A TASK PLAN METHOD FOR AUTO-CATALOGUING BASED ON SSPAR

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Abstract

The on-orbit object auto-cataloguing of Space Surveillance Phased Array Radar (SSPAR) contains two progresses, one is catalogue improvement, the other one is catalogue maintenance. In the catalogue improvement, SSPAR captures the new on-orbit objects in the search fence, and grows the record count of the catalogue database. In the catalogue maintenance, SSPAR samples the catalogued objects' arcs and updates their stable orbital elements. The auto-cataloguing capacity of SSPAR is highly dependent on the stable tracking and updating rate, which will be influenced by many radar parameters. If SSPAR's total time resource is allocated rationally between the searching task and tracking task according to SSPAR's work parameters and objects' orbital characteristics, SSPAR's auto-cataloguing capacity will be improved remarkably.

Key words: SSPAR, space object auto-cataloguing, catalogue capacity, searching task, tracking task.

1 Introduction

Since 1957, more than 4900 spaces launches have taken place. The space objects suffered disassembly, collision and explosion many times. This led to an on-orbit population of today more than 22000 track-able objects with size larger than 10cm. Approximately 1000 of these are operational spacecraft. The remaining 94% are space debris which no longer serves any useful purpose. An estimated number of 700000 objects larger than 1cm and 170 million objects larger than 1mm are expected to reside in Earth orbits. Space debris would collide with some satellites to threaten the operational spacecraft and produce more space debris. Therefore, the effective space surveillance system must be founded to protect the safety of the mankind's space activity.

The space surveillance system built up with ground-based/space-based radar and electro-optical sensors, plays an important role in the process of space exploitation, utilization and control. It implements versatile functions such as searching, tracking, measuring, cataloguing and identifying the space objects including artificial satellite, space workstation, rocket remains and space debris. It also watches the spacecraft's whole lifetime from into the space to out of the space, still monitors various space events such as near-range joining, collision, disassembling, explosion, falling-down and reentry. The space surveillance system is able to provide the safe satellite launch window, protect the safety of the on-orbit spacecraft, and produce the warning intelligence of the space abnormal accidents. The United States' Space Surveillance Network (SSN) built up with NAVSPASUR(Naval Space Surveillance System), FPS-85 and GEODSS(Ground-based Electro-Optical Deep Space Surveillance) has the stable catalogue capacity of more than 16000 space objects with size larger than 10cm. Russia and Europe also build up the primary space surveillance system.

Large-scale SSPAR is characteristic of far-range, freedom of weather conditions, multi-object tracking and multi-channel parallel processing. Its antenna, utilizes the electrical scanning, is free of the volume and weight constraint, consists of thousands of Transmitter/Receiver (T/R) components, and synthesizes the power in the space. SSPAR can detect the far-range object with the height of thousands of kilometers. SSPAR exploits the versatile techniques of time-serializing/paralleling multi-beam synthesis, multi-channel signal processing and smart resource management, rationally allocates time, energy and computation resources according to need, is capable of keeping scanning of the certain search volume and tracking a few objects, and is fit for large-scale space objects' catalogue and management[1,2]. The Eglin FPS-85 radar in the SSN, capable of real-time processing 100-200 batches of space objects and cataloguing 20-30 thousand point-trails, undertakes more than 70% space object's catalogue tasks.

As space launches take place more and more

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frequently, a lot of new spacecraft swarm into the crowd space, the operational spacecraft's threats from small debris (size less than 10cm) becomes more and more serious. This challenges SSPAR's catalogue capacity severely, then SSPAR needs to exploit its searching, tracking and cataloguing capability deeper and deeper. This paper contains four sections. The 2nd section is to analyze SSPAR's catalogue principle and workflow. The 3rd section is to calculate the time resource percentage between the searching task and the tracking task and the track-able object count in the complicated tracking states. The final section is to conclude SSPAR's catalogue capacity and the lifting methods

2 SSPAR's Catalogue Workflow

SSPAR has two basic work modes, searching and tracking, but often works in the mix mode of tracking and searching (TAS), then allocates proper time resource to scan the space, the remaining to track space objects[3,4].

