which indicates that the control equalization is good. J_3 indicates that five of the six satellites are able to complete the observation of the new observed target after reconstruction.

The above simulation test results show that the algorithm effectively derives multiple solutions with good coverage performance for the newly observed targets, constituting a Pareto frontier, and can select the solution with the best fuel consumption balance as the reconstruction scheme for the constellation.

5. Conclusion

This paper analyzes the performance characteristics of a surveillance constellation designed for detailed imaging of geosynchronous belt satellites by utilizing orbital altitude differences. Based on this constellation model, a constellation reconstruction optimization method is proposed for specific observed targets, and the mission flow for observing a specific geosynchronous belt target is discussed. Using simulation algorithms, a two-satellite reconstruction mission scenario is demonstrated based on a multi-objective optimization algorithm for a given observed target, verifying the usability of the proposed method.

The method proposed in this paper is primarily applied to satellite phase reconstruction within the geosynchronous belt surveillance regime. Future research directions include extending this approach to a continuous thrust framework and developing surveillance and reconstruction schemes for observed targets with highly eccentric or highly inclined orbits.

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