Orbital Debris Observation via Laser Illuminated Optical Measurement Techniques

Makoto TAGAWA
Kyushu University
Toshiya HANADA
Kyushu University
Kozue HASHIMOTO, Yukihito KITAZAWA, Aritsune KAWABE
IHI Corporation

Abstract

This paper focused on evaluation of space-based observation system with several observation scenarios. In order to conduct calculation, we assumed optical sensor's specification. According to calculation using sample client satellite and/or TLE data sets, we summarize several results as initial evaluation. Next, we also evaluate dominancy of parameters in some scenarios. Finally, we conclude initial guiding principle of space-based observation system.

1. Introduction

Since first satellite launched in 1957, number of orbital debris is growing day by day as shown in Figure. 1. What is worse is that growth rate is getting faster and faster because of several break-up events, collisions and anti-satellite experiments. [1],[2]

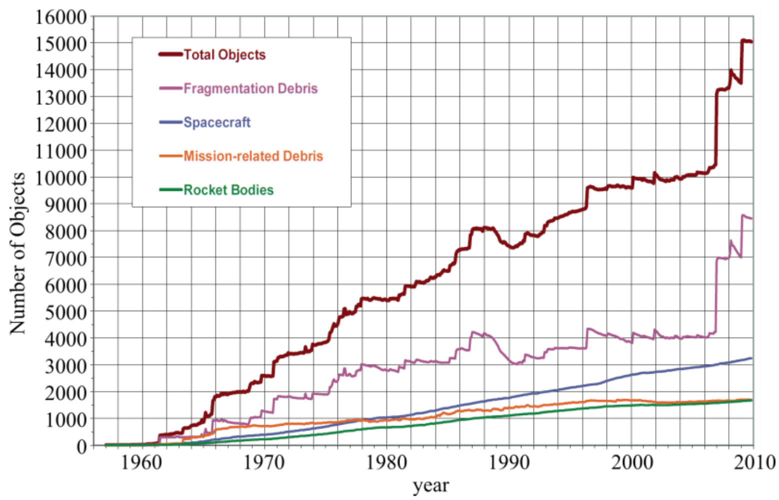

Figure. 1 Orbital objects number history [3]

Orbital debris related issues are very important for human space exploration and utilization. Therefore, we humans must undertake effective actions against those threats. Currently, there are four topics in this field. Observation, modeling, protection and mitigation measures. In this study, we focus on observation techniques. Generally, space observations are conducted from ground. It means observation capabilities are limited by atmospheric disturbance, weather, rotation of Earth and so on. Therefore, we propose space-based observation system. Final goal of this study is to evaluate space-based laser illuminated observation system totally. This paper focused on space-based systems as initial phase of study.

2. Current observation

In general, observation techniques are distributed in two major compartments. One is in-situ measurement and other is remote sensing.

2.1. In-situ measurement

This technique is mainly used for obtain statistical distribution data of orbital debris. The principle is detection and/or trace analysis of collisions. Because of such direct principle, this technique is excellent at minimum size of detectable objects. However, orbital data gathering and immediacy are weak points. This measurement technique is relatively easy to setup space-based system due to simple requirement for equips. Therefore, several observations are already conducted in space and studied even in universities.

Figure. 2. Long Duration Exposure Facility[4]

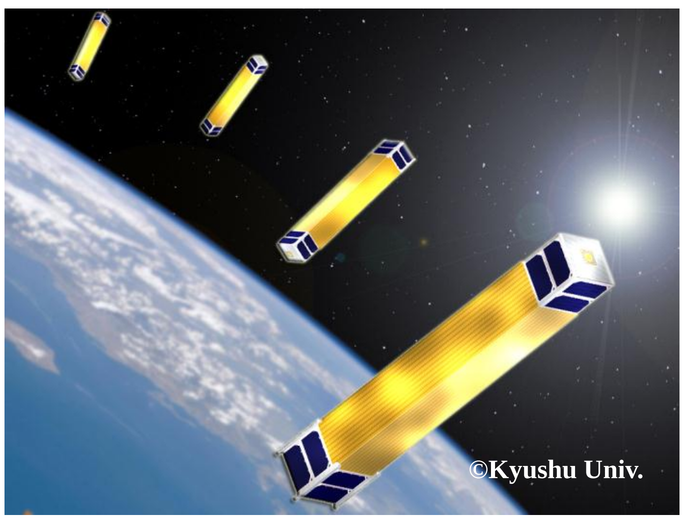

Figure. 3. Debris Measurement Constellation[5]