SSPAR does not scan the full space, but the search fence, as fig.1. The wave beam periodically scan the search fence, and the searching period is less than any object's pass-through time so as to capture them once they traverse the search fence. After capturing, SSPAR tracks the new object to form an observation arc by a proper tracking rate.

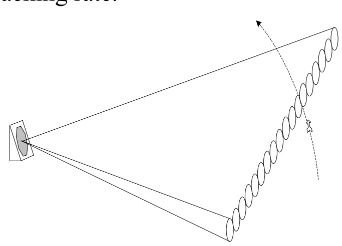

Figure 1. The sketch map of the fence.

All of the space objects such as spacecraft and debris have the fixed orbits. They can be expressed with 6 orbital elements. Only if obtained are the 6 orbital elements, the instantaneous location of space object will be computed, and the time and the position from when and where the space object traverse the search fence will be predicted, too. SSPAR only need to capture the space object on the predicted location at the predicted time, but not need to scan for a long time and a large volume. After tracking some time and building an observation arc, SSPAR then calculates the 6 orbital elements from the trajectory formulas, establishes the catalogue database and manage the space objects.

SSPAR does not utilize the orbital information from the other means, but only itself capability to implement versatile functions such as searching, tracking, measuring, cataloguing and identifying between the space objects, and to build up the orbital objects catalogue database. That is called auto-cataloguing. SSPAR's auto-cataloguing can be divided into two progresses, one is catalogue improvement, the other one is catalogue maintenance. In the catalogue improvement, SSPAR searches new object in the search fence, gets tracking arc, calculates the primary 6 orbital elements and saves a new record into the catalogue database. Once the database contains every space objects' record, the catalogue improvement progress finishes. Because of the atmospheric resistance and the solar light pressure, the 6 orbital elements of space object evolves continuously, then the error between the real values and the record values of the 6 orbital elements increases more and more. The catalogue maintenance progress unceasingly updates the record value by the new observation arcs so as to keep the real values and the record values identical.

While auto-cataloguing, if SSPAR only utilizes a few observation data to calculate the 6 orbital elements, here exists a big error. If more historic observation data are employed to improve the 6 orbital elements, the error will probably be convergent and the record values will be more precise.

According to SSPAR's acquaintance degree for the orbital objects, they can be divided into three types, as for Tab.1.

The two auto-cataloging progresses are not separated, but interleaved. In the catalogue improvement, the fresh-cataloguing object and the well-catalogued object in the database are accumulated step by step. During building up the 6 orbital elements of the unknown-new object, the 6 orbital elements' precision of the well-catalogued object would be fall below a certain threshold, so it need to be switch into the catalogue maintenance. Even in the catalogue maintenance, as that the space environment changes, the unknown-new object will appear at any time, so the catalogue improvement intervenes. Fig.3 is the full auto-cataloging workflow.

Table 1: orbital object type description

Type	Description
the unknown-new object	The unknown-new object does not be captured for any time, so there is no record data in the database, and its appearance time and location can not be predicted. It only can be captured by blindly searching the full fence, then be tracked and turned into the fresh-cataloguing object.
the fresh-cataloguing object	The fresh-cataloguing object's 6 orbital elements have been saved into the database, there exists a little historic observation data, but the error is not convergent. The fresh-cataloguing object needs be allocated time resources and tracked frequently. Its 6 orbital elements needs be improved by more historic observation data until its error is convergent and be turned into the well-catalogued object.
the well-catalogued object	The well-catalogued object's 6 orbital elements saved is precise, there exists more historic data, and the error is convergent. The well-cataloguing object does not need be tracked frequently. If only Its 6 orbital elements' error fall below a certain threshold, the well-catalogued object needs be allocated time resources to get some new observation data, and its 6 orbital elements will be improved by the new observation data and the historic data.

Step 1: establish the radar's observation task list. There are three type tasks. The first is to set up the search fence and establish the searching task plan. The second is to retrieve all the fresh-cataloguing objects from the database, to predict the pass-through time and location, and establish the tracking task plan. The last is to analyze the well-controlled objects from the database, to predict the pass- through time and location, and establish the tracking task plan for certain well-controlled objects whose 6 orbital elements' error fall below a certain threshold.

Step 2: schedule the radar's observation task list, allocate the time resource for searching task and tracking task separately by the compound priority algorithm [6, 7], and induct SSPAR's work.

