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ABSTRACT

The Global Change Observation Mission (GCOM) is JAXA's project for the global and long-term observation of the Earth environment. GCOM is expected to play an important role in monitoring global water circulation and climate change. It will be a kind of health checkup of the Earth from space. GCOM-W1 is the first satellite in the GCOM-W series and carries the Advanced Microwave Scanning Radiometer 2 (AMSR2), whose mission it is to observe the Earth's water cycle mechanism.

The Afternoon Constellation (A-Train) is an Earth observation satellite constellation led by NASA. The orbits of the satellites in the A-Train are strictly controlled so that the satellites can observe the same locations on Earth within approximately 10 minutes of each other. Currently, the A-Train consists of four satellites: Aqua (NASA), CloudSat (NASA), CALIPSO (NASA/CNES), and Aura (NASA).

GCOM-W1 will join the A-Train, and its participation will enable simultaneous observation with instruments mounted on other satellites and enhance scientific research using AMSR2 data.

This document describes the strategies of ascent maneuvers from launch to injection into the A-Train, recovery operations from contingency, and orbit maintenance operations after entering the A-Train.

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1. Introduction

The Japan Aerospace Exploration Agency (JAXA) is conducting a project known as the Global Change Observation Mission (GCOM) to observe the global environment, global water cycle mechanisms, and long-term climate change—a kind of "health checkup" of the Earth from space.

GCOM-W1 is the first satellite in the GCOM-W series. Its mission is to observe the Earth's water cycle mechanism. It is equipped with an advanced microwave radiometer (AMSR2) for observing precipitation, water vapor, sea surface temperature, wind speed, soil moisture, and snow depth.

The Afternoon Constellation, or "A-Train," is an Earth observation satellite constellation run by NASA. The A-Train consists of multiple satellites orbiting the Earth in close proximity at an altitude of about 700 km, crossing the equator at around 1:30 p.m. mean solar time. The orbits of the satellites in the A-Train are strictly controlled so that the satellites can observe the same locations on Earth within approximately 10 minutes of each other. Currently, the A-Train consists of four satellites: Aqua (NASA), CloudSat (NASA), CALIPSO (NASA/CNES), and Aura (NASA). GCOM-W1 is slated to join the A-Train with the goal of further expanding scientific research using data from AMSR2.

This document describes the detailed ascent plan and operations of GCOM-W1. This document was the material for the GCOM-W1 ascent plan review by A-Train members on July 7 and 8, 2011, and then is updated by the result of the review meeting. The study of the ascent plan was carried out under the condition that GCOM-W1 is launched between 1 February 2012 and 31 March 2012.

Sections 2 and 3 show the conditions of the GCOM-W1 ascent plan concerning the satellite and H-IIA launch vehicle that require consideration. Section 4 explains the designed ascent plan, which is based on the strategy and results of ascent maneuver simulations. Section 5 describes the countermeasures against contingencies during the ascent operation, for example, a missed burn, AMSR2 rotation anomaly, a close approach with Landsat 5/PARASOL, or the cancelation of Aqua's inclination maneuvers in 2012. Section 6 outlines the main operations of GCOM-W1 during ascent. Section 7 shows the operations concepts of in-plane orbit maintenance and the inclination maneuver for GCOM-W1.

