Application Development with High Definition SSA Information

Takao Sato, Daisuke Yamashita, Daiki Mori, Touko Yamada
NEC Aerospace Systems, Ltd.
Masatoshi Ebara, Takahiro Okada, Taichiro Sano
NEC Corporation

ABSTRACT

Space systems are now an important infrastructure for our daily life and national security for many countries. There are emerging risks such as the collision with increasing space debris and threats caused by anti-satellite systems etc., which prevent us from using the space environment safely and stably. In order to mitigate these risks, leveraging "safety of flight" capability with the space situational awareness (SSA) system is effective. NEC has experimentally started SSA operation in Japan for the first time with our unique SSA system, leveraging high definition SSA information which allows us to provide maximum value.

Along with these capabilities, we also find it important to utilize the SSA information to other needs which are more mission oriented such as the GPS information or Earth Observation (EO) images. Through interviews with our potential customers, about leveraging the SSA information, we were able to consider their issues and needs. The most important concern was the dependence on Two-line elements (TLEs) as the orbit information of the space object. We can get TLEs easily, however, they are not enough to complete particular missions which request higher accuracy because of large positon uncertainty and low update frequency. High definition SSA information would allow us to solve these problems. Especially, the application in the Low Earth Orbit (LEO) region seems to be much in demand. For example, we assume that the information are useful for defense missions, checking the health of a satellite, planning the trajectory for debris removal missions, and Middle-Man (MM) service functions like avoidance maneuver recommendations. In this paper, we did two studies to investigate how much the difference between TLEs and the high accuracy ephemeris is effective. For some of the studies, we have utilized the original application integrated by System Tool Kit (STK). We are confident that the application which help the analysis of space system operators and the judgment by decision makers will increase in demand.

- Study 1 : Access Computation for camouflaging a Specific Target Point

It is important for us to understand the position and attitude of specific space objects passing by specific ground points for some missions. We developed an access computation application to generate the information of the access window and output the countdown time until a target point is accessed by a satellite. As a result, in case of the operation with a potential maneuver performed, we found that we could not ignore the difference between TLEs and high accuracy ephemeris for some missions.

- Study 2 : Space Object observation from another Space Object

When the mega constellation satellites come to reality, we might have occasions where we will need to take pictures of anomaly space object from other close orbiting satellites for a health check. In this mission, SSA information like TLEs will play an important role as the orbit information. However, we found that there are many situations where this mission will not work with the TLEs capability and leveraging high accuracy ephemeris is mandatory for this use case.

In these studies, we focused on only the orbit information of TLEs and high accuracy ephemeris. In future, the advancement of SSA capability enables us to leverage the characterized information of each space objects like sensor Field of View (FOV) to perform an advanced analysis. Application development using these various information is left for our future work.

1. INTRODUCTION

In Japan, Quasi-Zenith Satellite System (QZSS) services, QZSS is sometimes called the "Japanese GPS", were started officially on 1 Nov. 2018[1]. It is expected that these services enable us to acquire stable and high accuracy positon information in urban and mountainous areas. Thus, space systems are now an important infrastructure for our daily life for many countries. On the other hand, there are emerging risks which prevent us from using the space environment safely and stably. One of the major risks is the increase of space debris. Fig. 1 shows the evolution of published space objects as a function of time[2]. As we can see in Fig. 1, the number of space debris will increase year by year, not just because of emerging additional launches, but chain-reaction collisions of space debris (Kessler Syndrome) are potentially a dominant threat. From these prospects, it is important to consider how we protect our asset from these increasing space debris. Another reason, we should not ignore are the impacts caused by the developments and experiments of the anti-satellite (ASAT) weapons. On 27 Mar. 2019, India attempted ASAT test of the 4th country of history. We can assume that not only India but also some other nations have the capability of determining target spacecraft's trajectory and intercepting the target accurately. In order to mitigate these risks, leveraging "safety of flight" capability with the Space Situational Awareness (SSA) system is effective. As a demand, NEC started to develop the unique commercial SSA system prototype in Japan, which we call the NEC Commercial Space Operation Center (NEC ComSpOC). The system is utilized with the help of various Analytical Graphic Inc. (AGI) products and we have experimentally started SSA operation in-Japan for-Japan. From the operations, we have been able to possess the various SSA information of some space objects such as High Definition Ephemeris, the trend of maneuver performance and the results of Conjunction Assessment (CA) uniquely.