2.2. Remote sensing

This technique is mainly used for ground-based space observation and space-based Earth observation missions. Generally, remote sensing techniques in space development can be classified into these two types. One is radar, another is optical one.

3. Optical measurement

To detect and analyze optical data via camera module, we need sufficient level of brightness. Unfortunately, orbital debris do not blaze out by themselves. Hence, we need to consider on illuminators.

3.1. Sun illuminator

Using Sun as an illuminator is major method of this technique.

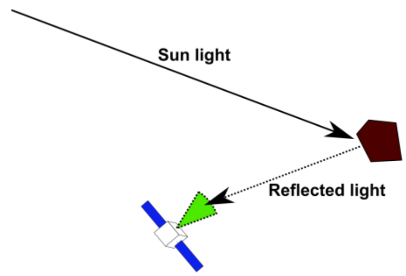

Figure. 4. Sun illuminator

This method is deeply depending on relative position between Sun, object and observation system. In addition, ground-based system would be bound by weather. For these reasons, observation capability would be restricted.

3.2. Laser illuminator

Using own equipment as an illuminator is good way to avoid capability limitation caused by relative position issue. And characteristics of illuminator can be configured what we want easily. Then system would potentially have capabilities not only detect and track objects but also identify those material or attitude change.

For these advantages, we choose laser-illuminated optical observation system as orbital debris observer. But this system requires additional power supply compare to Sun-illuminated system which is using natural resource as an illuminator. Therefore, we need to carefully consider observation capability.

4. Detection capability analysis

We calculate observation capability of space-based observation system using actual and generated TLE data sets of orbital debris. We defined two types of mission called “safeguard” and “surveillance”. In “safeguard” mission we calculate observation capability in terms of client’s threat coverage ratio and number of pictures on each object. In “surveillance” mission we also calculate coverage ratio toward all debris and conducted dominant factor analysis.

4.1. Prior conditions

4.1.1. TLE data sets

Current tracked-debris orbital information is only available for approximately bigger than 10 cm. And this number is bigger than 1 cm which is our target on limitation. Therefore, we generated imaginary TLE data sets premised on several break-up events in this decade. In process of generation we used NASA’s standard break-up model.

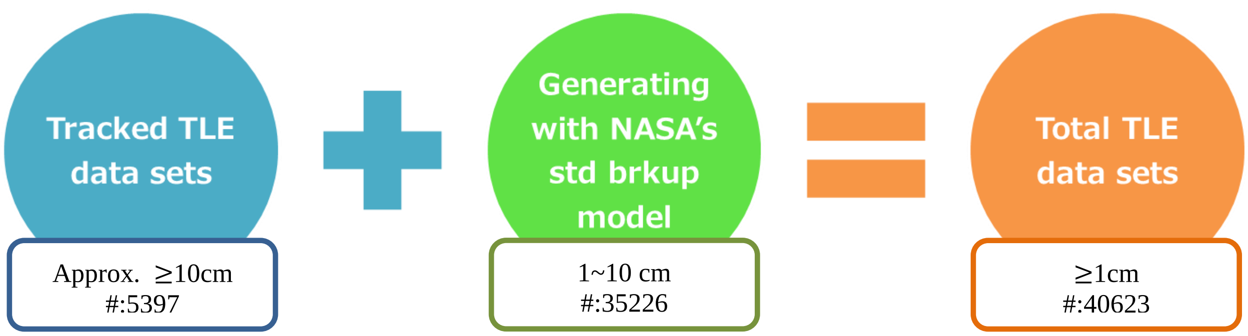

Figure. 5 TLE data sets

We used break-up events in this decade as source of NASA’s standard breakup model.