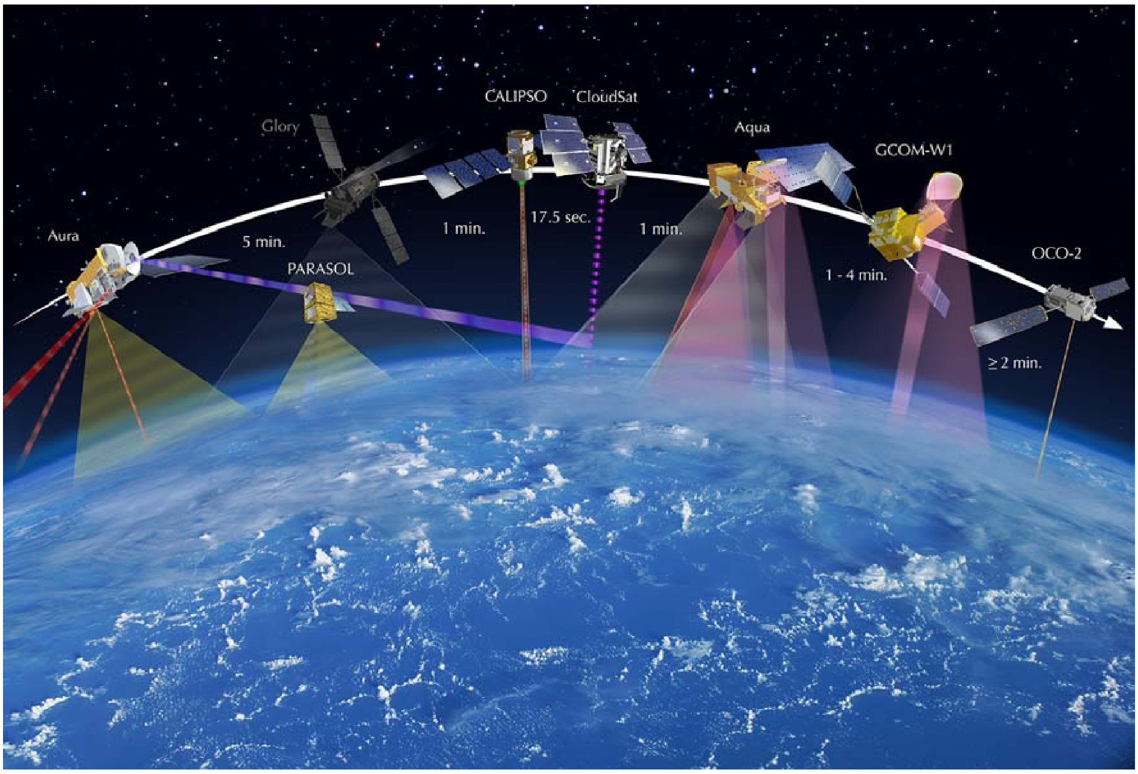


Figure 1-1　Afternoon Constellation

2. GCOM-W1 satellite design

This section describes the satellite design concerning maneuvers.

(1) Design of the Reaction Control Subsystem

The Reaction Control Subsystem (RCS) has 12 thrusters, and its nominal thrust is 4 N. As all thrusters are installed on the -X panel of GCOM-W1, attitude maneuvers around the yaw axis are needed for deceleration maneuvers (±180 deg.) and inclination adjustment maneuvers (±90 deg.). Because the thrusters are used for attitude control, unexpected disturbances may occur to the orbit during the deceleration and inclination adjustment maneuvers. The minimum ΔV of GCOM-W1 is 0.01 m/s. Four of the thrusters, which have full redundancy, are used for attitude control and another four thrusters are used for orbit control.

During normal operation, the Attitude and Orbit Control Subsystem (AOCS) controls the satellite's attitude using the Reaction Wheel Assemblies (RWAs). If GCOM-W1 detects an attitude anomaly, it changes actuators from RWAs to thrusters and tries to recover normal attitude. Therefore, an attitude anomaly may cause orbital disturbances (0.2 m/s (worst case)).

The budget of ΔV is shown in Table 2-1, and the satellite configuration is shown in Figures 2-1 and 2-2.

Table 2-1 Budget of ΔV

Operation	Maneuver	ΔV	Comment
Ascent operation	Test maneuvers	2 m/s	Acceleration and out-of-plane test maneuvers are performed.
	Ascent maneuvers	50 m/s	The amount of ΔV depends on the launch date. The maximum ΔV includes the correction of the rocket injection error (3σ).
Nominal operation	Drag make-up maneuvers	18 m/s	The period of solar activity used in this analysis is from 2012 to 2017.
	Inclination maneuvers	25 m/s	The amount of ΔV is based on the inclination maneuver plan of the A-Train from 2012 to 2017.
Deorbit operation	Deorbit maneuvers	43 m/s	After completion of deorbit maneuvers, the apogee and perigee altitude are 692 km and 550 km, respectively.
Margin		125 m/s	
Total		263 m/s	