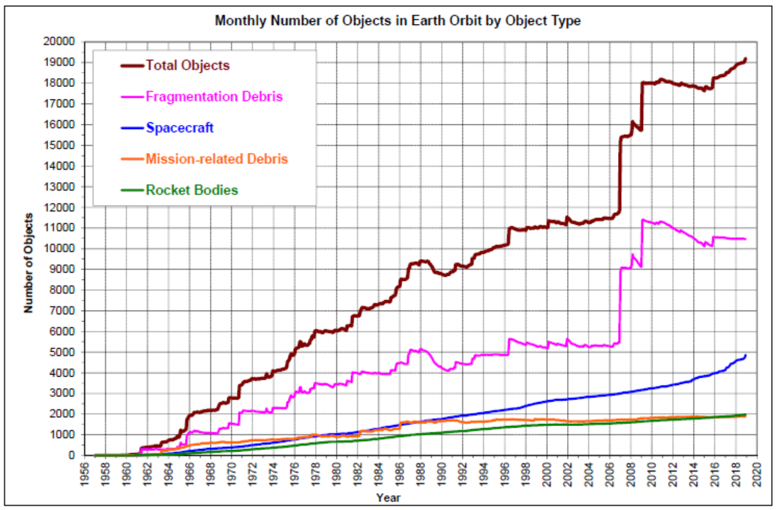

Fig. 1 Number of published space objects[2]

2. CONCERNS AND HYPOTHESES

2.1 Our potential customer concerns

Along with the capability to possess the SSA information, we also find it important to utilize the SSA information to other needs which are more mission oriented. For example, the positioning information like Global Navigation Satellite System (GNSS) is utilized to the navigation functions such as those used in car navigation systems and smartphones. Also, Earth Observation (EO) images are utilized to the prevention of disaster such as the volcanic eruption and flood, and the grasp of the earth resources and environments. Through interviews about leveraging the SSA information with our potential customers, we were able to consider their concerns and needs. The most important concern was the dependence on Two-Line Elements (TLEs) as the orbit information of the space objects. Though TLEs are very convenient, they are sometimes not enough to achieve particular missions which demand higher accuracy because of larger positon uncertainty and lower update frequency the TLEs face. High accuracy ephemeris would allow us to solve these problems.

2.2 Our hypotheses

Recently, many mega constellation satellites are planned in Low Earth Orbit (LEO) as shown by Tab. 1[3]. In fact, the first large batch of the deployment of the SpaceX Starlink constellation, occurred on 24 May 2019 when the first 60 operational satellites were launched, gave people the actual sensation that the LEO region would be crowded more and more. Therefore, Owners and Operators (O/O) of each satellites would have to take various measures to leverage the satellite constellation system safety. For self-defense and undercover missions especially, there are cases where these missions on the ground do not like to be potentially visible from these satellites existing in LEO.

Due to these backgrounds, the high definition SSA information is likely to be demanded in the LEO region especially. The following are a few example cases, where to be applied.

(1) Camouflage of the target point
For some operations, it is necessary to camouflage activity points which can be potentially observed from LEO satellites. It will help decision makers to grasp the time spans when they should camouflage their actions on the ground correctly by utilizing ephemeris and predicting the time window accessed by the LEO satellites.

(2) Space object health check
When the mega constellation satellites are fully operated, we might have occasions where we will need to take pictures of anomaly space objects from other close orbiting satellites for a health check. In this mission, SSA information like TLEs will play an important role as the orbit information in order for the other satellite's sensor to point toward the target space object.

(3) Active Debris Removal (ADR) missions
One of the big issues of the ADR missions is how the ADR satellites approach and rendezvous with the non-cooperative (more non-responsive) space objects like the space debris. According to [4], the basic approach procedure is considered like below.

1. Rendezvous Phase based on TLEs : - 100km
2. Rendezvous Phase based on Angles-Only Navigation (AON) : - 1km
3. Proximity Operation Phase based on Model Matching Navigation (MMN) : - 30m
4. Final Approach Phase : Within 30m

Within this approach strategy, there is a possibility that we can skip the AON Rendezvous Phase and the ADR satellites are able to approach the target debris more quickly by utilizing ephemeris instead of TLEs.

(4) Middle-Man service functions like avoidance maneuver recommendations
Many O/O rely on the Conjunction Data Messages (CDMs) from the Combined Space Operations Center (CSpOC) to perform CA and operate the maneuver for the debris avoidance. In this process, it is difficult for O/O to do timely decisions, and some O/O even do not have the capability to decide the correct options. NEC ComSpOC can work as Middle-Man (MM) function[5] and offer the CDMs created with utilizing ephemeris. We believe that these CDMs would enable O/O to do more accurate and timely operation.

In this paper, we did two studies about (1) and (2) to investigate how much the difference between TLEs and ephemeris is effective. For some of the studies, we have utilized the original application integrated by System Tool Kit (STK). We are confident that the demand for the application which help the analysis by space system operators and the judgment by decision makers will increase.

