Inclination Adjustment Maneuver and Frozen Orbit Keeping of The Advanced Land Observing Satellite (ALOS)

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The Advanced Land Observing Satellite "Daichi" (ALOS) was successfully injected into its mission orbit on March 26, 2006. ALOS’ missions require the orbit to be precisely recurrent regarding both the ground track and altitude. Therefore, the ALOS mission orbit is a sun-synchronous sub-recurrent frozen orbit. A sun-synchronous orbit has to be maintained by compensating inclination change caused by lunisolar gravity perturbation. In the ALOS case, inclination adjustment is planned every two and a half years. The inclination adjustment should be done by out-of-plane maneuvers. During the inclination adjustment, it is also required that the ground track and altitude error should be minimized. However, it is difficult because there are some restrictions on the out-of-plane maneuvers; such as necessity of attitude change maneuver, extra in-plane accelerations by the attitude change maneuver. JAXA planned and performed the inclination adjustment which kept the ground track and altitude error as small as possible by estimating extra in-plane accelerations and exploiting rotation of eccentricity vector caused by gravity perturbations. In this paper, we review the ALOS requirements for orbit keeping, and discuss the challenges of ALOS inclination adjustment maneuvers due to the restrictions. Our strategies and the theoretical background are also presented with subsequent evaluation of flight results.

Key Words: Inclination Adjustment Maneuver, Frozen Orbit, Orbit Maintenance, ALOS

1. Introduction

The Advanced Land Observing Satellite (ALOS) is used for fields of mapping, precise regional land coverage observation, and resource surveying. The ALOS’ mission orbit is determined for these missions, and is required to be kept constant during the ALOS’ mission life. The mission orbital properties are listed in Table 1. The actual orbit will be deviated from the mission orbit by the effects of lunisolar gravity perturbation, atmospheric drag and other external forces. Japan Aerospace Exploration Agency (JAXA) has to maintain the orbit at regular intervals. Particularly, the planning of the out-of-plane control is difficult compared with the in-plan control, because this control such as inclination adjustment maneuver has many constraints. The ALOS has to continue its mission observation during the inclination adjustment. Therefore, we were required to develop a plan of inclination adjustment that minimizes the adverse effect on the mission.

One of ALOS’ new missions is Synthetic Aperture Radar (SAR) interferometer observation. Interferometry is a technique that compares a pair of SAR data acquired by two observations over the same ground point and extracts difference of the data pair of the observed terrain. Therefore, ALOS is required to fly over the same orbit to observe the same ground point. In order to meet this demand, there are three orbit requirements.

The first requirement is a recurrent orbit, also called a repeating orbit, which is regulated within ±2.5 km for cross-track deviations from geo-fixed reference paths at the equator. These reference paths are called Reference System for Planning (RSP) defined by 671 points on the equator with a recurrent period of 46 days as shown in Figure 1. We will

<table>
<thead>
<tr>
<th>Orbit type</th>
<th>Sun-synchronous, sub-recurrent, frozen orbit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Recurrent period</td>
<td>46 days</td>
</tr>
<tr>
<td>Revolutions per day</td>
<td>14/27/46rev./day</td>
</tr>
<tr>
<td>Local sun time at descending node</td>
<td>10:15 – 10:45 (AM)</td>
</tr>
<tr>
<td>Equatorial orbit altitude</td>
<td>691.65 km</td>
</tr>
<tr>
<td>Inclination</td>
<td>98.16deg</td>
</tr>
<tr>
<td>Equator crossing point deviation (Requirement of RSP control)</td>
<td>±2.5 km (target: ±0.5 km)</td>
</tr>
<tr>
<td>Repeat-pass altitude variation</td>
<td>±2.0 km (target: ±0.5 km)</td>
</tr>
</tbody>
</table>

![Fig. 1. ALOS’ RSP ground track (1day) and RSP error.](image)
call orbit control for meeting this requirement as “RSP control”. In order to improve interferometer observation, the target of RSP control is set to keep the range within ±0.5 km.