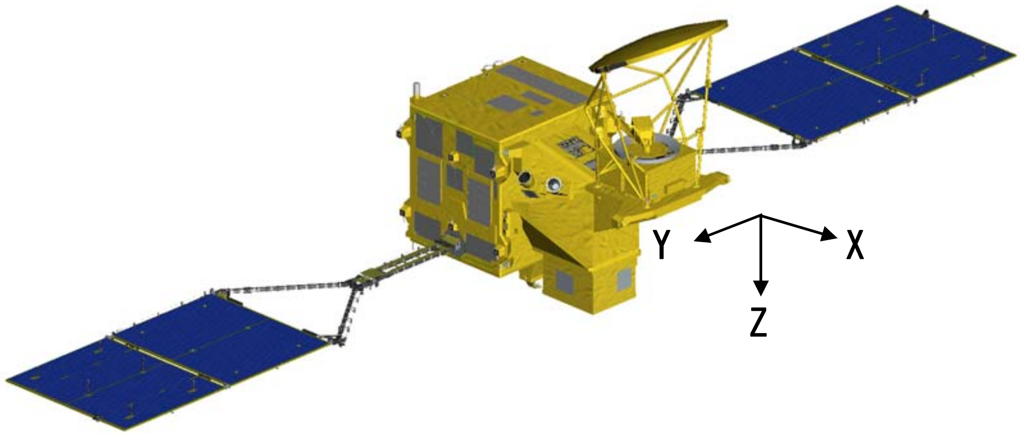


Figure 2-1 GCOM-W1 in orbit

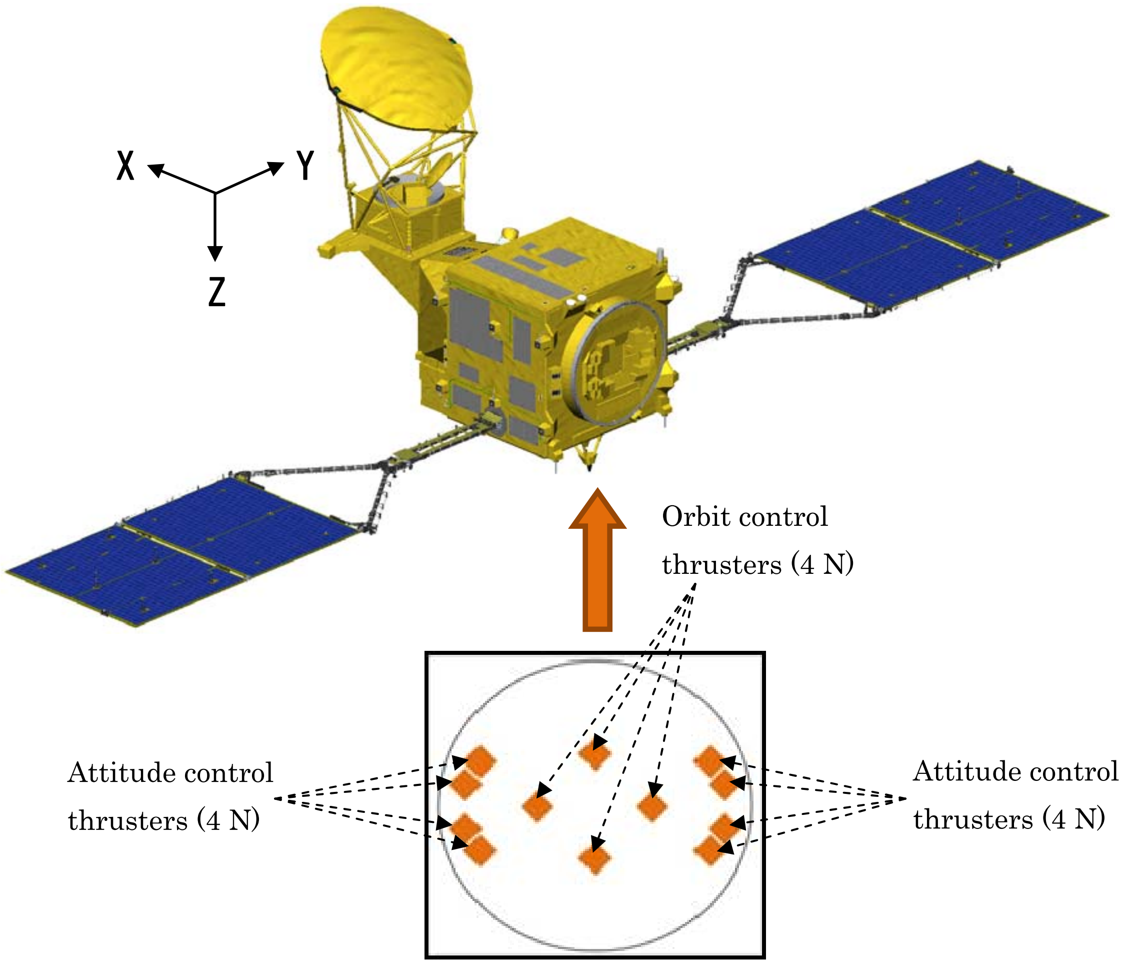


Figure 2-2 Thruster arrangement of GCOM-W1

(2) Constraints on the maneuvers

Understanding the constraints that may arise from the limitations of the GCOM-W1 spacecraft and ground operations are important when designing the ascent plan. Table 2-2 shows a list of such constraints.

Table 2-2 Constraints of GCOM-W1 ascent plan design

Max. ΔV for each maneuver event	14 m/s
Max. duration of each burn (out-of-plane, deceleration)	20 min
Min. interval between maneuver events	48 hrs
Min. interval between acceleration burns	1.5 orbital periods
Min. interval between out-of-plane burns	3 orbital periods

The maximum duration of each burn (out-of-plane, deceleration) is 20 minutes. This limitation comes from the restriction of electrical power. The amount of ΔV generated by 20 minutes of burn is about 7 m/s when four thrusters are used for orbit control, and 3.5 m/s when two thrusters are used. The maximum ΔV for each maneuver event is 14 m/s. This value can be achieved by dividing the event into plural burns.