Tab. 1 A subset of proposed LEO Satellite Constellation[3]

Company	Number of Satellites
Space X	11943
Boeing	2956
OneWeb	2720
Hongyan	324
TeleSat	234
Kepler Communications	140

3. CASE STUDIES

We utilized the data of ASNARO-2 (AS2), which is an earth observation satellite that NEC owns and operates, as the example of the LEO satellites. We chose the data span including maneuvers because we assumed that the difference between TLEs and ephemeris become larger in this span. Hereinafter, we refer to the data of AS2 based on TLEs and ephemeris as "AS2_TLE" and "AS2_EPH" respectively. Tab. 2 shows the details of test data for these studies. Fig. 2 shows the relative range between AS2_TLE and AS2_EPH in this data span. From Fig. 2, after 18

July, we found that there was a large difference between TLEs and ephemeris (the relative range was nearly 17 km). Based on the behavior of this relative range, we considered the analysis spans of each studies.

Tab. 2 Details of test data

Satellite	ASNARO-2 (SSN.43152)
Data Span	17 Jul 2019 00:00:00 – 21 Jul 2019 00:00:00
TLE Epoch*	■ 17 Jul 2019 02:17:08.012 UTCG ■ 17 Jul 2019 12:02:00.508 UTCG ■ 17 Jul 2019 19:47:41.204 UTCG ■ 18 Jul 2019 01:56:39.283 UTCG ■ 18 Jul 2019 06:48:06.951 UTCG ■ 18 Jul 2019 14:47:58.676 UTCG ■ 18 Jul 2019 19:15:36.043 UTCG ■ 19 Jul 2019 04:40:33.155 UTCG ■ 19 Jul 2019 11:22:08.222 UTCG ■ 19 Jul 2019 20:40:42.056 UTCG ■ 20 Jul 2019 02:50:40.927 UTCG ■ 20 Jul 2019 12:26:16.893 UTCG ■ 20 Jul 2019 18:37:34.050 UTCG

*We got the TLEs data from SPACE-TRACK.ORG (https://www.space-track.org/#/tle) and propagated each TLEs data by SGP4 propagation.

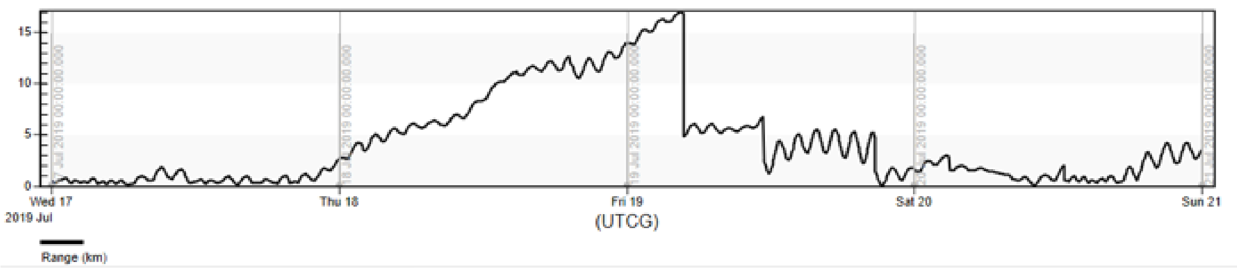

Fig. 2 Relative range between TLEs and ephemeris

3.1 Access computation for camouflaging a specific target

We set a voluntary target point on the ground and consider that some missions are performed on this point. In order to camouflage these target points, we need to grasp when this point is potentially visible by the LEO satellites, in a demanded accuracy. Therefore, we investigated how much difference between TLEs and ephemeris there was in the access timing by the sensor attached on a satellite. We assumed that this satellite has a simple rectangular swath sensor and we can set the sensor half angle, which is Field of View (FOV) angle, arbitrarily. As a target point, we used the latitude and longitude of Tokyo (35.6°W and 139.7°N respectively).

Fig. 3 shows the relative range if TLEs data were not updated after 18 July. In this case, the relative range increase to 40 km as the maximum value. Therefore, in this study, we assumed two test cases which TLEs data was updated or not and adopted the two data spans like below.

