Simulation Analysis of Multi-satellite Joint Detection Activity Target Capability

Huang HUANG, Ji-guang ZHAO and Bin WEI
University of aerospace engineering, Beijing 101400, China

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Abstract. Under the condition of informatization, multi-star situational awareness of active targets in the mission area can greatly determine the trend of the whole mission. In order to measure the capability of multi-satellite joint detection active target, this paper introduces the concept of perception degree, deeply analyzes the probability of optical satellite detection, and USES the call search method to determine the calculation model of effective time of satellite detection. Aiming at the specific task area, the grid space is introduced and the simulation evaluation process is given. Finally, taking a certain region of China's territorial sea as the detection object, taking the existing five optical satellites as the basis, and using STK software for simulation analysis, the results show that the established perception model can better reflect the joint detection effect of multiple satellites.

Introduction

Satellite systems are not affected by national boundaries, regions and airspace, and it is difficult for modern weapons and equipment to strike them. Satellite systems are widely used in ground target reconnaissance, regional target monitoring, and regional target mapping. It provides information support for the establishment of some battlefield situations and the strike of ground targets.

Now for a specific task, most of it is a multi-satellite joint effect. Yuan-zhuo CI and Yue-jin TAN et al. took the combination of observation activity information return and discovery target return as the objective function and established the multi-satellite joint earth search task planning model. By studying the optimization model of time and space coverage, Xi LI established the efficiency optimization of multi-satellite region observation task. Yu-hua GUO studied the earth observation mission planning of multi-type satellites and analyzed the multi-sensor observation and multi-resolution observation. However, for multi-satellite joint detection, only planning research is generally carried out, and a specific quantitative index cannot be given for multi-satellite joint detection ability.

Aiming at the above problems, this paper analyzes the detection probability of optical satellites based on the joint detection of moving targets by multi-optical satellites. In order to better measure the ability of multi-star joint detection, the concept of perceptibility is introduced. Considering the timeliness of multi-star detection and the activity characteristics of the target, the multi-star detection capability is analyzed quantitatively.

Perceptive Meaning

In order to more comprehensively evaluate the satellite's reconnaissance ability for activities, the concept of perceptibility was proposed based on the effective time. Perceptibility was defined as the product of the probability of multi-satellite optical sensor detecting the target and the effective time of information:

\[ S = P \times Y \] (1)

Where, \( P \) is the detection probability of optical satellite; \( Y \) is the effective time of the information.

Unit perception: the ratio of the product of the detection probability of the optical satellite to the effective time of the information and the time window of the time window within the target area.
Regional unit perception: the product of the unit perception and the unit area and the ratio of the area.
Total perception of region: the sum of perception of all regional units in the target region.
Average perception of the region: the ratio of the total perception of the target region to the number of units.

**Probability Analysis of Optical Satellite Detection**

The detection probability of optical imaging satellite is related to the satellite theory detection probability, illumination influence factor, contrast influence factor, weather influence factor and satellite attitude factor.

(1) Calculation formula of theoretical detection probability of satellite\(^4\).

\[ P_2 = \exp(-(BL_f / L)^2) \]

(2) Where, \( B \) is the correction factor of the target shape, \( L \) is the geometric size of the target, \( L_f \) is the ground resolution of the satellite. Where, as the correction factor, when the target shape is relatively easy to recognize, it is usually 1 and 0.8 when it is difficult to recognize.

Optical reconnaissance satellites can use Rayleigh criterion to determine the upper limit of the performance of their optical system. According to Rayleigh criterion: \( \sigma = 1.22 \lambda / D \), \( \sigma \) is the limit resolution Angle, \( \lambda \) is the wavelength of light wave, \( D \) is the aperture of objective lens, \( L_f = \sigma \times H \) is the resolution of ground objects, and \( H \) is the orbital height.

(2) Illumination influence factor: for the photo sensor in the detector, it can only start to work when the photo sensor receives enough illumination, that is, it has to reach a certain amount of exposure.

Set the exposure time of the photo sensor as \( t \), the radiation flux \( E_0 \) received by the camera, the exposure of the camera as \( E = E_d^f \), and the utility function of the exposure is

\[ f_r = e^{-\left(\frac{E - E_0}{\sigma}\right)^2} \]

(3) Where, \( E_0 \) is the optimal exposure; \( \sigma \) depends on the sensitivity of the camera. Correct exposure refers to the use of the appropriate amount of light to shoot, to obtain a good visual brightness, the standard of correct exposure is relatively fuzzy, which brightness is the best, in fact, and the photographer's intention to shoot has a very close relationship. Correct exposure usually falls naturally within a certain brightness range. When brightness exceeds this range significantly, it is called "overexposure"; conversely, it is called "underexposure."