4.1.2. Mission epoch

We set mission epoch for 1 year as 1/Jan/2009 to 31/Dec/2009.

4.2. Safeguard

In this mission, main objective is to observe threat debris for client satellite. To calculate coverage ratio of threats for client satellite, firstly we conducted simple close approach analysis. Next, we also calculated observed objects by observation system.

4.2.1. Client

We picked up Japanese Earth observation satellite named GOSAT as a sample client satellite. [6]

Figure. 6 GOSAT

Orbital information of GOSAT is as follows.

Table. 1. GOSAT's orbital information

Launch date	Altitude approx.	Eccentricity	Inclination	Orbit type	Propagated RAAN at epoch start date
23/Jan/2009	667 [km]	0 [-]	98 [deg]	Sun synchronous sub-recurrent orbit	113[deg]

(RAAN stands for Right Ascension of the Ascending Node)

According these information and TLE data sets, we calculated close approached objects within 50 km from client satellite. Results of close approach analysis are to be described below.

Table 2 Close approach ratio

Number of all debris	Number of close approach debris	Close approach ratio
40623	3556	8.7[%]

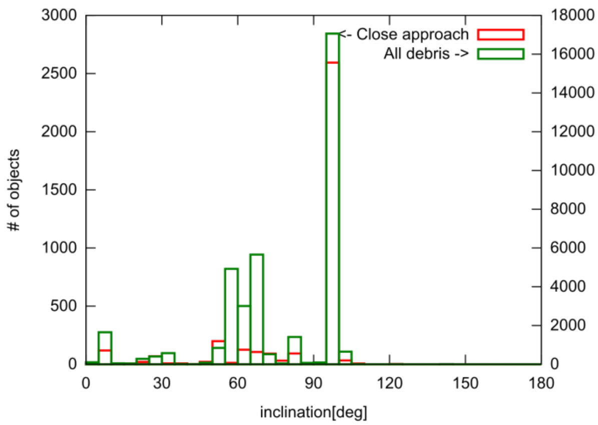

Figure. 7. Inclination distribution comparison

As shown in Figure. 7, number of close approach objects marks higher value when objects' inclination is near to client's one.

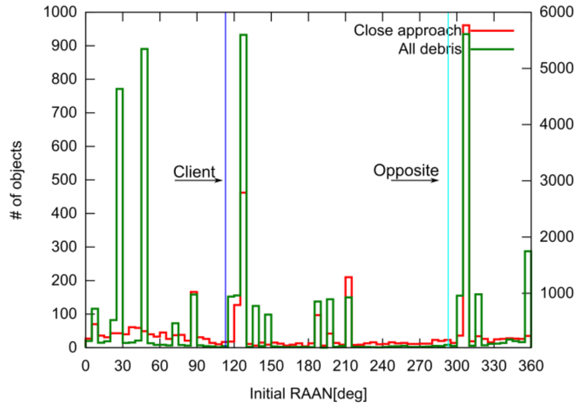

Figure. 8. RAAN distribution comparison

In Figure. 8. blue lines shows initial RAAN of client satellite and light blue line shows opposite. As shown in Figure. 8, RAAN distribution of close approach objects has two peaks. One is nearby client and another is opposite to client.

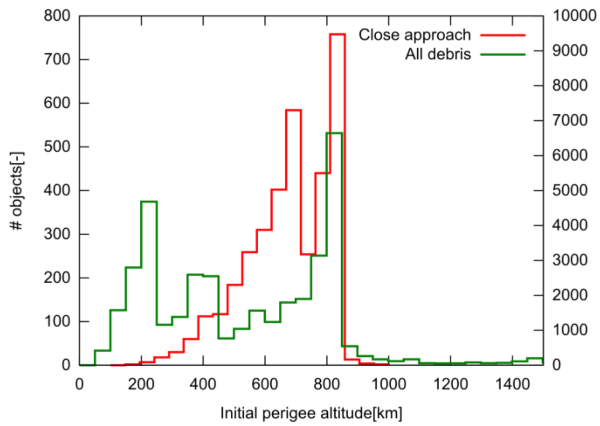

Figure. 9. Initial perigee altitude distribution comparison

As shown in Figure. 9, most of close approach objects are distributed around altitude approximately 400 – 900 km. This result mainly assumed to be due to altitude change caused by perturbations such as atmospheric drag.