- Analysis data spans
  - 1st Data Span: 17 Jul. 2019 00:00:00 - 19 Jul. 2019 00:00:00
  - 2nd Data Span: 17 Jul. 2019 00:00:00 - 21 Jul. 2019 00:00:00

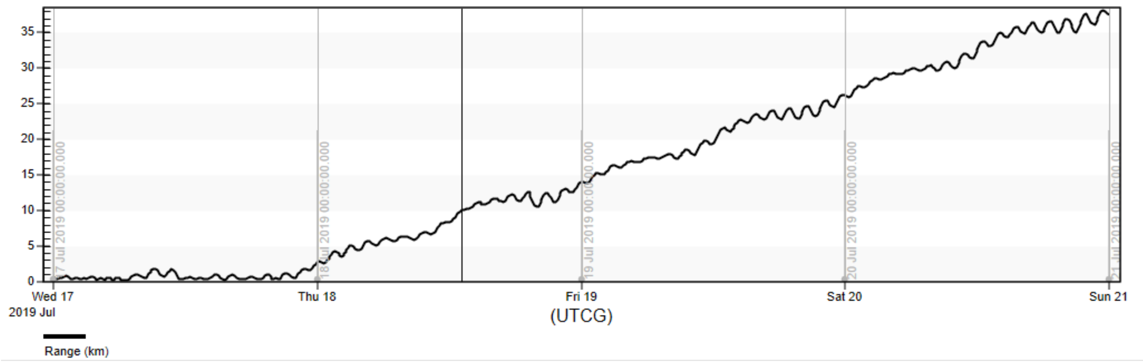

Fig. 3 Relative range between TLEs and ephemeris if the TLEs data were not updated after 18 July 2019.

3.1.1 Results of 1st data span

Fig. 4 shows the results of the access timing in the cases which the sensor half angle is 20° and 45°. Also, Tab. 3 shows the differences of the access start time between ephemeris and TLEs. From these results, we find that the difference of up to 2 seconds in the access timing occurred when the sensor half angle is 45°.

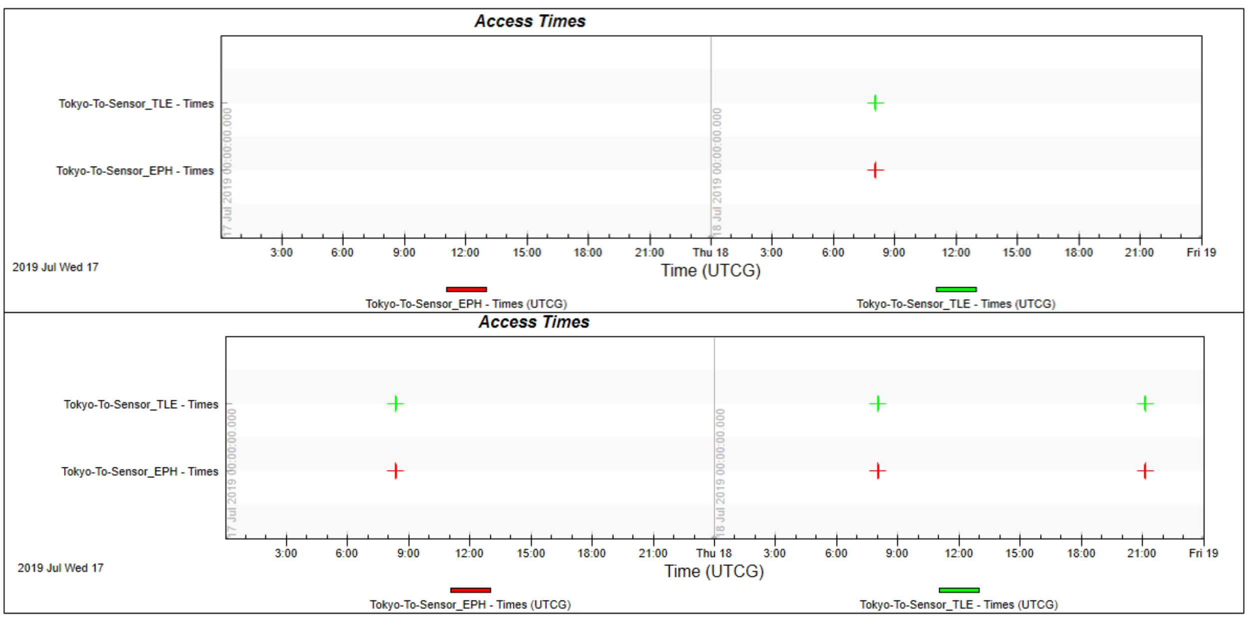

Fig. 4 Results of Access Timing. Top: the sensor half angle is 20°. Bottom: the sensor half angle is 45°.

Tab. 3 Comparison of access start time between TLEs and ephemeris

Sensor Half Angle [°]	Access Count	TLEs	Ephemeris	Difference between TLEs and ephemeris [s]
20	1	18 Jul 2019 08:01:45.458	18 Jul 2019 08:01:46.289	0.831
45	1	17 Jul 2019 08:21:04.197	17 Jul 2019 08:21:04.139	-0.058
45	2	18 Jul 2019 08:00:57.313	18 Jul 2019 08:00:58.150	0.837
45	3	18 Jul 2019 21:06:18.820	18 Jul 2019 21:06:20.428	1.608

3.1.2 Results of 2nd data span

Fig. 5 shows the results of the access timing in the cases which the sensor half angle is 20° and 45°. Tab. 4 shows the differences of the access timing between ephemeris and TLEs. From these results, we find that the difference of up to 5 seconds in the access timing occurred when the sensor half angle is 45°. We hear that there are some missions for which this time difference is critical.

