ASTORO-2021-C011Practical satellite constellation operation for orbit phasing and maintenance

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Abstract

The proliferation of low earth orbit small satellites for various applications, these satellites often work as a constellation to provide network effect advantages and commercial values. Constellation operation has become an essential capability to ensure the satellites could coordinate, phase and maintain their orbit. This paper aims at addressing challenges of constellation formation between existing and newly inserted satellites and how the orbit is maintained throughout the mission using the practical case of the GRUS-1 satellites forming the AxelGlobe constellation for earth observation application.

1. Introduction

On Mar 22nd 2021, Axelspace launched 4 satellites that are production model satellites for earth observation. They were launched from Baikonur. The same year, from April to May, Axelspace did the operation for aligning satellites in the same orbit plane - the so-called phasing operation. The constellation was named AxelGlobe and is the first constellation of earth observation satellites in Japan.

For the phasing operation, Axelspace used the Orbital Dynamics System (ODS) which was developed by Axelspace for creating an orbit control plan. In this paper, we introduce the notion of phasing operations and the main algorithm of ODS.

2. Regarding AxelGlobe

AxelGlobe launched its service from May 2019 with 1 satellite. From June 10th AxelGlobe started to provide the service with 5 satellites.

The satellites in the AxelGlobe constellation are named Grus. They are identified alphabetically, like GRUS-1A, GRUS-1B, etc.. Axelspace has a plan to launch 5 more satellites until 2023 and make AxelGlobe a 10-satellite-constellation.

The service is providing earth observation images which are being captured by the Grus satellites constantly and frequently. In 2021, AxelGlobe can provide max 6 images per month by 5 satellites. The Satellites are revisiting same places in roughly 2~3 days, depending on the location.

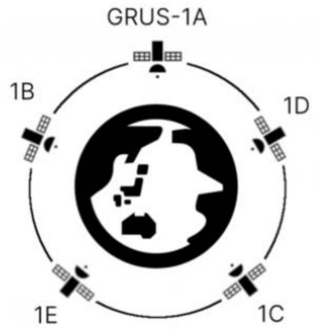

Figure 2.1 AxelGlobe on orbit layout

3. Ground system for orbit

An overview of ODS and the peripheral systems is shown in Figure 3.1. All systems of Figure 3.1 are automated. After data is downlinked in X-band downlink passes, the latest orbital information will be created and visualized without human operations.

For X-band downlink, Axelspace is using the KSAT Svalsat ground station in Svalbard. The system is running as a cloud service on AWS (Amazon Web Service)

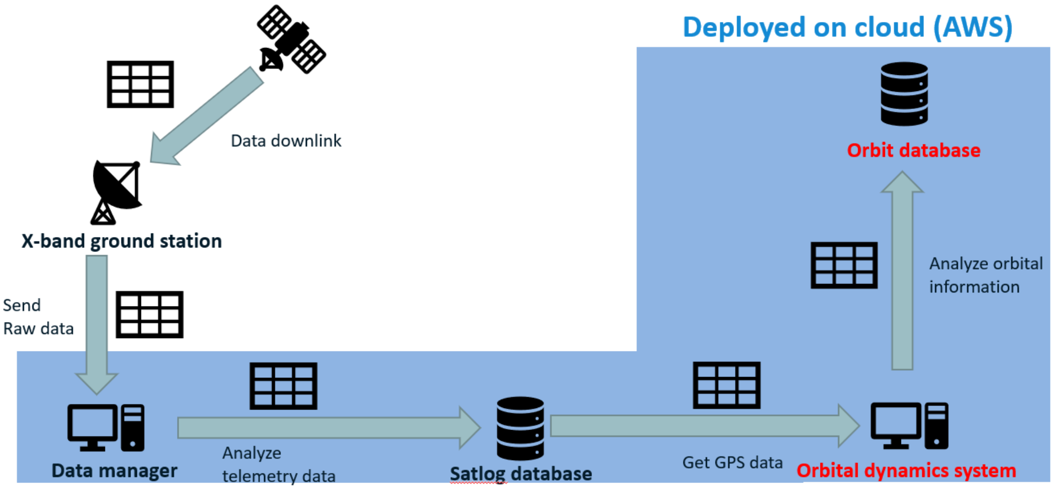

Figure3.1 Overview of ODS and peripheral systems

4. Visualize orbital information

Axelspace is visualizing all telemetry by Grafana since the RAPIS-1 project in 2019. Grafana is a web application which was released in 2014. Everyone can visualize time series data easily by selecting table names and field names on a web GUI.