Step 3: under the control of the well-planed time schedule, SSPAR scans the search fence, detects the unknown-new objects, auto-allocates the idle time bin to track them, gets new observation data, calculates their 6 primary orbital elements and saves them into database as the fresh-cataloguing objects.

Step 4: under the control of the well-planed time schedule, SSPAR captures the fresh-cataloguing objects at the predicted time on the predicted location, turns into tracking phases successfully, gets new observation data, calculates their 6 precise orbital elements with a few historic observation data. If the error is convergent, then saved as the well-controlled objects, otherwise still saved as the fresh-cataloguing objects.

Step 5: under the control of the well-planed time schedule, SSPAR captures the well-catalogued objects at the predicted time on the predicted location, turns into tracking phases successfully, gets new observation data, calculates their precise orbital elements with a few historic observation data, and updates the 6 orbital elements in the database.

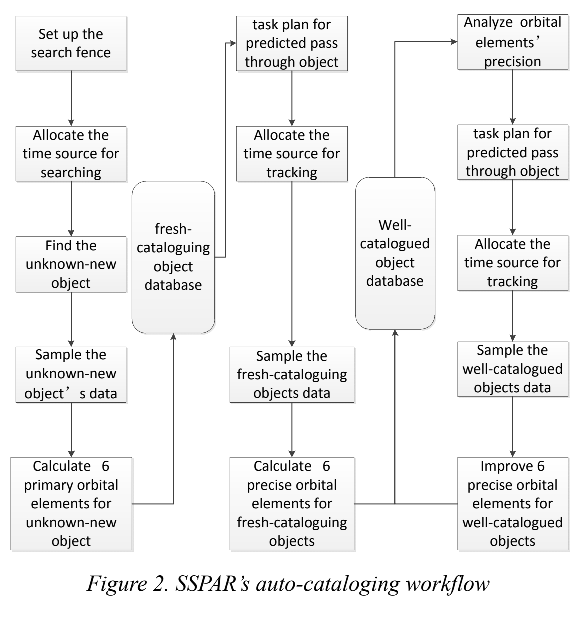

Figure 2. SSPAR's auto-cataloging workflow

3 Search/Tracking Task Analysis and Track-able Object Count Calculation

SSPAR has two task modes, one is the searching mode for the unknown-new objects, the other one is the tracking mode for the fresh-cataloguing and well-catalogued objects. For the first task mode, SSPAR has no previous knowledge about them. Thus, it has to scan the full search fence blindly to capture them. For the second task mode, SSPAR is able to predict the emergent time and location of them. So it only need to spend a short time scanning a small area to capture and track them when they pass through the fence. Following calculates the time resource for searching task and tracking task respectively and the catalogue capacity[5].

3.1 Time Resource for Searching Task

Supposing that N_s search fences have been setup in the surveillance volume, the corresponding searching frame period is P_{si}, the j th search fence contains B_{nj} beam bins, its working priority is pri_{sj} $(j = 1, 2, ..., N)$, and the resident time is Δt_{si} on every beam bin. When the preceded searching task finishes, the same searching task will be produced before the next searching frame period, circulated once and once.

The time resource for the searching task is the function of N_s, B_{nj} and t Δt_{si}, so

$$Time_S = \sum_{j=1}^{N} B_{nj} * \Delta t_{si} \tag{1}$$

The beam bin number B_{nj} on the j th search fence is constrained by the size of the azimuth scanning range A_j and the transmission antenna beam width $\theta_{0.5}$.

$$B_{nj} = \mathrm{A}_j / \theta_{0.5} \tag{2}$$

The resident time Δt_{si} is constrained by the searching pulse period T_{si} and searching pulse count M_s, and T_{si} is correlated with the range R.

$$\Delta t_{si} = M_s \bullet T_{si} \tag{3}$$

In the above formula (3), the variable M_s denotes the pulse integration detection times at the same beam bin.