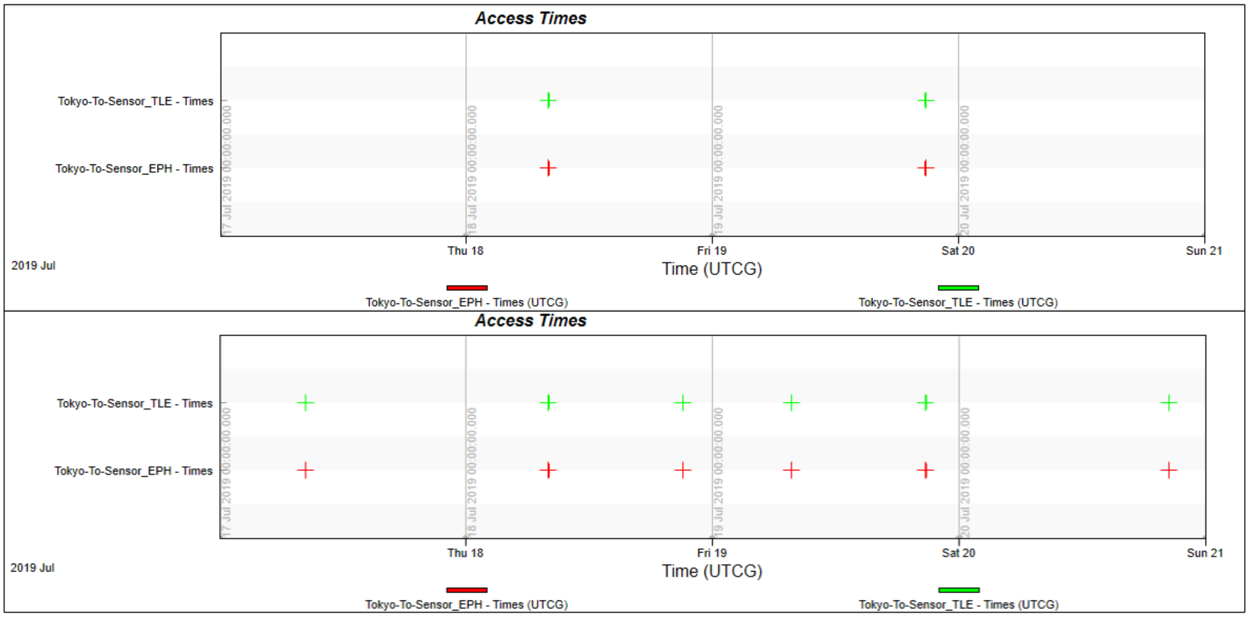

Fig. 5 Results of Access Timing. Top: the sensor half angle is 20°. Bottom: the sensor half angle is 45°.

Tab. 4 Comparison of access start time between TLEs and ephemeris

Sensor Half Angle [°]	Access Count	TLEs	Ephemeris	Difference between TLEs and ephemeris [s]
20	1	18 Jul 2019 08:01:45.458	18 Jul 2019 08:01:46.289	0.84
20	2	19 Jul 2019 20:47:02.099	19 Jul 2019 20:47:05.285	3.186
45	1	17 Jul 2019 08:21:04.197	17 Jul 2019 08:21:04.139	-0.058
45	2	18 Jul 2019 08:00:57.313	18 Jul 2019 08:00:58.150	0.837
45	3	18 Jul 2019 21:06:18.820	18 Jul 2019 21:06:20.428	1.608
45	4	19 Jul 2019 07:42:52.097	19 Jul 2019 07:42:53.295	1.198
45	5	19 Jul 2019 20:46:14.215	19 Jul 2019 20:46:17.441	3.226
45	6	20 Jul 2019 20:26:01.029	20 Jul 2019 20:26:05.873	4.844

3.1.3 Application development for camouflaging a specific target

From the results of this study, in case that the operation with a potential maneuver performed, we find that we cannot ignore the difference between TLEs and ephemeris for some missions. Due to this fact, it is important that the decision makers correctly understand "when and by which satellites the target point is visible" and "how long and when it is physically impossible to be so" in order to camouflage missions on the ground. We assumed these needs and developed the original application integrated by STK, which outputs the graph of the access timing and computes the countdown time until the satellites approach a target point. Fig. 6 shows the image of this application. The explanation of this application is shown in the following.

a. Create scenario

We set the start and stop time of the analysis span and push "Create Scenario" button.

b. Set of target point

We set the latitude, longitude and altitude of a target point and push "Set Target Point" button.

c. Get satellites information

We choose the kind of satellites and the source of orbit information, set the sensor half angle and push “Get Satellites”.