(3) contrast impact factor\(^5\): contrast impact refers to the degree of difference between the target and the background required by the detection of the target. The stronger the contrast between the target and the background, the clearer the image and the easier it is to recognize. On the contrary, the image edge is fuzzy and difficult to distinguish. The visible light mainly considers the color contrast factor, the infrared imaging mainly considers the temperature difference contrast influence.

Contrast impact factor \( f_r \). The specific expression is as follows:

\[ f_r = \begin{cases} 
1 & (r \geq 0.4) \\
\left(\frac{r - 0.2}{0.2}\right)^{0.5} & (0.2 \leq r < 0.4) \\
0 & (r < 0.2)
\end{cases} \]

(4) meteorological influencing factors\(^6\): the thickness and coverage of clouds are the main factors that directly affect whether the reconnaissance mission can be successfully completed among weather factors. The presence of clouds not only greatly reduces the reconnaissance efficiency of satellites, but
also may lead to the loss of imaging opportunities. The influence of clouds on solar radiation is mainly the indiscriminate scattering and absorption.

Table 1. Cloud cover level corresponds to cloud thickness and atmospheric pass rate.

| Level of cloud cover | 1  | 2  | 3  | 4  | 5  | 6  | 7  | 8  | 9  | 10 |
|----------------------|----|----|----|----|----|----|----|----|----|----|
| The thickness (m)    | 0  | 20 | 30 | 40 | 50 | 70 | 80 | 100| 500| 1200|
| Atmospheric transmittance(%) | 1 | 0.6 | 0.5 | 0.45 | 0.4 | 0.32 | 0.3 | 0.26 | 0.14 | 0 |

Cloud cover level can be divided into level 1 to level 10, and the influencing factors of cloud cover on visible light imaging reconnaissance can be expressed as

\[ f_e = 1 - \frac{(N-1)^2}{81} (1 \leq N \leq 10) \]  

(5) Influence of satellite attitude factor[7]: in the literature, starting from the particularity of spacecraft remote sensing, vibration of satellite is divided into three directions: along the optical axis direction, push and sweep direction and transverse direction. The influence of three kinds of vibration direction for satellite imaging, including along the optical axis direction and the direction for satellite imaging push sweeping negligible, satellite mainly under the influence of lateral is larger, the vibration of the satellite will cause in the process of sports load, in the process of optical satellite imaging, the vibration period of satellite platform is associated with the exposure time ratio of load, when the exposure time and the ratio of vibration period is less than 0.25 for low frequency vibration, greater than 0.25, for the high frequency vibration.

\[ f_e = \begin{cases} 
\frac{\sin(c\pi N\delta)}{2\pi Na} & \text{low-frequency vibration} \\
J_e(2\pi Na) & \text{high-frequency vibration}
\end{cases} \]  

(6)

As can be seen from the above, the detection probability of the satellite is:

\[ P_T = P_c f_e f_e f_e \]  

(7)

**Satellite Effective Time Analysis**

For a stationary target, the stationary target remains unchanged at a fixed position, so for satellite detection, the effective time is the time window of the satellite.

Assumes that the moving target is located in the grid point, when analyzing a grid point, the anchor point (latitude and longitude) is accurate, measuring the speed of the target as a priori information, the distribution of the moving target error for \( \varepsilon \), say, centered on the target radius \( \varepsilon \) for moving target within the scope of activities is to satisfy the reconnaissance mission requirements, when moving object range \( x \in (\varepsilon, \lambda) \), exercise obey normal distribution, the activities of \( \lambda \) the target distribution for unilateral confidence limit of the normal distribution curve \( x \in (\lambda, +\infty) \);At that time, the moving target distributed in this region is zero.

The target activity distribution error[8] is \( X_1 - X_2 \), so the contribution is 1 when the error occurs \( \leq X_1 \) and 0 when the error occurs \( \geq X_2 \).

There are also two thresholds, \( T_{11} = X_1 / V \) and \( T_{12} = X_2 / V \).