In Axelspace, an operator can monitor orbit status easily by using this application.

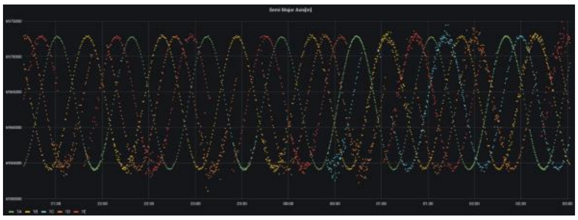

Figure 4.1 Visualized orbit example by Grafana

5. Operation history

In this chapter, we introduce the phasing operation's detailed history. At first, the operation phase was separated into 3 phases which are **injection to the parking orbit**, **phasing** and **injection to the target orbit**.

5.1. Injection to the parking orbit

In this phase, each satellite's altitude was changed in order to reach the target within 90 days after launch. 90 days was determined by AxelGlobe service as the target time to complete the phasing operation since Axelspace was planning to finish the phasing operation before service-in.

Figure 5.1 shows each satellite's phasing geometry immediately before phasing operation started (Apr 5th in 2021) The vertical axis is the semi major axis and the horizontal axis is the phase angle difference from 1A. Orange lines are lined by 72[deg] interval. Each line indicates the target phase of each satellite. These phase angles are calculated by mean latitude argument difference.

Immediately after launch, because all satellites altitude were higher than 1A, they were moving rear from 1A. Satellites were lined up E, D, C, B in ascending order of altitude. So, every time the satellites reached the target phase, the lowest altitude satellite was planned to inject into the target orbit.

Then, from Apr 9th to 12th 1E's altitude was lowered. At that time, completion of the phasing operation was scheduled for early June.

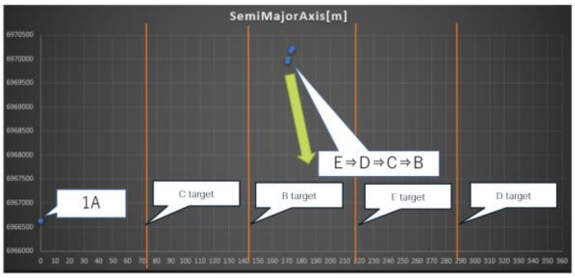

Figure5.1 constellation diagram at 2021-04-05

Figure5.2 is a constellation diagram from Apr 14th 2021.At that stage, the operation schedule was updated and the deadline was changed from early June to the end of May because some extra margin days for service-in were planned. As a result, 1E changed the target where 1B was originally planned to inject. 1B was changed the target where C was originally planned to inject. In that way, the phasing operation end could be moved to an earlier date. But for finishing by the end of May, the altitude of 1B had to be raised. This was done on Apr 13rd and 14th around 1.0[km].

On the other hand, because 1E had to be backed to the front, 1E altitude was lowered by around 1.5[km]

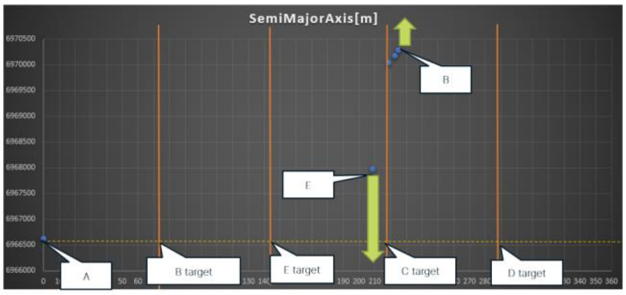

Figure 5.2 constellation diagram at 2021-04-14

Figure5.3 shows the constellation diagram from Apr 19th 2021. Because it was necessary to inject 1C or 1D into the third position from 1A, 1C or 1D had to be backed to the front. At that time, D altitude was lower than 1C, but because 1D did not establish fine 3-axis attitude control, 1C's altitude was lowered by 700[m] on Apr 19th and 20th.