■ Satellites select

Satellites are specified by Space Surveillance Network (SSN) number (NORAD ID) or selected by owners. When we specify SSN numbers, we can select the multiple satellites with using commas separator (Ex., 11111,22222,33333,…). When we specify owners, we can select one or multiple from Japan (JPN), U.S.A (US), China (PRC), Russia (CIS) and OTHERS. By the way, this time the satellite information is of only “Active” satellites in LEO region, and “Inactive” satellites, space debris and Geosynchronous Earth Orbit (GEO) satellites are out of scope, for simplicity.

■ Data source select

We can select from Online, Offline database, NEC ComSpOC data and ephemeris files with STK format as the data source. When we select Online or Offline data, we utilize TLEs data and propagate with SGP4 propagation in the scenario span. When we select NEC ComSpOC data, we can utilize ephemeris possessed in our system and get the analysis results with high precision.

d. Access computation and graph output

In order to compute the access timing between a target point and the sensors attached on each satellite, we push “Access Computation”. Based on these access computation results, the graph which enable us to figure out the access or non-access windows of the selected satellites is outputted.

e. Animation

By pushing “Play” button, we can confirm the situation of satellite approach in visualization. According to the animation time, the application users are notified of by which satellite the target point is seen with the countdown time.

We tried to calculate the access window with utilizing this application in the following setting.

■ Settings

- Scenario span: 20 Aug. 2019 00:00:00 – 21 Aug. 2019 00:00:00
- Target point: Tokyo (Latitude: 35.6°N / Longitude: 139.7°W)
- Satellite information
  - Owners: US, PRC, CIS
  - Date Source: Offline TLEs
  - Sensor Half Angle: 45°

Fig. 7 shows the result of the access window calculation. From this result, when we assume that the target point is seen by all LEO satellites possessed by US, PRC and CIS, we find that the timing when that point is not seen by any satellites is infinitely small. In this calculation we utilized TLEs data, however, we would be able to obtain more meaningful information with selecting the satellite more specifically and utilizing ephemeris possessed in our system.

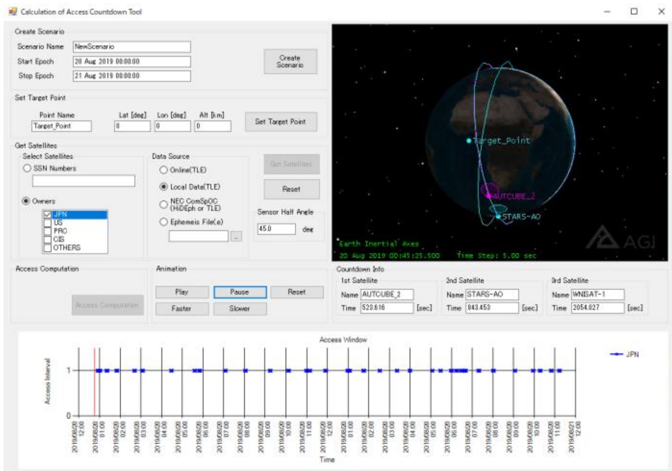

Fig. 6 Image of our original application

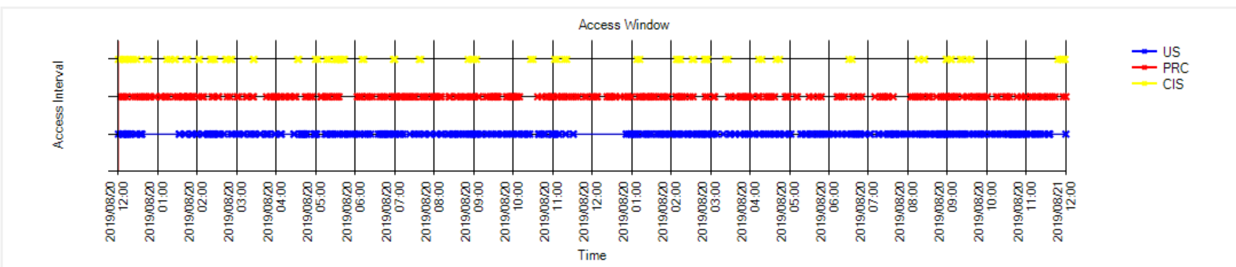

Fig. 7 Access window calculated by our original application.