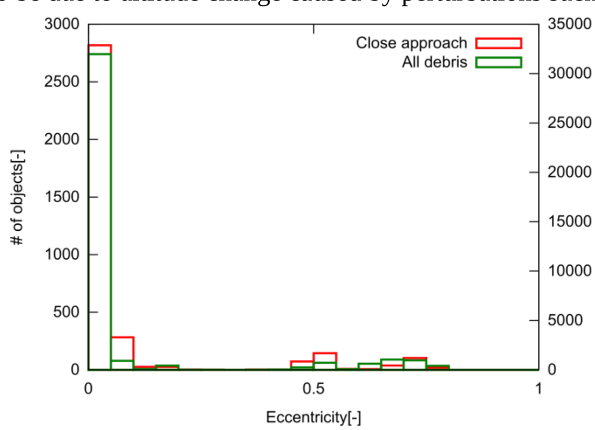

Figure. 10. Eccentricity distribution comparison

As shown in Figure. 10, most of debris are circular orbit. And most of close approach objects are also circular orbit. Now we summarize these four results as follows. Potential of close approach on each object is depended on orbital geometry and plane. Most of threat debris has almost same orbit with client satellite. We defined several observation scenarios with variation in terms of orbit to confirm relation between threats' orbit and observation system's orbit.

4.2.2. Agent

We assumed five scenarios shown in below as agent satellites. And calculate threat detection capability for each scenario.

Table. 3. Observation scenarios

Scenario name	Orbital characteristics
Look up from lower orbit	Same initial orbital plane with client. Different altitude with client - 600 km. Optical sensor points to outer space direction
Look down from higher orbit	Same initial orbital plane with client Different altitude with client - 900 km. Optical sensor points to Earth direction.
Phase shifted chaser	Same orbital plane with client 180-turned phase Optical sensor points to direction of movement
RAAN shifted traverser	Same orbital plane with client except RAAN 90-turned RAAN Optical sensor points to direction of movement
Equatorial traverser	Same altitude with client Equatorial orbital plane Optical sensor points to direction of movement

With optical sensor which details are shown in Table. 4.

Table. 4. Detector specification

Range	View angle	Sampling freq
300[km]	±15[deg]	5[Hz]

This study does not focused on certain system. And to calculate detection capability depend on several parameters, we assumed detector as such imaginary specification.Next, calculation results are shown in below.

Table 5. Detection ratios

Scenario	# of detected objects	Ratio to all debris	# of detected threats to client	Ratio to threats
Lower orbit	7242	17.8[%]	3333	**93.7[%]**
Higher orbit	7327	18.0[%]	3369	**94.7[%]**
Phase shifted	4853	11.9[%]	3365	**94.6[%]**
RAAN shifted	4900	12.1[%]	3367	**94.7[%]**
Equatorial orbit	4744	11.7[%]	3344	**94.0[%]**

According to Table 5, detection ratios of threats to client differ only slightly. Therefore, we need to use another evaluation approach. We focused on total number of pictures on each object taken by observation satellite.

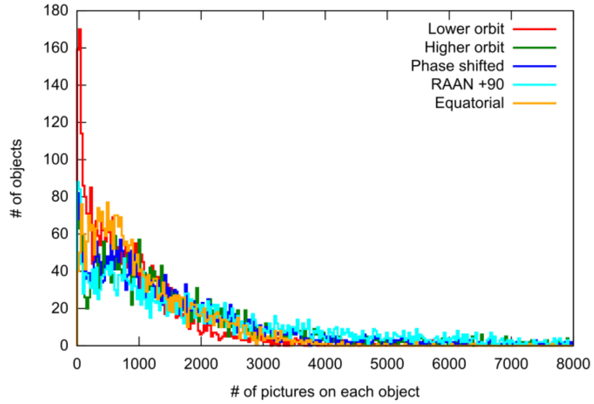

Figure. 11. Picture acquisition number distribution comparison

Figure. 11 shows distribution of total number of pictures. From this result “RAAN +90” scenario has better distribution profile because of number of object which has large number of pictures is greater than other scenarios.