The minimum interval between maneuver events is to be 48 hours during the ascent operation. This limitation comes from the workload of tasks related to orbital maneuvers, such as orbit determination, maneuver planning, maneuver commanding, etc. During the ascent operation, the interval is shorter than usual since JAXA allocates the maximum of human resources during the launch and ascent operations.

Figure 2-3 shows how to divide a maneuver event into plural burns. The 14-m/s out-of-plane maneuver event is divided into two 7-m/s burns with an interval of three orbital periods. Forty-eight hours later, the next maneuver event begins. It is a 14-m/s in-plane maneuver event, and it is divided into two 7-m/s burns with an interval of 1.5 orbital periods.

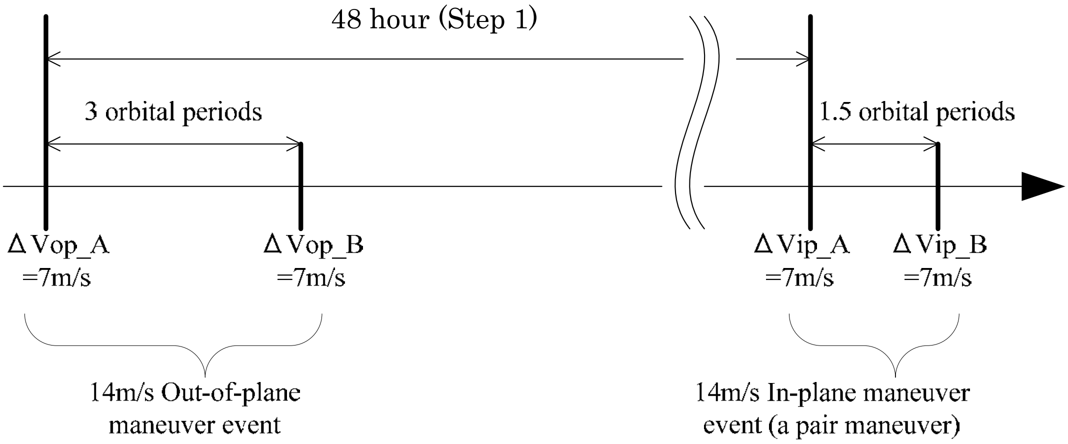


Figure 2-3 An example of the maneuver divided into plural burns

3. Launch by H-IIA rocket

GCOM-W1 is planned to be launched by the H-IIA launch vehicle. The requirements for the operational orbit of GCOM-W1 are shown in Table 3-1.