3.2 Space object observation from another space object

We considered a mission that needs to take pictures of a space object from other close orbiting satellite. In order to investigate that effects to be caused when we utilize TLEs or ephemeris as the orbital information, we assumed that we take pictures of AS2 from the simulated satellite (hereafter we refer to this simulated satellite as SimSat). In particular, we investigated whether AS2_EPH exists in the imaging area of SimSat or not when we take pictures with assuming that AS2_TLE is correct. In this study, we did not consider that SimSat rendezvous with AS2 and took a picture when the relative range between SimSat and AS2 becomes under 500 km. In addition, we assumed that SimSat has the sensor with a half angle of 0.573°, which means that the imaging area becomes 10km square at the relative range of 500 km. The orbital information of SimSat is below.

- SimSat orbital information
  - Orbit Epoch : 17 July 2019 00:00:00
  - Apogee Altitude : 500km
  - Perigee Altitude : 500km
  - Inclination : 80°
  - Right Ascension of Ascending Node : 0°
  - Argument of Perigee : 103°
  - True Anomaly : 151°

From Fig. 2, we adopted the two data spans like below.

- Analysis data spans
  - 1st Data Span: 17 July 2019 00:00:00 - 18 July 2019 00:00:00
  - 2nd Data Span: 18 July 2019 00:00:00 - 19 July 2019 00:00:00

3.2.1 Results of 1st data span

Fig. 8 shows the relative range between SimSat and AS_EPH. This relative range is outputted only when AS2_EPH exists in the imaging area of SimSat. From this result, when the relative range between these two satellites becomes under 500 km, we can find that AS2_EPH exists in the imaging area of SimSat certainly. In addition, Fig. 9 shows the visualization of the imaging area of the sensor attached on SimSat when the relative range becomes 500 km. We are also able to find that AS2_EPH exists in that area. Therefore, we can consider that we are able to take pictures with utilizing TLEs if the relative range between AS2_TLE and AS2_EPH is small enough.

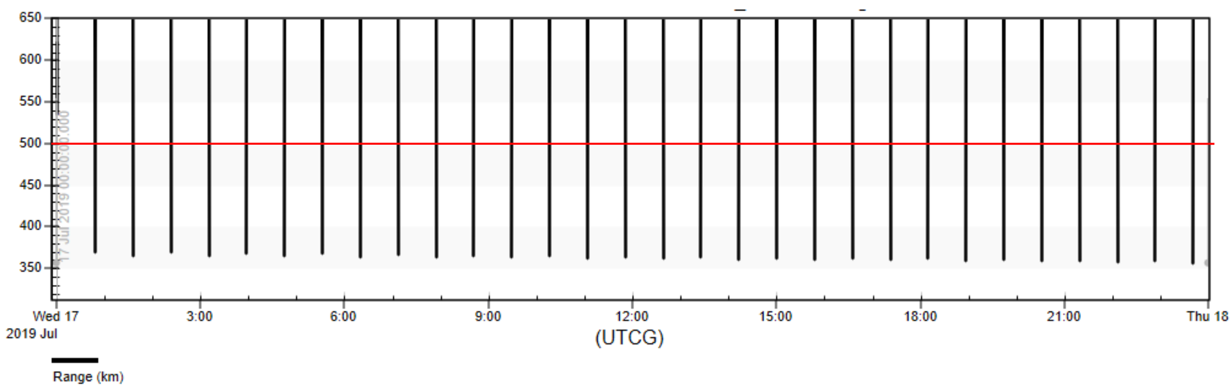

Fig. 8 Relative range between SimSat and AS2_EPH

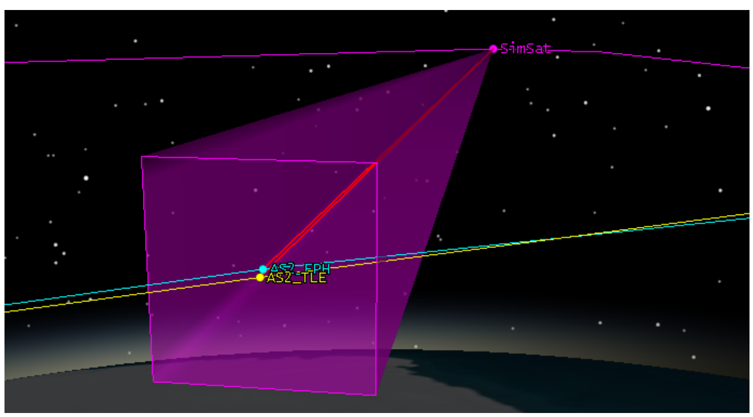

Fig. 9 Visualization of the imaging area of the sensor attached on SimSat. In this case, both of AS2_TLE and AS2_EPH exist in the imaging area because AS2_TLE is close to AS2_EPH enough.