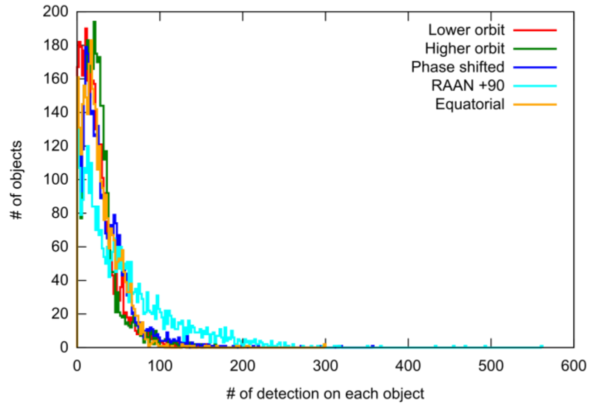

Figure. 12. Detection frequency distribution comparison

Figure. 12 shows total number of detection in mission epoch on each object. As shown in Figure. 12, “RAAN +90” scenario has tendency to detect in higher frequency. Other scenarios have almost same distribution profile.

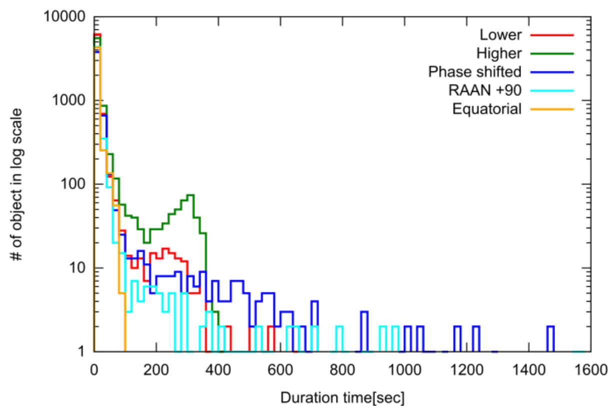

Figure. 13 Maximum duration time distribution

Figure. 13 shows maximum duration time on each object. In order to emphasize lower number of object region we used log scale as vertical axis in this figure. From this result “RAAN +90” scenario has tendency to detect object with shorter duration time. According to above results we conclude that orbit determination capability cannot be evaluated by number of pictures on each object. If the systems have same number of pictures on certain object, there would be two patterns of observation such as “continuous” and “intermissive”. Therefore, when evaluating orbit determination capability we should consider about these variance. It means orbit determination method takes big part of orbit planning of the space-based observation system.

Now, we mentioned undiscovered threats which account approx. 6% in each scenario. Following figures show orbital features of undiscovered threats.

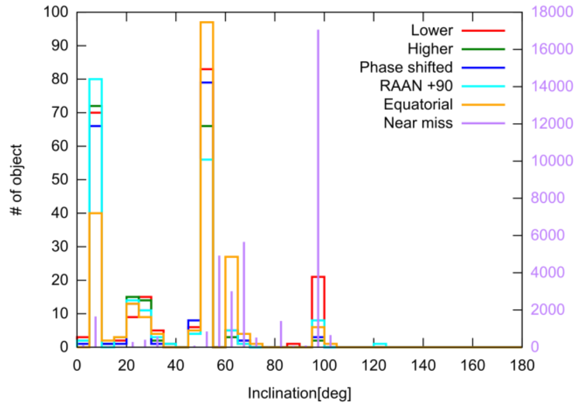

Figure. 14 Undiscovered threats' inclination distribution

Figure. 14 shows difference between safeguard scenarios and all threats' inclination distribution profile. There is a trend that object which has different inclination from client is difficult to detect compare to object which has almost same inclination of client. On the other hand, variances between scenarios are relatively small than that trend. It indicates that inclination difference between observation system and client satellite is not dominant for observation capability.