Table 3-1 Requirements for operational orbit of GCOM-W1

Type of orbit	sun-synchronous, frozen, recurrent
Altitude	approximately 705 km
Recurrent period	16 days (233 revolutions)
Descending node longitude of Path #1	295.4 deg. (WRS-2)
Mean Local Time of Ascending Node (MLTAN)	13:30 ±15 minutes

The operational orbit of GCOM-W1 is a sun-synchronous, frozen, recurrent ground-track orbit with an altitude of approximately 705 km (here “altitude” means the geocentric distance subtracted by the equatorial radius of the Earth). The same 16-day, 233-revolution recurrent period has been used by Landsat 4, Landsat 5, the Morning Constellation satellites, and the Afternoon Constellation satellites. Each spacecraft maintains its ground track at the descending node within a specified distance of the reference path of the Worldwide Reference System 2 (WRS-2), a standard reference ground track developed by the Landsat project.

Figure 3-1 shows the Mean Local Time of Ascending Node (MLTAN) trend of Aqua and GCOM-W1. Aqua is planned to perform inclination maneuvers in spring 2012. Let us consider the case of GCOM-W1 being launched before Aqua’s inclination maneuver in spring 2012. If GCOM-W1 is injected to the target orbit, which is determined by the actual MLTAN trend of Aqua, GCOM-W1 will have to perform inclination maneuvers to catch up with Aqua just after the ascent operation. However, if GCOM-W1 is injected to the target orbit based on the predicted MLTAN trend including the planned inclination maneuvers of Aqua, then inclination maneuvers of GCOM-W1 are not necessary after the ascent since Aqua is then supposed to catch up with GCOM-W1 afterwards.

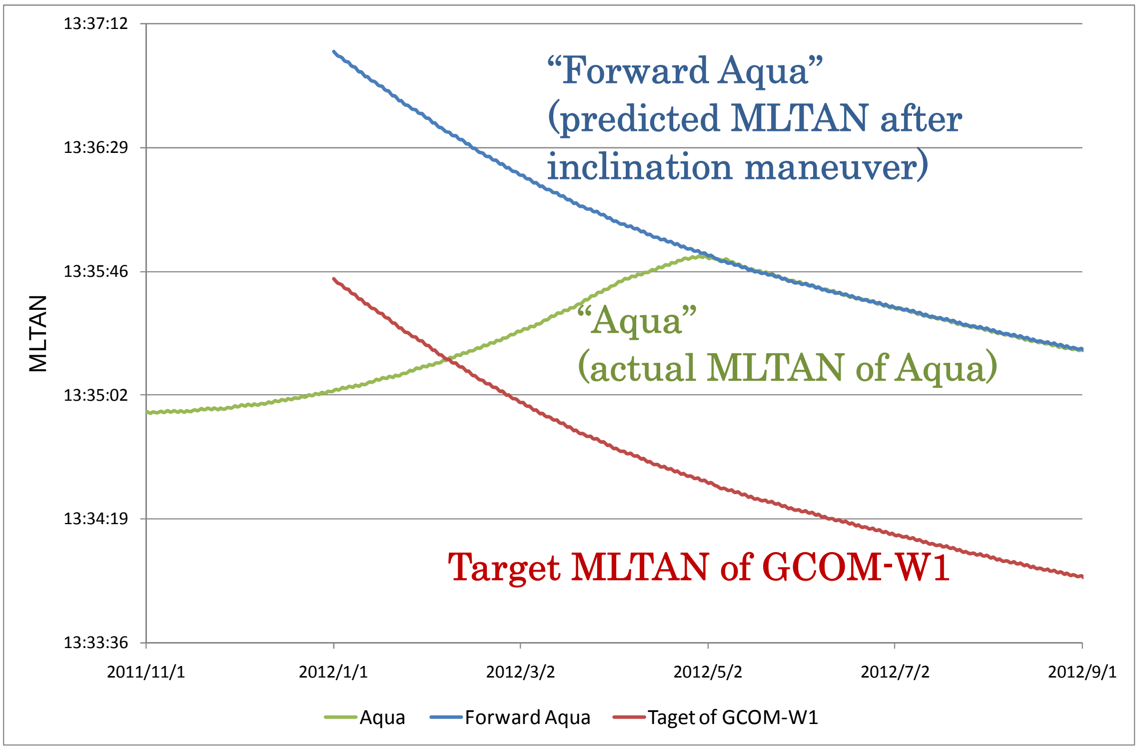


Figure 3-1 MLTAN trend of Aqua and GCOM-W1

The nominal target orbit of GCOM-W1 is then selected to be the orbit of Aqua after the inclination maneuvers in spring 2012 (called "Forward Aqua" hereafter). Whether GCOM-W1 is launched before or after Aqua's planned inclination maneuvers in 2012, as long as Aqua's plan does not change, the launch time of GCOM-W1 will be determined based on the MLTAN trend of Aqua after the inclination maneuvers.