3.2.2 Results of 2nd data span

Fig. 10 shows the relative range same as Fig. 8. From this figure, we can find that there are some spans when AS2_EPH doesn't appear in the imaging area of the sensor attached on SimSat at the relative range of under 500 km. In addition, Fig. 11 shows the visualization image same as Fig. 9. We are also able to find that AS2_EPH is out of the imaging area of SimSat's sensor. This study suggests that it is difficult for us to take pictures with utilizing only TLEs when the relative range between AS2_TLE and AS2_EPH is large because of the maneuver operation.

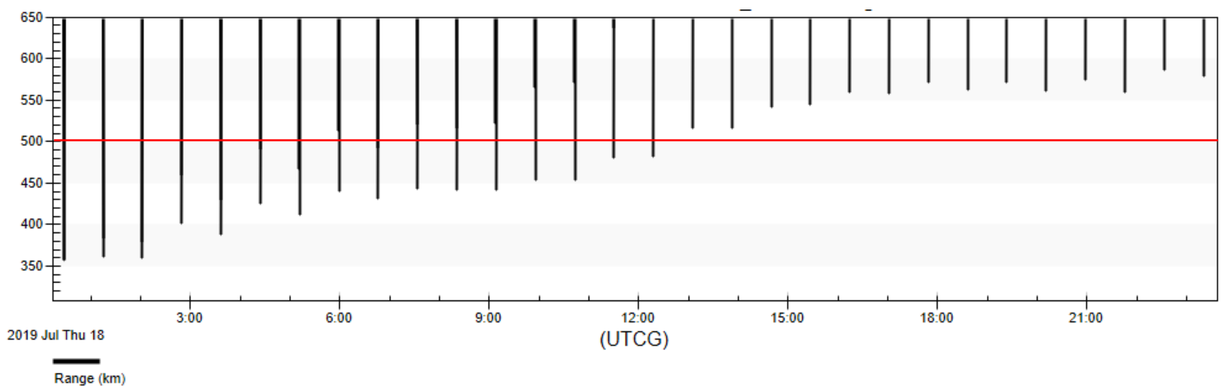

Fig. 10 Relative range between SimSat and AS2_EPH

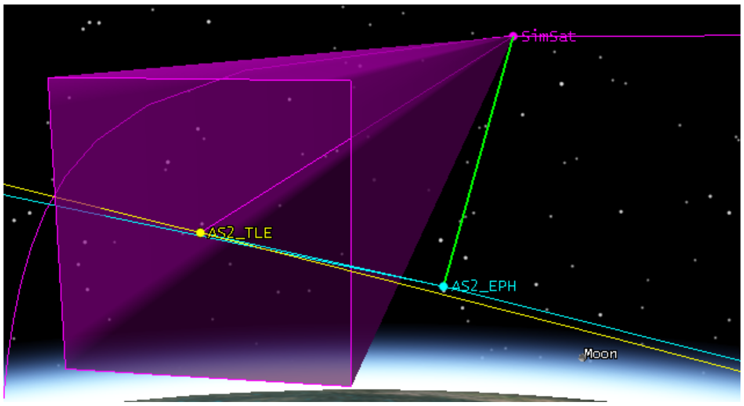

Fig. 11 Visualization of the imaging area of the sensor attached on SimSat. In this case, AS2_EPH is out of the imaging area.

4. SUMMARY AND FUTURE WORK

We focused on the difference between TLEs and ephemeris and did two studies in order to consider the way of leveraging the high definition SSA information. We also developed the original application for these studies. With a maneuver-performed operation by the target, we found that difference could not be ignorable depending on the mission. In these studies, we focused only on the orbit information of TLEs and ephemeris. In future, the advancement of SSA capability enables us to leverage the characterized information of each space object like sensor FOV to perform an advanced analysis. Application development using these various information is left for our future work.

REFERENCES

[1] https://qzss.go.jp/en/overview/notices/qzss_181101.html, Accessed 21 Aug. 2019
[2] Orbital Debris Quarterly News, Volume 23, Issue 1&2, May 2019, NASA/JSC
[3] Adam Archuleta, Michael Nicolls, Space Debris Mapping Services for use by LEO Satellite Operators, In *Advanced Maui Optical and Space Surveillance Technologies Conference*, September 2018.
[4] Naomi Murakami, Toru Yamamoto, “Rendezvous Strategy for the Active Debris Removal Missions”, In *Space Debris Workshop*, 2016.
[5] François Laporte, JAC Software, Solving Conjunction Assessment Issues, In *Advanced Maui Optical and Space Surveillance Technologies Conference*, September 2014.