The second requirement is a frozen orbit that keeps the altitude difference within ±2.0 km over the same ground point on the same RSP paths in different recurrent cycles. In the operation, the target of this orbit is set to keep the difference within ±0.5 km. We will call orbit control for meeting this requirement as “frozen orbit control”.

The third requirement is a sun-synchronous orbit that keeps the ground track error should be minimized as much as possible. For compensating RSP error, a set of deceleration and acceleration maneuvers are performed immediately after the inclination adjustment maneuver. Because ALOS is allowed to perform the inclination adjustment and deceleration maneuvers only at the ascending node, a series of resulting in-plane velocity changes cause a deviation from a frozen orbit and an altitude error.

Efforts prior to the inclination control which precisely regulates the ALOS’ orbit against various adverse effects were reported in Reference 1.

The purpose of this paper describes the difficulties to develop a plan of ALOS inclination adjustment due to some restrictions. ALOS deviates from the RSP and frozen orbit due to unwanted along-track acceleration generated by attitude maneuvers which accompany the inclination adjustment maneuver. JAXA planned and performed the inclination adjustment by keeping the ground track and altitude error as small as possible utilizing maneuvers for return to the RSP and the rotation of eccentricity vector caused by gravity perturbations. Our strategies and the theoretical background are also presented with subsequent evaluation result.

2. Orbit Control Strategy

2.1. Strategy of RSP control and frozen orbit keeping

RSP and frozen orbit control are performed using along-track acceleration/deceleration by in-plane maneuvers. The in-plane maneuvers are performed in weekly routine operations. If a semi-major axis (SMA) decreases due to deceleration by atmospheric drag, the ground track is shifted eastward from the RSP paths. Therefore, in the routine operation, ALOS performs acceleration maneuvers intended to increase the SMA to counteract the effects of atmospheric drag. Along-track deceleration might be performed in an emergency case or a special case.

When considering frozen orbit control, the eccentricity vector \( \vec{e} = [e \cos \phi \sin \omega] \) is used, where \( e \) and \( \omega \) denote the eccentricity and argument of perigee, respectively. In terms of the eccentricity vector, the frozen point is given by approximately \( e = 0.001 \) and \( \omega = 90 \text{deg} \). The eccentricity vector is changed due to along-track acceleration,

\[
\Delta \vec{e} = \frac{2\Delta V}{na} \begin{bmatrix} \cos \phi \\ \sin \phi \end{bmatrix}
\]  

where \( \Delta V, n, a \) and \( \phi \) denote velocity increment by the maneuver, mean motion, SMA and argument of latitude of ALOS at maneuver, respectively. Change of the eccentricity vector depends on the argument of latitude at maneuver from the Eq. (1). In the routine operation, the eccentricity vector is controlled by in-plane maneuver at the properly-selected argument of latitude. This control is executed at the same time with the RSP control. The magnitude of maneuver is predominated by RSP control, and the maneuver point (\( \phi \)) is determined by \( \Delta \vec{e} \) required for frozen orbit control. If only the eccentricity vector has to be changed, it is necessary to plan two-part maneuvers. This is because a combination of acceleration and deceleration maneuvers is required for eccentricity control. In other words, a couple of in-plane maneuvers keep SMA and RSP unchanged.

2.2. Inclination adjustment strategy

A unique combination of ideal SMA and inclination values allows the orbit to meet both the sun-synchronous and repeating orbit conditions simultaneously. In order to maintain
the sun-synchronous orbit, or the LST, the inclination has to be adjusted by out-of-plane maneuvers. In the case of ALOS, the inclination adjustment campaign is planned every two and a half years. In this campaign, the inclination was planned to be increased by 0.084°. This value was equal to the changes of inclination for 2.5 years after the mission orbit insertion. The inclination of the nominal mission orbit minimizes the variation of LST for 2.5 years. In other words, a similar change of LST and inclination will be reproduced for next 2.5 years.

In addition, since ALOS continues its observation during the inclination adjustment campaign, we have two requirements from its mission:
1) RSP error should be minimized during the campaign and returned to within ±0.5 km after the campaign.
2) The eccentricity vector should be returned to the initial frozen point after the campaign.