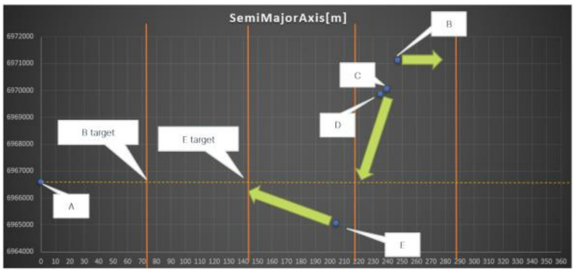

Figure 5.3 constellation diagram at 2021-04-19

Figure5.4 shows the constellation diagram from Apr 23rd 2021. At that time, 1D had established fine 3-axis attitude control and its altitude was lowered by around 500[m] on Apr 28th and 29th.

With this operation, all satellites had been successfully injected into the parking orbit, marking the end of phase1.

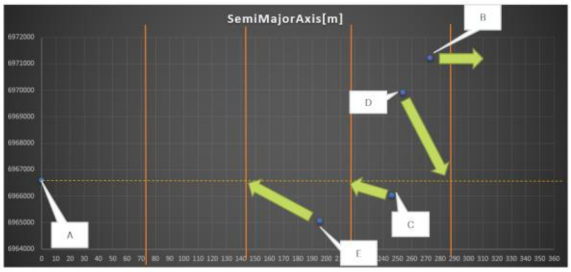

Figure5.4 constellation diagram at 2021-04-23

5. 2. Phasing

In this phase, the phase angles were monitored until phase angle states reached the target. The satellites' altitudes were not controlled as this was considered for the Phase3 operation plan.

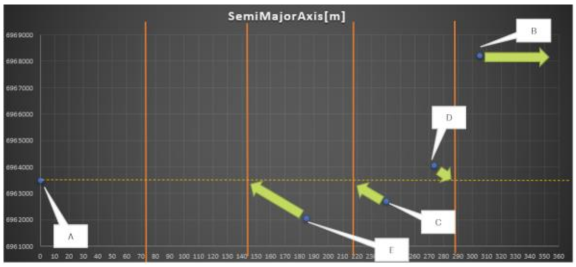

Figure5.5 constellation diagram at 2021-04-30

5.3. Injection to the target orbit

Figure 5.6 shows the constellation diagram from May 19th, 2021. All satellites roughly reached the target phase. Now, each satellite's altitude was changed as follows:

- 1B lowered altitude 5/21,22,26
- 1C raised altitude 5/21,26
- 1D lowered altitude 6/7
- 1E raised altitude 5/26

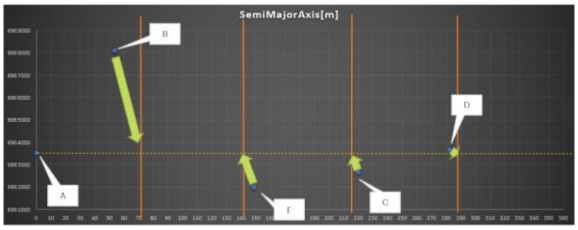

Figure5.6 constellation diagram at 2021-05-19

6. Operation evaluates

6.1. Phase transition

Phase transition in phasing operation is shown below. From mid of April to the end of May, it was confirmed that the satellites were going separated. After early June, it was confirmed that all satellites reached the target and stabilized.

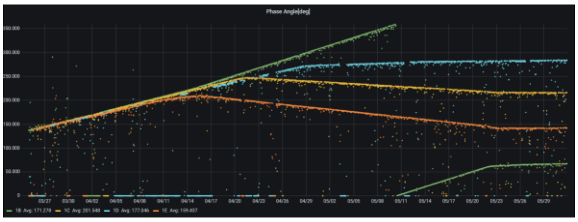

Figure6.1 phase transition

Phase error transition is shown below. It was confirmed that all satellites were converging in early June. After it, they became stabilized.

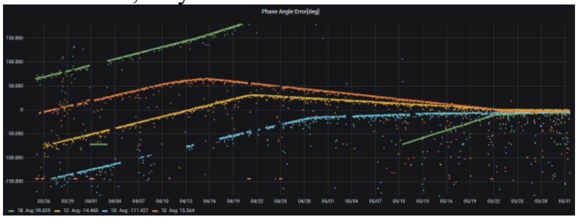

Figure 6.2 phase error transition

The AxelGlobe service requires the revisit interval to be 2 or 3 days. To satisfy this requirement, the satellites have to make phase angle error converging under +-10.0[deg] At Nov 15th 2021, it was staying under +-4.0[deg] error and proved to be stable.