The moment \( T_1 \) unit area is covered by satellite 1, and the moment \( T_2 \) this area is covered by satellite 2, \( \Delta t = T_2 - T_1 (t \in [0, \Delta T]) \)

Let the positioning accuracy of satellite 1 is \( D_1 \), and the time error is \( \delta_1 = D_1 / V \).

1) When \( \delta_1 \leq T_{11} \) then

(1) If the \( \Delta t \geq T_{22} \)

Effective time contribution rate:
\[ y = \begin{cases} 
1 & \delta_i < t < T_{i1} \\
1 - \frac{t - T_{i1}}{T_{22} - T_{i1}} & T_{i1} < t < T_{22} \\
0 & t > T_{22}
\end{cases} \]

Effective time contribution:

\[ Y = \frac{T_{22} + T_{i1}}{2} - \delta_i \]  
(9)

(2) If the \( T_{i1} < \Delta T < T_{22} \)

Effective time contribution rate:

\[ y = \begin{cases} 
1 & \delta_i < t < T_{i1} \\
1 - \frac{t - T_{i1}}{T_{22} - T_{i1}} & T_{i1} < t < \Delta T
\end{cases} \]

Effective time contribution:

\[ Y = \frac{2T_{i2}\Delta T - T_{i2}^2 - \Delta T^2}{2(T_{22} - T_{i1})} - \delta_i \]  
(11)

(3) If the \( \Delta T < T_{i1} \)

Effective time contribution rate:

\[ y = 1 \quad \delta_i < t < \Delta T \]

Effective time contribution:

\[ Y = \Delta T - \delta_i \]  
(13)

2) When \( T_{i1} < \delta_i < T_{22} \), then

(1) If the \( \Delta T \geq T_{22} \)

Effective time contribution rate:

\[ y = \begin{cases} 
1 - \frac{t - T_{i1}}{T_{i1} - T_{i1}} & \delta_i < t < T_{i1} \\
0 & t > T_{i1}
\end{cases} \]

Effective time contribution:

\[ Y = \frac{T_{22}^2 - 2T_{i2}\delta_i + \delta_i^2}{2(T_{22} - T_{i1})} \]  
(15)

(2) If the \( T_{i1} < \Delta T < T_{22} \)

Effective time contribution rate:

\[ y = 1 - \frac{t - T_{i1}}{T_{22} - T_{i1}} \quad \delta_i < t < \Delta T \]

Effective time contribution:

\[ Y = \frac{2T_{22}\Delta T - 2T_{i2}\delta_i - \Delta T^2 + \delta_i^2}{2(T_{22} - T_{i1})} \]  
(17)

(3) There is no \( \Delta T < T_{i1} \) case for this model

3) When \( T_{22} < \delta_i \), then
Effective time contribution rate and effective time contribution is 0.
4) Within the time window, the valid time is the window time.

Simulated Analysis

Simulation Data

According to France’s spot-5 satellite, China’s gf-1 satellite, gf-2 satellite, cbers-4 satellite and Russia’s Person-3 satellite establishes the following satellite parameter table.

| project          | satellite1  | satellite2  | satellite3  | satellite4 | satellite5  |
|------------------|-------------|-------------|-------------|------------|-------------|
| satellite designation | SPOT-5      | GF-2        | GF-1        | CBERS-4    | Person-3    |
| home country     | The French  | China       | China       | China and Pakistan | Russia      |
| launch time      | 2002        | 2014        | 2010        | 2014       | 2015        |
| Spaceborne remote sensor | Sensor1     | Sensor2     | Sensor3     | Sensor4    | Sensor5     |
| Imaging method   | Push the sweep type | Push the sweep type | Push the sweep type | Push the sweep type | Push the sweep type |
| altitude         | 822km       | 631 km      | 645km       | 778 km     | 732km       |
| As the radial range | 60km        | 45 km       | 60km        | 60km       | 60km        |
| Spatial resolution | 10m         | 0.8m        | 2m          | 5m         | 5m          |
| Orbital inclination | 40.03      | 97.9080     | 98.0506     | 98.5       | 98.3        |
| eccentricity     | 0.0025579   | 0.0024442   | 0.002322    | 0.002400   | 0.00225     |
| Ascension of focus | 136.696    | 11.3115     | 13.9648     | 219.0335   | 94.8469     |
| Perigee argument | 354.305     | 4.5868      | 135.5644    | 94.8469    | 219.0335    |
| The initial phase | 135.622     | 355.336     | 330.063     | 140.9936   | 27.3630     |

The south China sea region is selected as the detection region, and the general scope is as follows:
In the simulation of moving target perception degree, according to the expert experience, the acceptable distribution error of moving target is $\epsilon = 125$ meters, unilateral confidence $\lambda = 5$ km, $v = 50$ km/h. The positioning accuracy of the five satellites is $\phi_1 = 10m, \phi_2 = 1m, \phi_3 = 5m, \phi_4 = 8m, \phi_5 = 8m$.