Since large deviation from the mission orbit will result in poor-quality data, we were required to develop a plan that minimizes the adverse effect on the orbit and observation.

3. Constraints on Inclination Adjustment Maneuver

If you place high priority only on RSP control, eccentricity vector will be deviated from the frozen point. This process is shown in Figure 3. During the inclination adjustment campaign, we must minimize not only RSP error but also altitude error. This is a difficult task because of constraints on the inclination adjustment maneuver. In this section, the constraints and the difficulties of RSP control and frozen orbit control during the inclination adjustment campaign are discussed.

3.1. Limitation in thruster firing time per maneuver

ALOS has four pieces of 4N thrusters, eight pieces of primary 1N thrusters, and eight pieces of redundant 1N thrusters. 4N thrusters are designed to produce orbit control ΔV, and are used for inclination control. 1N thrusters are assigned to control the attitude or the small change in the orbit. This thrusters system is called Reaction Control Subsystem (RCS).

The firing time of the 4N thrusters is limited to be less than 495 sec according to its specification. In this campaign, 11.0 m/s velocity increment is required to change the inclination into 0.084°. This acceleration corresponds to 3520 sec firing by the 4N thrusters, which is beyond the limitation of the thrusters. Therefore, the inclination adjustment must be performed by eight separate thruster burns.

3.2. Extra ΔV by yaw-around attitude maneuver

All of the thrusters are assembled on a –X panel of the satellite body and are canted to –X direction to guarantee sufficient torque, as shown in Figure 4. Therefore, they are limited in their firing time. The extra ΔV required to adjust the inclination can be achieved by yaw-around attitude maneuvers. However, this process will deviate the eccentricity vector from the frozen point.

Fig. 3. Process of deviating eccentricity vector from the frozen point.

Fig. 4. RCS thruster configuration. Two types of thrusters are assembled on ALOS’ RCS according to its –X panel.
generate translational acceleration in +X direction even when its firing objective is merely to generate rotational torque for controlling attitude.

In order to perform the inclination adjustment maneuver or the deceleration maneuver, ALOS has to make +90 deg, −90 deg or 180 deg yaw-around attitude maneuver by 1N thrusters. Other yaw-around angles cannot be selected due to its specification.

If a maneuver performs to increase the inclination in this campaign, −90 deg yaw-around attitude maneuver is required as shown in Figure 5. In addition, the −90 deg yaw-around attitude maneuver causes along-track acceleration. The attitude maneuver changing from nominal attitude to −90 deg yaw-around attitude is larger magnitude of along-track acceleration than attitude maneuver for return to nominal attitude. In the case of 180 deg yaw-around attitude maneuver performing for a deceleration maneuver, theoretically, extra along-track acceleration does not occur. Because two outward and return attitude maneuvers cancel each other out.

Also, the yaw-around attitude maneuvers and resulting along-track acceleration perturb the eccentricity vector. Based on a simple model, changes in the eccentricity vector are estimated to be \( \Delta \hat{e} = [ -1.03 \times 10^{-5} \ 0.47 \times 10^{-5} ] \) for 180 deg maneuver and \( \Delta \hat{e} = [ 0.58 \times 10^{-5} \ -0.24 \times 10^{-5} ] \) for −90 deg maneuver.

3.3. Inclination adjustment maneuver and deceleration maneuver around ascending node only

The inclination adjustment and deceleration maneuvers have to be performed only in eclipse because of a restriction from optical sensors and power. Inclination adjustment maneuver and deceleration maneuver with yaw-around attitude maneuvers must be performed only around ascending node. Due to these restrictions, the changes in the eccentricity vector are accumulated in one direction each time at which the yaw-around attitude maneuvers are performed. This results in the deviation from the frozen orbit.

3.4. Phase shifting after inclination adjustment maneuver performing

The sequences of the inclination adjustment maneuvers shown in Figure 5 are called “stage”. This stage consists of attitude maneuver for changing to −90 deg yaw-around attitude, inclination adjustment maneuver, attitude maneuver returning to nominal attitude and thruster cool-down. It takes three revolutions to finish one stage. We can perform four stages in a day. Therefore, we planned the inclination adjustment maneuver in two sets of four stages, total eight stages. In one set including four stages, the inclination was increased to 0.042 deg, about half of the total.