6. 2. Mean semi major axis transition

Figure 6.3 shows the Mean semi major axis transition. It can be confirmed that satellites were injected into the parking altitude around the end of Apr. And in early June, all satellites were injected into the same altitude as 1A.

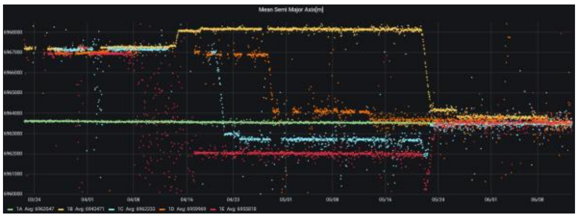

Figure 6.3 mean semi major axis transition

Figure 6.4 shows 1A's semi-major axis transition in phasing operation term. In 2 months, it can be confirmed to be lowered by around 100[m]

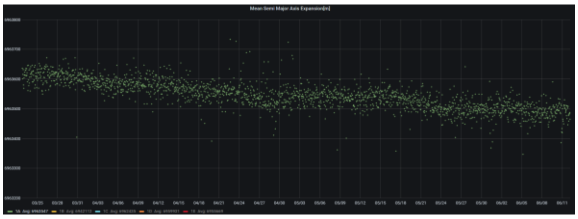

Figure6.4 mean semi major axis transition (only 1A)

6. 3. Right ascension of ascending node

For confirming the orbit plane of the constellation, right ascension of the ascending node can be visualized. Figure 6.5 shows it on Apr 08th 2021 before the phasing operation. At that time, the error converged under 0.01[deg]

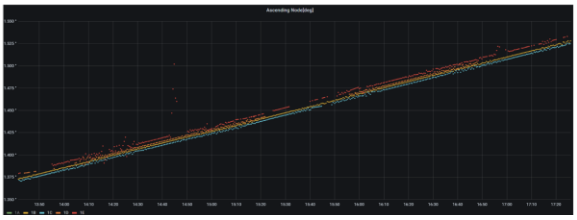

Figure6.5 right ascension of ascending node (2021-04-08)

Figure 6.6 shows the right ascension of the ascending node on June 8th, 2021, immediately after the phasing operation. During the phasing operation, there were differences of the semi-major axis between all satellites. It caused a permanent perturbation difference of right ascension of the ascending node. Then, 0.15[deg] variation was created. This is 0.6[min] as LST and it will not cause problems in regular operation.

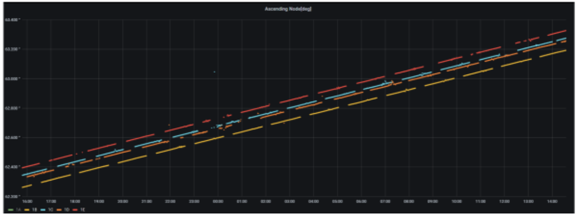

Figure6.6 right ascension of ascending node (2021-06-08)

7. ODS Algorithms

7. 1. Algorithm overview

Algorithm overview is below.

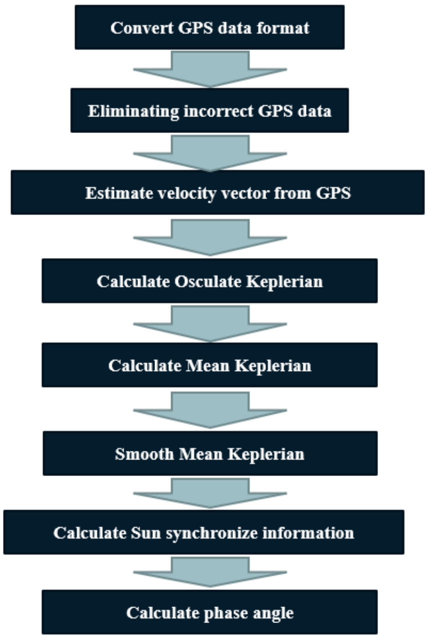

Figure7.1 Algorithm overview

7. 2. Eliminate GPS data

At first, eliminate GPS data by test of rejection Smirnov-Grubbs for altitude. When sample average $\underline{x}$, standard deviation SD, sample altitude x_i, statistics T becomes (7.1)

$$T = \frac{|x_i - \underline{x}|}{SD} \tag{7.1}$$

Calculate T with all altitudes and chose max value as T_{max}. Then, compare with significance k which is written below.

$$k = \frac{(n-1)t}{\sqrt{n(n-2)+nt^2}} \tag{7.2}$$

n is data size, t is value which is given from Smirnov-Grubbs test rejection table.