The rocket injection orbit is shown in Table 3-2.

Table 3-2 Rocket injection orbit

Rocket injection orbit (True of Date)			
Parameter	Injection point	First ascending node	
	Osculating elements		Mean elements
Semi-major axis [km]	7055.972	7058.583	7049.400
Eccentricity	0.000704	0.00114	0.00105
Inclination [deg.]	98.160	98.158	98.164
Arg. perigee [deg.]	92.707	66.698	90.453
True anomaly [deg.]	109.527	293.366	-
Mean anomaly [deg.]	109.451	293.486	269.731
Right ascension of ascending node [deg.]	depending on the launch time		
Mean local time at the first ascending node	13:25-13:35 (to be adjusted by the launch time)		

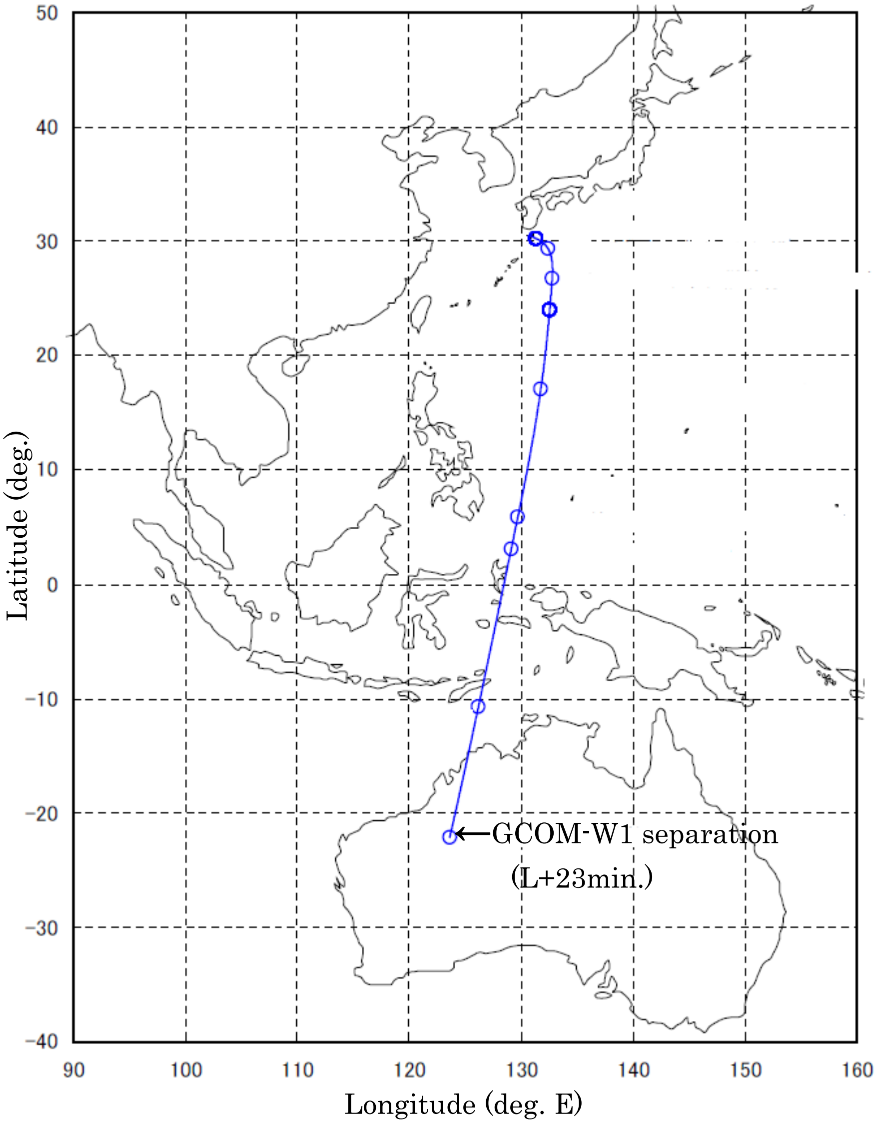


Figure 3-2 Ground track of H-IIA rocket trajectory for GCOM-W1

The mean semi-major axis of the rocket injection orbit is 29 km lower than that of the Afternoon Constellation orbit. This arises from the restriction of the “fleet envelope.” The fleet envelope is defined as the region between the perigee and apogee limits of the Afternoon Constellation, defined as 694 km and 711 km, respectively, above a spherical Earth equatorial radius of 6378.137 km. The apogee of the rocket injection orbit should have a minimum of 2 km separation from the lowest perigee of the Afternoon Constellation when considering the worst case: 3-sigma combination of all launch injection parameter errors. The value of the injection altitude selected is not to violate this restriction. Figure 3-3 shows the result of the worst-case analysis.