The SMA should be maintained to increase to approximately 140 m for keeping a recurrent orbit when inclination is adjusted 0.084 deg in total eight stages (two sets of four stages). The change of inclination causes fast moving of the orbital plane. Then, a satellite passes a different point on equator compared with the orbit before inclination change. This variation is canceled to use phase shifting by the SMA +140 m change. However, from the result of the inclination adjustment maneuver performed in the check-out phase, the SMA was estimated as +200 m change per one stage. In the case of performing one set of four stages, we estimated that the SMA will be increased about +800 m. Therefore, after the SMA increased +800 m, large phase shifting which leads to an increase of the deviations from a recurrent orbit (RSP error) is generated. This phase shifting increases over time. In order to reset a phase shifting and to adjust the SMA, the RSP control by a deceleration maneuver and some acceleration maneuvers is needed immediately after the four stages of inclination adjustment maneuvers. After the RSP control, the second four stages of inclination adjustment maneuvers are planned.

3.5. Deviation from frozen orbit by RSP control

By performing four stages of inclination adjustment maneuvers and the RSP control alternately, RSP error caused by a phase shifting can be removed. However, the problem is that the eccentricity vector is deviated far from the frozen point by RSP control. In this case, the variation of repeat-pass altitude is increased to ±1.2 km for 40 days before the eccentricity vector is controlled to frozen point by a two-part maneuver. This large altitude variation was unacceptable in terms of the SAR interferometry. We were required to develop a plan that minimizes the adverse effect on the frozen orbit and subsequently interferometry.

4. Inclination Adjustment Plan

We planned the inclination adjustment campaign composed of two sets of inclination adjustment maneuvers, RSP control (deceleration and acceleration maneuvers), and rotation of eccentricity vector (for about fifty days) caused by gravity perturbations in between.

Figure 6 illustrates estimated changes of the eccentricity vector during the inclination adjustment campaign. The arrow-A in this figure was estimated using the value of four −90 deg yaw-around attitude maneuvers described in section 3.2. The yaw-around attitude maneuvers change the eccentricity vector to constant directions because they can be performed only at the ascending node as mentioned in section 3.3. Due to the constraints described in section 3.4, it was necessary to perform the deceleration maneuver to control RSP error every four stages. However, the magnitude of deceleration maneuver was so large that the eccentricity vector was deviated far from the frozen orbit as shown by the arrow-B (in Figure 6). In addition, the arrow-B are includes the effect of 180 deg yaw-around attitude maneuvers which accompanies the deceleration maneuver. Theoretically, the...
changes of eccentricity vector caused by these maneuvers were always the same (move toward the left in Figure 6) regardless the initial position of the eccentricity vector. The following maneuvers were acceleration maneuvers for adjusting the SMA to the nominal value and stopping the phase return. The arrow-C (in Figure 6) shows the effect of these maneuvers.

At this point, we have completed half of required inclination adjustments, and the RSP error is no longer existed. However, the eccentricity vector was deviated far from frozen orbit. If we implement the remaining half of required inclination adjustments and the following RSP control, the deviation of the eccentricity vector will be expanding.

Consequently, we developed a plan utilizing a drift of eccentricity vector caused by perturbation by the high order terms of gravity potential. As you know, an eccentricity vector is rotated at the center of froze point. The movement distances of both the first and second sets are same. Therefore, the eccentricity vector is able to return to frozen area by changing movement distance equal to the first set at the opposite side of frozen point. That is to say, we will wait, after the first set of inclination adjustment maneuvers and RSP control, the eccentricity vector rotating to the opposite side across the vicinity of the frozen point, and then perform the second set of maneuvers (the arrow-D, E and F in Figure 6). The rotation cycle $T_e$ is shown as below,

$$T_e = \frac{2\pi}{2n \left( \frac{R_e}{a} \right)^2 J_2 \left( 1 - \frac{5}{4} \sin^2 i \right)} \approx 115 \text{days} \quad (2)$$

where $n$, $a$, $R_e$, $J_2$ and $i$ denote mean motion, SMA, earth equatorial radius, the 2nd order zonal harmonics, and inclination, respectively. One cycle is about 115 days from Eq. (2), it means that we have to wait about fifty days between the first and second set of maneuvers.