The orbit shape of space object is an approximate circle, the object's height is almost un-variable. When the SSPAR observes the same object, the object's range R varies with the search fence elevation, so the different searching period can be utilized for the different search fence. Supposing that space object flies along the circle orbit, the object's height is h, the flying velocity is V, the elevation of the j th search fence is E_j, the earth radius is R_0, and the light velocity is c, then

$$\mathrm{R} = \sqrt{(h + R_0)^2 - (R_0 \cos E_j)^2} - R_0 \sin E_j \tag{4}$$

$$T_{si} = 2R / c \tag{5}$$

Replace the variables in the formula (1) with the formulae (2)~(5), we can get

$$\mathrm{Time_s} = \frac{2M_s}{c\theta_{0.5}} \sum_{j=1}^{N} (A_j \bullet (\sqrt{(h + R_0)^2 - (R_0 \cos E_j)^2} - R_0 \sin E_j)) \tag{6}$$

3.2 Searching Frame Period

SSPAR's searching frame period P_{si} is often decided by the pass-through time Δt_{pass} (see fig.3). if $P_{si} \le \Delta t_{pass}$, only if the object's echo is greater than the detection threshold, it should be captured when it passes through the search fence. Otherwise it would be missed. In the fig.3, supposing that space object is passing through a search fence, flying from point C to point A, the beam elevation is E_j, and the beam width is $\theta_{0.5}$, the arc ABC is the orbit segment that SSPAR can observe in one beam width. The length of the arc ABC can be calculated through the geocentric angle β between point A to point C, then the pass-through time Δt_{pass} can be calculated through the space object's orbit angle velocity.

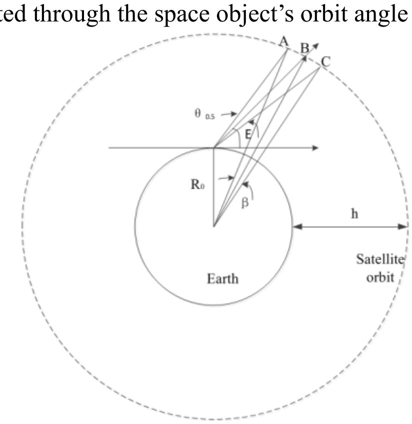

Figure 3. pass-through time calculation of space object

$$\begin{cases} ABC = (R_0 + h) * (\beta(h, E_j + \theta_{0.5}/2) - \beta(h, E_j - \theta_{0.5}/2)) \\ \beta(h, E_j + \theta_{0.5}/2) = \pi/2 - \arcsin(R_2 \cos(E_j + \theta_{0.5}/2)/(R_0 + h)) \\ \beta(h, E_j - \theta_{0.5}/2) = \pi/2 - \arcsin(R_2 \cos(E_j - \theta_{0.5}/2)/(R_0 + h)) \\ \mathrm{R}_2 = \sqrt{(h+R_0)^2 - (R_0 \cos(E_j + \theta_{0.5}/2))^2} - R_0 \sin(E_j + \theta_{0.5}/2) \\ \mathrm{R}_1 = \sqrt{(h+R_0)^2 - (R_0 \cos(E_j - \theta_{0.5}/2))^2} - R_0 \sin(E_j - \theta_{0.5}/2) \\ V = \sqrt{\mu/(R_0 + h)} \end{cases} \quad (7)$$

$$\mu = G(M+m) = 0.398602 \times 10^{15} m^3/s^2, \; R_0 = 6378135m$$

$$\Delta t_{pass} = ABC/V \quad (8)$$

Here supposing that $P_{si} = \Delta t_{pass}$, that is to say, the searching frame period is equal to the pass-through time. Generally, the searching frame period is greater than the time resource that searching task consumes, searching task consumes time resource is $Time_s$, the remaining time resource is for the tracking task[6,7]. So

$$P_{si} = Time_S + Time_T \quad (9)$$

$Time_T$ is the tracking time.