When $T_{max} > k$, x_i is outlier, then delete x_i from samples. While $T_{max} > k$, continue to iterate.

7. 3. Estimate velocity vector from GPS

After eliminating GPS data, estimate velocity vector from GPS. In general, when determining the orbit, determine position and velocity. But now, because there is still no developed orbit determination, estimate the velocity by using shooting method.

An overview of the shooting method is shown in Figure7.2.

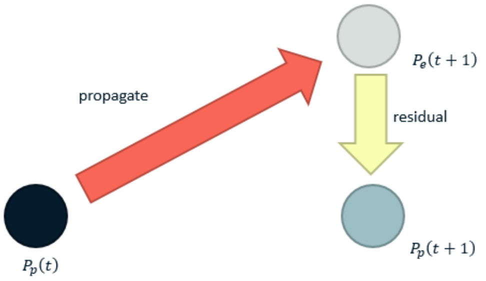

Figure7.2 shooting method overview

$P_p(t)$, $P_p(t+1)$ is the position vector of the GPS positioning result.

$P_e(t+1)$ is the position vector which is estimated by propagating the orbit.

Propagation epoch is $P_p(t)$

Then, the algorithm becomes as below.

1 assume that initial velocity vector is (7.3)

$$\frac{P_p(t+1) - P_p(t)}{(t+1) - t} \tag{7.3}$$

2 Propagate orbit from t to $t+1$ by using velocity vector

3 Calculate (7.4) as residual vector

$$P_p(t+1) - P_e(t+1) \tag{7.4}$$

4 While absolute value of residual vector is bigger than threshold σ, improve velocity vector by first-order Newton's method and iterate from step ②

For improving velocity vector, using basic style of first-order Newton's method which is explained below.

$$v_{n+1} = v_n - J_n^{-1} f_n \qquad (7.5)$$

$$v_n = \left(v_x \; v_y \; v_z \right) \qquad (7.6)$$

$$f_n = \left(f_x(v_n) \; f_y(v_n) \; f_z(v_n) \right) = P_p(t+1) - P_e(t+1) (7.7)$$

$$J_n = \left(\frac{\partial f_x}{\partial v_x} \frac{\partial f_x}{\partial v_y} \frac{\partial f_x}{\partial v_z} \; \frac{\partial f_y}{\partial v_x} \frac{\partial f_y}{\partial v_y} \frac{\partial f_y}{\partial v_z} \; \frac{\partial f_z}{\partial v_x} \frac{\partial f_z}{\partial v_y} \frac{\partial f_z}{\partial v_z} \right) \quad (7.8)$$

f_n is the residual between propagated position and positioned position. It can treat this as the problem of parameter optimization with using f_n as objective function.

For calculating Jacobian J_n, use numerical differentiation of Romberg first-order formula. The basic formula for $\acute{f}(x)$ which is differentiation of $f(x)$ is written in (7.9), (7.10).

$$\acute{f}(x) = \frac{f(x,h) - \left(\frac{3}{4}\right) f(x,2h)}{1 - \left(\frac{1}{4}\right)} \qquad (7.9)$$

$$f(x,h) = \frac{f(x+h) - f(x-h)}{2h} \qquad (7.10)$$

7. 4. Calculate mean Keplerian

Regarding mean Keplerian, it is based on analytical general perturbation method.

When osculating Keplerian at $t+1$ is $K_O(t+1)$ and mean Keplerian at t is $K_M(t)$, the relationship between osculating Keplerian and mean Keplerian is (7.11).

$$K_O(t+1) = K_M(t) + n(t) \times \left((t+1) - (t) \right)$$
$$+ dK_L(t+1) + dK_S(t+1) \qquad (7.11)$$

$dK_L(t+1)$ is long term perturbation at $t+1$, $dK_S(t+1)$ is short term perturbation at $t+1$.

$n(t)$ is permanent perturbation at t.At first, assume $K_M(t) = K_O(t)$ and iterate until converge.