Following this plan, the required inclination adjustment was achieved by the arrow-A and D, the RSP control was done with respect to each inclination adjustment maneuver by the arrow-B+C and the arrow-E+F and eccentricity vector control was done by all the maneuvers and the rotation caused by gravity perturbation. The variation of repeat-pass altitude was estimated as $\pm 0.6km$, which was acceptable in terms of the SAR interferometry during the drift phase.

5. Inclination Adjustment Campaign Results

5.1. Changes of the eccentricity vector

The changes of the eccentricity vector in this campaign are shown in Figure 7. The horizontal axis shows $e \cos \omega$, and the vertical axis shows $e \sin \omega$. This figure is drawn by linearly interpolating the orbit determination results (averaged values for three days). The starting point of eccentricity vector (June 11, 2008) stayed within the frozen orbit area. The first four stages of inclination adjustment maneuvers caused a deviation of the eccentricity vector from frozen orbit (the arrow-A). The change of the eccentricity vector by the subsequent RSP control corresponded to the arrow-B and C-1 and C-2. This RSP control was performed by one deceleration maneuver (the arrow-B) and the subsequent two acceleration maneuvers (the arrow C-1 and C-2). After the drift phase, with the second four stages of inclination adjustment maneuvers (the arrow-D) and the following RSP control (the arrow-E, F-1 and F-2), the eccentricity vector was successfully moved to the vicinity of the frozen point on Aug 11, 2008.

The actual changes of the eccentricity vector caused by the inclination adjustment maneuvers (the arrow-A and D) and the deceleration maneuver (the arrow-B and E) are sufficiently close to the estimated changes shown in Section 4. The both of actual changes performing the deceleration maneuvers are little different from estimated amount, because the attitude maneuver for 180 deg yaw-around produced small unexpected extra along-track acceleration. It is able to recovery using the subsequent acceleration maneuvers. The acceleration maneuvers can be performed everywhere without constraint on the maneuver point. Therefore, those maneuvers can be used for compensating some errors result from inclination and deceleration maneuvers. We perform the acceleration in twice to increase the accuracy.

5.2. RSP control

A time history of the RSP error is shown in Figure 8. The horizontal axis shows epoch, and the vertical axis shows RSP error. The RSP error continued to increase after the inclination adjustment maneuvers (the arrow-A and D) as expected. The maximum value achieved just before the deceleration maneuver reached about $-17km$. However, after the RSP control (the arrow-B, C-1 and C-2 and the arrow-E, F-1 and F-2), the RSP error was kept small enough for the observations (close to the target of $\pm 0.5km$).
5.3. LST maintenance

The transition of the LST is shown in Figure 9. The predicted values are on and after May 18, 2009. The horizontal axis shows epoch for 5 years after the launch, and the vertical axis shows the LST at the descending node. The trend of LST change was successfully corrected by this inclination adjustment maneuvers. The LST will be kept within a required range for the next 2.5 years. In fact, inclination was changed from 98.133° to 98.222°.

6. Conclusions

We have successfully performed the operation to adjust the inclination and the LST by utilizing rotation of the eccentricity vector caused by gravity perturbations. During the inclination adjustment, ALOS' orbit was kept the ground track and altitude error as small as possible for continuing its observation. After the campaign, ALOS accurately returned to RSP and frozen orbit. On the next inclination adjustment campaign, we will perform the plan in the similar method based on this campaign.

In recent years, since many satellites have all thrusters on one panel such as the ALOS, the method is effective in these satellites. However, if a satellite could perform orbit maneuvers at any location on orbit and change its attitude to any orientation for maneuver, we could develop more efficient plans for inclination adjustment campaign.

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References