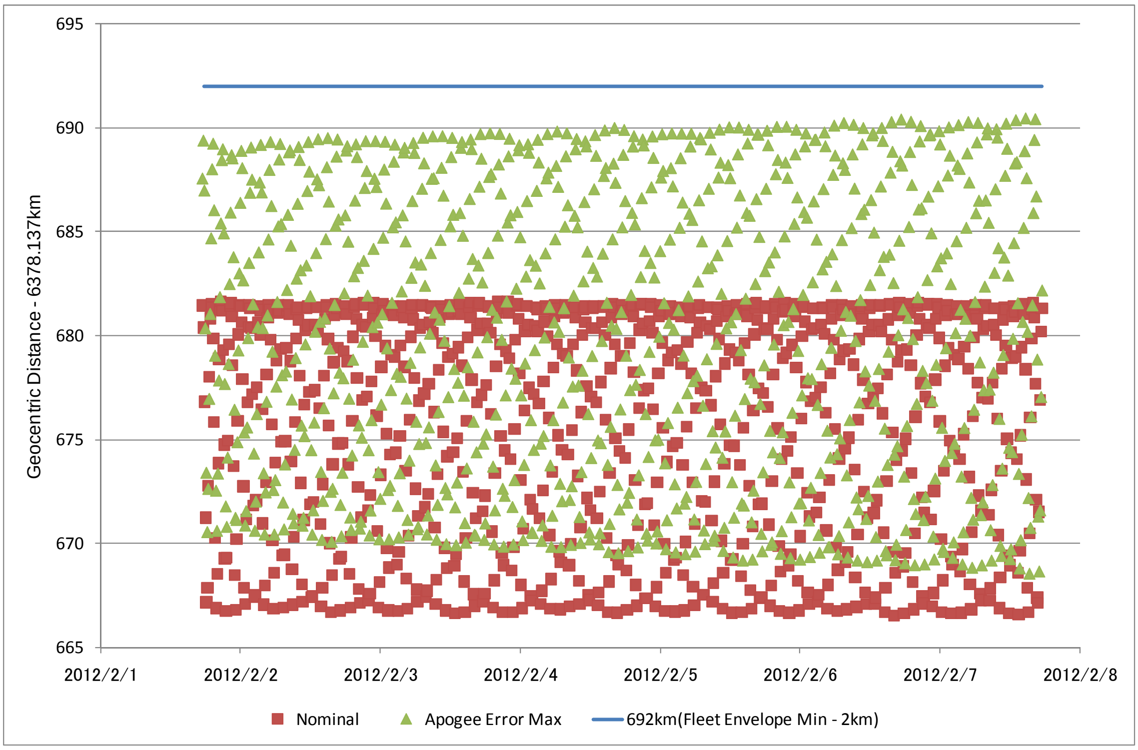


Figure 3-3 Maximum apogee error due to launch vehicle injection dispersions (3-sigma)

Even if the 3-sigma launch injection errors are considered, the maximum altitude of apogee (green line) is lower than 692 km (blue line), which is 2 km below the minimum perigee of the constellation (694 km). Here “altitude” means the osculating geocentric distance subtracted by the equatorial radius of the Earth.

The inclination was determined to be 98.158 deg. (TOD, osculating), which is the middle value between the target of GCOM-W1 (the inclination of the Forward Aqua) and that of the partner satellite in dual launch. Therefore, the rocket injection orbit is not sun-synchronous. The mean eccentricity and argument of perigee are chosen to be almost frozen values in order to keep the argument of perigee of GCOM-W1 in the same direction with those of the Afternoon Constellation.