3.3 Track-able Object Count in the Simple Tracking State

As for SSPAR, every tracking task denotes the whole tracking procedure, contains several tens of tracking periods[8]. In the formula (9), during the search frame period P_{si}, the total tracking time is $Time_T$. The time resource consumed by n_t objects' one-time tracking is the function of the tracking beam resident time $M_t T_{ti}$ and the tracking period P_{ti}. Supposing that there is only a simple tracking state, every tracking period consumes the same beam resident time, then

$$T_t = n_t M_t T_{ti} \quad (10)$$

Because the searching frame period is far greater than the tracking period P_{ti}, the multi-tracking operation can be performed in a tracking period P_{ti}, the total tracking times in P_{si} is P_{si}/P_{ti}. So the total tracking time is $Time_T$ in P_{si} is

$$Time_T = n_t M_t T_{ti} \bullet P_{si}/P_{ti} \quad (11)$$

Replace formulae(6) and (11) into formula (9), then

$$P_{si} = Time_S + n_t M_t T_{ti} \bullet P_{si}/P_{ti} \quad (12)$$

Supposing that all the tracking operations utilize the same tracking period P_{ti} and the same tracking beam resident time $M_t T_{ti}$, this is called the simple tracking state, the track-able object count is

$$n_t = (P_{si} - Time_S) \bullet \frac{P_{ti}}{P_{si}} \bullet \frac{1}{M_t T_{ti}} \quad (13)$$

The formula (14) shows that the track-able object count in the simple tracking state is the function of the tracking period, the searching frame period and other variables. In order to reduce the total tracking time $Time_T$, if the track-able object count n_t keeps constant, the tracking beam resident time $M_t T_{ti}$ should decrease, and the tracking period P_{ti} should increase. Sometimes, M_t can decrease the lowest, $M_t = 1$, but T_{ti} should not be lower than the object's delay time. The total tracking time $Time_T$ can increase properly so as not to deteriorate the precise measurement and stable tracking capability. In conclusion, it is not correct to chase the highest tracking sampling rate unilaterally.

3.4 Track-able Object Count in the complicated Tracking State

Another adaption method of the total tracking time $Time_T$ is to partition into several different tracking states according to the objects' importance, threat and height etc., every tracking state utilize a different tracking sampling rate. This is called the complicated tracking state[9,10].

Supposing that there are K complicated tracking states, there are $n_{tk}(k = 1, 2, ..., K)$ objects in every tracking state, and the beam resident time is $N_{tk} T_{rk}$ in every tracking state, so

$$T_{tk} = n_{tk} N_{tk} T_{rk} (k = 1, 2, ..., K) \quad (14)$$

In formula (14), N_{tk} is the pulse number in every tracking operation, equals the pulse repetition, and T_{rk} is the tracking pulse period.

If the symbol $p_{tik}(k = 1, 2, ..., K)$ denotes the proportion of the searching frame period P_{si} and the tracking period of every tracking state $T_{tik}(k = 1, 2, ..., K)$ (that is the average tracking times in the searching frame period), then

$$\sum_{k=1}^{K} p_{tk} T_{tk} = P_{si} - Time_S \quad (15)$$

namely

$$\sum_{k=1}^{K} p_{tk} n_{tk} N_{tk} T_{rk} = P_{si} - Time_S \qquad (16)$$

The total tracking object count is

$$n_t = \sum_{k=1}^{K} n_{tk} \qquad (17)$$

4 Object Cataloging capacity of SSPAR

As for fig.2, When SSPAR just begins to auto-catalogue, all the space objects belong to the unknown-new object, the cataloguing database is null, and all the time resource can be used for the searching task. While improving space object's catalogue, the well-cataloged objects' count increases more and more, a part of time resource will be allocated for the fresh-cataloguing and well-cataloged objects' tracking task. SSPAR keeps working in the catalogue improvement procedure until there exists no the unknown-new object. In the catalogue maintenance, all the time resource is used for the well-cataloged object's tracking task. Generally, there always exist some unknown-new objects, so SSPAR at least keeps one search fence task, the remaining time resource is for the tracking task. Following divides 2 kinds of conditions to analyze space object's catalogue question.

4.1 Relationship between Searching Frame Period, Searching Consumed Time and Scanning Fence Elevation

Supposing that SSPAR's search fence range is 120°, SSPAR's pencil beam width is 1.5°, SSPAR only scans one time on every beam bin, space objects fly on the circle orbit with the height of 900km, the Relationship between searching frame period, time resource searching consumed and scanning fence elevation is in fig.4.