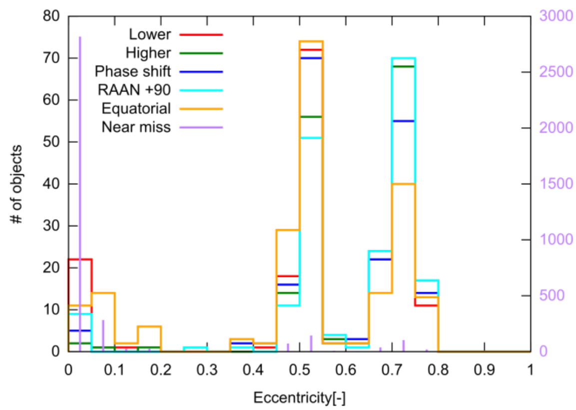

Figure. 15 Undiscovered threats' eccentricity distribution

Figure. 15 shows difference between safeguard scenarios and all threats' eccentricity distribution profile. This result indicates that non-circular orbit objects are difficult to be detected. But most of threats are circular orbit originally. Therefore, we summarized as observation system should focus on circular orbit object. From these two results we conclude that orbital geometry is more dominant compare to orbital plane.

4.3. Surveillance

We estimate importance of parameters from results as referred to above and modified observable region. According to Table 5 “Lower” and “Higher” scenarios have higher ratio compare to other scenarios. We focused altitude coverage ratio as cause for the result.

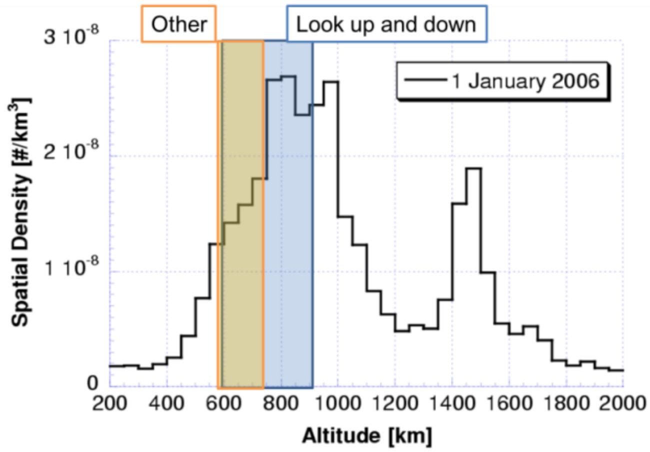

Figure. 16 Altitude coverage ratio comparison on spatial density distribution[7]

In Figure. 16 blue rectangular shows “Lower” and “Higher” scenario’s coverage region and yellow one covers other scenarios’ region. This figure basically shows spatial density distribution versus altitude. From this result “Lower” and “Higher” scenarios have potentially high capability to detect orbital debris in LEO compare to other scenarios. And from results in Table 5, no variance in threat detection ratio is confirmed. As we mentioned in above when we conclude total detection and orbit determination capability totally, we should consider on determination algorithm. But, for now, we recommend that observation system should be positioned on different altitude from target region and cover them.

Next, we discuss on optical sensor’s specification. We calculated picture acquisition capability in these two cases. “Longer range” and “Wider angle”. In both cases, observable volume is same as two times of original volume. To conduct this calculation, we selected two scenarios as objective. One is “Lower orbit” and another is “RAAN shifted orbit”.