Simulation Results

In STK, the simulation time is set as 12 Nov 2018 22:00:00.000 UTCG to 13 Nov 2018 10:00:00.000 UTCG. The time step is 60 seconds. The detection area is divided into 342 points by grid analysis method, and each point represents an area of about 800 square kilometers, because the area is divided according to the grid. The perceptibility of each point is used to represent the detection ability of the satellite group to this kind of ship target. Finally, the average perception degree in the region is obtained. The simulation coverage figure obtained is as follows.

The green area in the grid represents the range that the satellite can detect.
For the whole region, the relation between the coverage ratio detected by multi-star joint reconnaissance and the time is as follows:

Figure 1. Satellite coverage map and Satellite coverage ratio.
Finally, the coverage rate of the region reached 30.9%. A total of 80 grid points were covered. And 13 points were detected twice by two satellites.

According to the previous analysis, if the target is not known, the perceptibility of a target is given to the detected region, so the detection probability of each detector is calculated.

Table 3. Detector detection.

| project | Coverage probability | Theoretical detection probability | Illumination factor | Contrast factor | Meteorologic al factors | Detection probability |
|---------|----------------------|----------------------------------|--------------------|----------------|------------------------|----------------------|
| Sensor1 | 0.0741               | 0.9408                           | 0.5                | 0.5            | 0.5                    | 0.11785              |
| Sensor2 | 0.0847               | 0.9951                           | 0.5                | 0.5            | 0.5                    | 0.12439              |
| Sensor3 | 0.1198               | 0.9879                           | 0.5                | 0.5            | 0.5                    | 0.12349              |
| Sensor4 | 0.0462               | 0.97                             | 0.5                | 0.5            | 0.5                    | 0.12125              |
| Sensor5 | 0.2105               | 0.97                             | 0.5                | 0.5            | 0.5                    | 0.12125              |

According to the coverage of each point in the region and the previous definition of perception degree, the total perception degree of the target region is obtained to be 0.044. Finally, the average perception of the region is 0.00054968.

As can be seen from the above figure, it can be found that for the region of a mission, the regional perception of the satellite in the time window is different, and different satellites have different perception of the same region. During the mission time, when a specific region is covered by multiple satellites at different times, the perception degree of the region can be greatly increased. For these areas with high perception, we can pay more attention to them when detecting targets. Of course, the solution of regional perception ignores the main factor and objectively evaluates the effect of multi-star joint reconnaissance and surveillance on key regions to some extent.

![Figure 2. Regional perception.](image)

Summary

The satellite joint detection and evaluation model can provide technical support for the satellite reconnaissance and surveillance application system. And multi-star joint detection is a future development trend, for specific tasks, the efficiency of multi-star joint will be greatly improved.

References

[1] Yuan-zhuo Ci, Ju-fang Li, Yue-jin Tan, et al. Multi-star joint earth search task planning technology research[J]. Journal of aerospace, 2008, 29(2):653-658.

[2] Xi Li. Study on the efficiency optimization method of multi-star region observation mission[D]. National University of Defense Technology, 2005.

[3] Yu-hua Guo. Research on key technologies of multi-type joint mission planning for earth observation satellites[D]. National University of Defense Technology, 2009.
[4] Tao Zhen. Evaluation method for operational effectiveness of surface-to-surface missile weapons[M]. National defense industry press, 2005.

[5] Bin Wang, San-ming Yang. Discussion on the application of civil satellite in military affairs[J]. Journal of equipment college, 2005, 16(5):52-55.

[6] Gang-yong Wang. Introduction to military satellites and applications[M]. 2003.

[7] Peng Xu, Chang-ning Huang, Qun Hao. Simulation analysis of the influence of satellite vibration on imaging quality[J]. Journal of aerospace, 2003, 24(3):259-263.

[8] Bin Yu. Fundamentals of military operations research[M]. 2015.