From fig.4, if the search fence elevation is 30°, the pass-through time is 8.4s, that is to say, the searching frame period is 8.4s, but SSPAR performing one scanning along the search fence only consumes 0.83s. So the search-fence-consumed time resource is far below the searching frame period. Therefore: (a) SSPAR can stay 10 periods on every beam bin and perform 10 pulses' accumulation detection. (b) SSPAR can select stay 5 periods on every beam bin, then the search-fence-consumed time resource is 4.15s, the remaining 4.25s can be used for the tracking task.

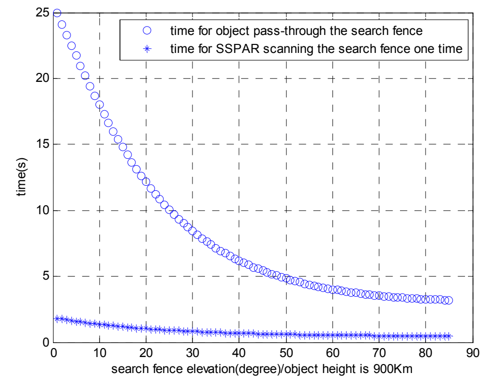

Figure 4 Relationship between Searching Frame Period, Searching Consumed Time and Scanning Fence Elevation

4.2 Track-able Object Count Analysis

In the simple tracking state, supposing that a half of the time is used for the tracking task in one searching frame period, that is to say $(P_{si} - Time_S) = 4.2s$, the tracking period for all the object is $P_{ti} = 2$s, the tracking beam stay time is $M_t T_{ti} = 10ms$, we can get $n_t = 100$ in formula (13). That is to say PAR can track 100 objects at the same time in the simple tracking state.

In the complicated state, still supposing that a half of the time is used for the tracking task in one searching frame period, there are 4 tracking states: st1,st2,st3 and st4, the tracking periods are 0.5s,1s, 2s,3s respectively, the tracking pulse number is the same, all equal 1, the pulse periods are 8ms,10ms,12ms,15ms. The table 2 shows the result. st1 consumes the most time resource, st4 consumes the least time resource, this is because st1 has the highest tracking sampling rate, and st1 has the lowest tracking sampling rate. As every state consumed time resource varies, the track-able object count changes, too. If all the time resource is allocated to the st4, the track-able object count is biggest, 100. If all the time resource is allocated to the st1, the track-able object count is smallest, 25. In the other conditions, the track-able object count changes between 25 and 100.

Table 2 track-able object count

condition	St1	St2	St3	St4	count
1	25	0	0	0	25
2	0	50	0	0	50
3	0	0	100	0	100
4	0	0	0	150	150
5	10	10	10	45	75
6	10	10	33	10	63
7	10	21	10	10	51
8	15	10	10	10	45

5 Conclusion

The auto-cataloguing capacity of SSPAR is highly dependent on the stable tracking sampling rate, which will be influenced by many radar parameters including the time resource, the searching/tracking sampling rate and the wave resident time. SSPAR's total time resource is limited. If the searching task consumes more, then the tracking task will share less, the performance of SSPAR will descend. During the catalogue improvement, when the well-catalogued objects approach to the upper limit the time resource consumed for keeping the well-catalogued objects' orbital elements precision maybe take up most, and it could even exceed SSPAR's capability.

However, the unknown-new objects always exist in SSPAR's surveillance space. SSPAR should firstly satisfy the requirement of a searching task for the unknown-new objects, and the remaining can be used for the tracking tasks. If SSPAR's total time resource is allocated rationally between the searching and tracking tasks according to SSPAR's work parameters and objects' orbital characteristics, SSPAR's auto-cataloguing capacity will be improved remarkably.

Assuming that SSPAR's effective range is 5000Km and the total time resource is 12 hours, the simulation result shows that, if the search fence with 25°elevation is reserved, SSPAR is able to track and catalogue 7600 orbital objects stably; while the search fence is not reserved, the number rises up to 13000. Further analysis also suggests that, if some orbital objects' update period are extended from one time every day to one time every two or three days, SSPAR's auto-cataloguing capacity can improves more obviously. There is a well-known example that among all the orbital objects larger than 10cm catalogued by the US space surveillance network, SSPAR Eglin AN/FPS-85 is capable of real-time processing 100-200 batches of space objects and cataloging 20-30 thousand point-trails, undertakes more than 70% space object's catalogue tasks.

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