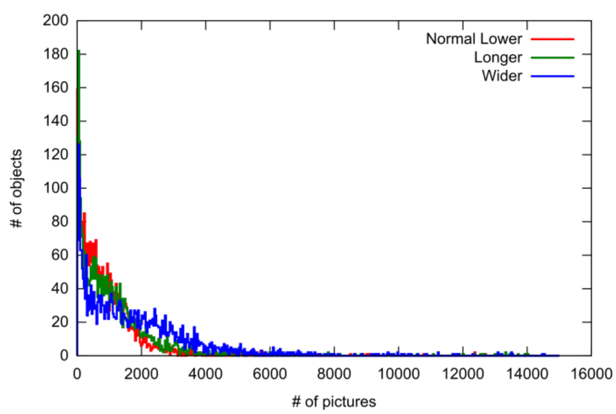

Figure. 17 Picture acquisition number distribution comparison in “Lower” scenarios

Figure. 17 shows comparison result of picture acquisition number in “Lower” and “Modified lower” scenarios. According to this result, expansion of observable volume has advantage in terms of picture acquisition number. And wider view angle modification has greater influence compare to longer range modification.

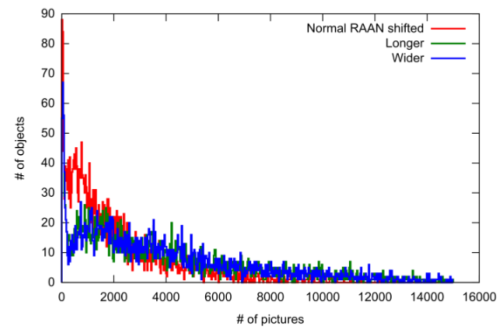

Figure. 18 Picture acquisition number distribution comparison in "RAAN shifted" scenarios

Figure. 18 also shows comparison result of picture acquisition number comparison along "RAAN shifted" scenarios. There is less advantage of observable volume expansion in terms of picture acquisition number than "Lower" scenarios. It indicates that parallel-to-orbit sensors are hardly affected by observable volume expansion compare to normal-to-orbit sensors.

5. Requirement study

Orbital determination calculation should be executed simultaneously. But simultaneous processing needs wider memory region and parallel processor. And resources on spacecraft are strictly limited. Therefore, we assumed simultaneous requirements. We defined pictures which were taken in every 10 seconds as a unit data. Results are follows.

Table 6 Simultaneous existence

Scenario name	Lower	Higher	Phase shifted	RAAN shifted	Equatorial
Maximum simultaneous #	7	6	7	5	4

From this result, we conclude as observation system should have processing performance which can process 7 objects at one time. However we should note that this calculation result came from current assumption.

6. Conclusion

When we consider coverage capability of client's threats, we should focus on client's orbital geometry especially altitude because of its low level of influence from orbital plane. And approximately 95 % of threats can be detected with every scenario using assumed detector. However, number of pictures on each object and continuity of observation are varies along scenarios. Therefore, we need to consider requirements from orbit determination algorithm and so on to evaluate observation capability totally. In surveillance mission, altitude covering is a key of evaluation. Therefore, if you have an almost same specification detector with we assumed, we recommend you to put the system "Lower" or "Higher" orbit.

Our future tasks are consisting of three major parts. First is calculating with real specifications such as intensity decay, object's attitude and reflectivity change and so on as space-based side. Second is considering object's physical characteristics such as orbit, attitude and material specify capability as laser illuminated side. And finally, we combine these two results and conclude capabilities totally.

7. References

1. NASA Orbital Debris Program Office: Orbital Debris Quarterly News,NASA,Vol13,Issue2,April 2009
2. NASA Orbital Debris Program Office: Orbital Debris Quarterly News,NASA,Vol11,Issue2,April 2007
3. NASA Orbital Debris Program Office: Orbital Debris Quarterly News,NASA,Vol13,Issue1,January 2009
4. Orbital Debris Surface Examinations: http://orbitaldebris.jsc.nasa.gov/index.html
5. Kenta Nagamine et al.: Proceedings of the 2009 Asia-Pacific International Symposium on Aerospace Technology (APISAT 2009), November 4-5, 2009
6. GOSAT Overview: http://www.jaxa.jp/projects/sat/gosat/index_e.html
7. Maniwa, Kazuaki et al.: Benefits of Active Debris Removal on the LEO Debris Population, 27th ISTS, 2009-r-2-04, July 7, 2009