For calculating high accuracy mean orbit, it needs to consider many models. For example, high order earth gravity[5)6)], sun and moon gravity[4)], atmosphere drag[7)].

7. 5. Smooth mean Keplerian

After calculating mean Keplerian, smooth data by using below.

1. Delete outlier value by test rejection of Smirnov-Grubbs
2. Delete noise value which are out of 2-3σ in Gauss distribution
3. Fill blank data by moving average

7. 6. Calculate phase angle

(1) For calculating phase angle, use mean latitude argument of mean Keplerian. When $\boldsymbol{l}$ is mean anomaly, $\boldsymbol{\omega}$ is periapsis argument, $\boldsymbol{L_{mean}}$ is mean latitude argument, sometimes it treated as $\boldsymbol{l} + \boldsymbol{\omega} = \boldsymbol{L_{mean}}$ But in this case we calculated $\boldsymbol{L_{mean}}$ from $\boldsymbol{l}$ accurately by below.

$$cosu_{asc} = \frac{cos\,cos\,(-\omega)\; + e}{1 + e(-\omega)} \qquad (7.12)$$

$$sinu_{asc} = \frac{\left(\sqrt{1-e^2}\right) sin\,sin\,(-\omega)}{1 + e\,cos\,cos\,(-\omega)} \qquad (7.13)$$

$$l_{asc} = u_{asc} - esinu_{asc} \qquad (7.14)$$

$$L_{mean} = l + l_{asc} \qquad (7.15)$$

Eccentric anomaly at ascending node is u_{asc}, eccentricity is e, mean anomaly at ascending node is l_{asc}.

At first, calculate mean anomaly at ascending node by using true anomaly and eccentric anomaly. After calculating mean latitude argument by adding mean anomaly at ascending node to current mean anomaly.

Then phase angle overview becomes Figure 7.3

$$Phase_A = 0$$
$$Phase_B = L_{mean,A} - L_{mean,B}$$
$$Phase_C = L_{mean,A} - L_{mean,C}$$
$$Phase_D = L_{mean,A} - L_{mean,D}$$
$$Phase_E = L_{mean,A} - L_{mean,E}$$

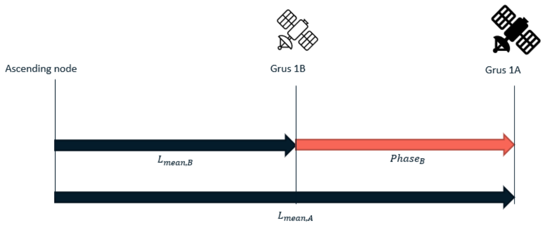

Figure7.3 phase angle overview

7. 7. Time and coordinate system

The time system and the coordinate system are the basic parts of all calculations. The ones used in Axelspace are shown in Figure7.4 and 7.5.

Figure7.4 coordinate system overview

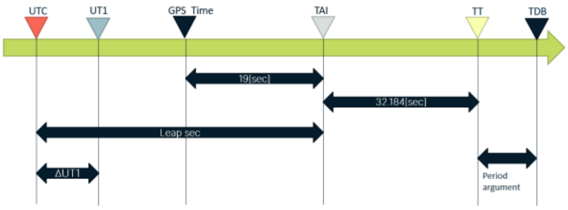

Figure7.5 phase angle overview

Regarding nutation and precession, based on IAU2006[3)].

For calculating period term between TT and TDB, using USNO circular 179²⁾.

7. 8. Perturbation models

Perturbation is table7.1(Partially unimplemented). These are based on IERS2010 conventions¹⁾.

Table7.1 Perturbation model

Perturbation	**Detail**
Earth gravity	EGM2008 model 90-order
Atmosphere drag	NRLMSISE-00
Other celestial gravity	Solar system Sun, Moon, Pluto DE441
Solar radiation pressure	Available
Earth tide	Solid earth tide Ocean tide Solid earth pole tide
Relativistic effect	Available

8. Conclusion

Axelspace launched 4 new satellites to extend its earth observation satellite constellation AxelGlobe. For phasing each satellite, the Orbital Dynamics System (ODS) has been developed.

In this paper, the phasing operation history and the ODS basic algorithms were introduced. As of Nov 2021, Axelspace is doing nominal operations. As a next step, ODS will be improved to allow fully automated orbit control operation.

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