As described in the following section, the launch time of GCOM-W1 is derived from the MLTAN of the operation (target) orbit plus an offset corresponding to an estimated total amount of $\Delta\delta MLTAN$ caused by the non-sun-synchronous feature during the ascent operation, where δ denotes relative MLTAN of GCOM-W1 with respect to the MLTAN of the target and Δ denotes its changes over time. The total amount of $\Delta\delta MLTAN$ depends on the total phase angle during the ascent operation.

As shown in Figure 3-4, the initial relative phase of GCOM-W1 with respect to Aqua has only 16 patterns, since the orbit of Aqua is a recurrent orbit with a 16-day cycle.

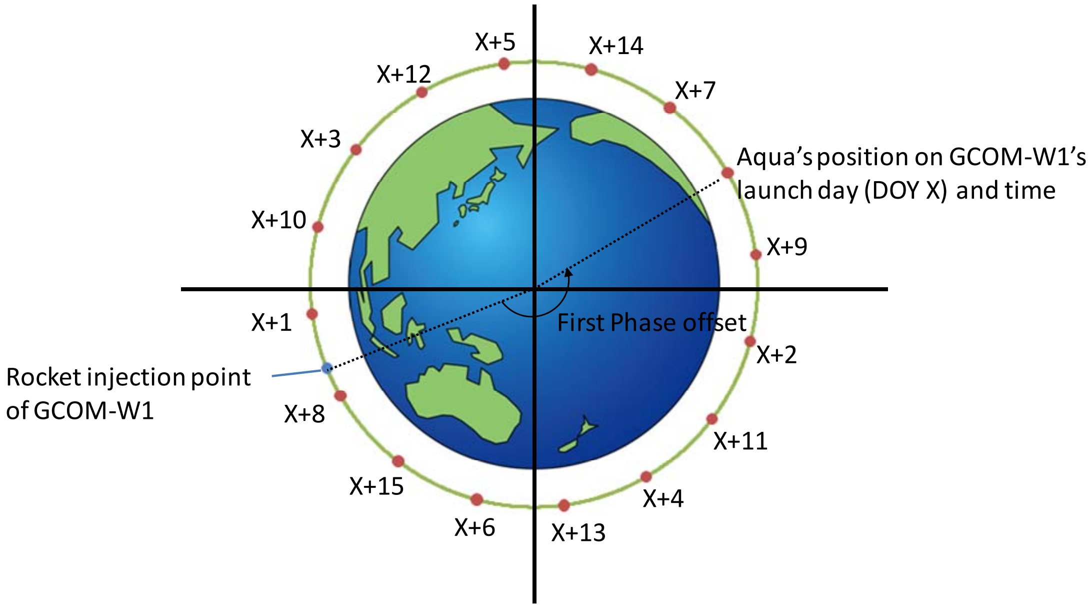


Figure 3-4 Patterns of initial relative phase (DOY= launch day)

Therefore, there are 16 different amounts of $\Delta\delta MLTAN$ or shifts of launch time. Combined with the MLTAN trend of the Afternoon Constellation, the launch time of GCOM-W1 differs on each launch date.

4. GCOM-W1 ascent plan

4.1 Position of GCOM-W1 in the Afternoon Constellation

There are three requirements on the position of GCOM-W1 in the Afternoon Constellation, as shown in Table 4.1-1.

Table 4.1-1 Requirements on the position of GCOM-W1 in the A-Train

Requirements from science team	(a) The ground track of AMSR2 coincides with that of Aqua. (b) The difference of observation time between AMSR2 and Aqua is less than 10 minutes.
Proposal from H-IIA rocket	Secure a 3-minute launch window to reduce the risk of launch postponement.
Requirement from A-Train	Keep the distance between control boxes at more than 15 seconds in equator crossing time.

JAXA analyzed the position of GCOM-W1 in the Afternoon Constellation with the above requirements in mind and proposed GCOM-W1's position in the Afternoon Constellation to the A-Train members. JAXA proposed that GCOM-W1 maintain a MLTAN between 79.5 and 259.5 seconds earlier than Aqua's MLTAN, depending on when GCOM-W1 launches within its 3-minute launch window, and that the ground track of GCOM-W1 be the same as Aqua's (WRS-2). GCOM-W1 will operate within a pre-defined ground-track control box of ±20 km measured at the descending node around the reference point.

The members of the Afternoon Constellation approved the proposal from JAXA in summer 2009.

Figure 4.1-1 shows the position of GCOM-W1 in the Afternoon Constellation.

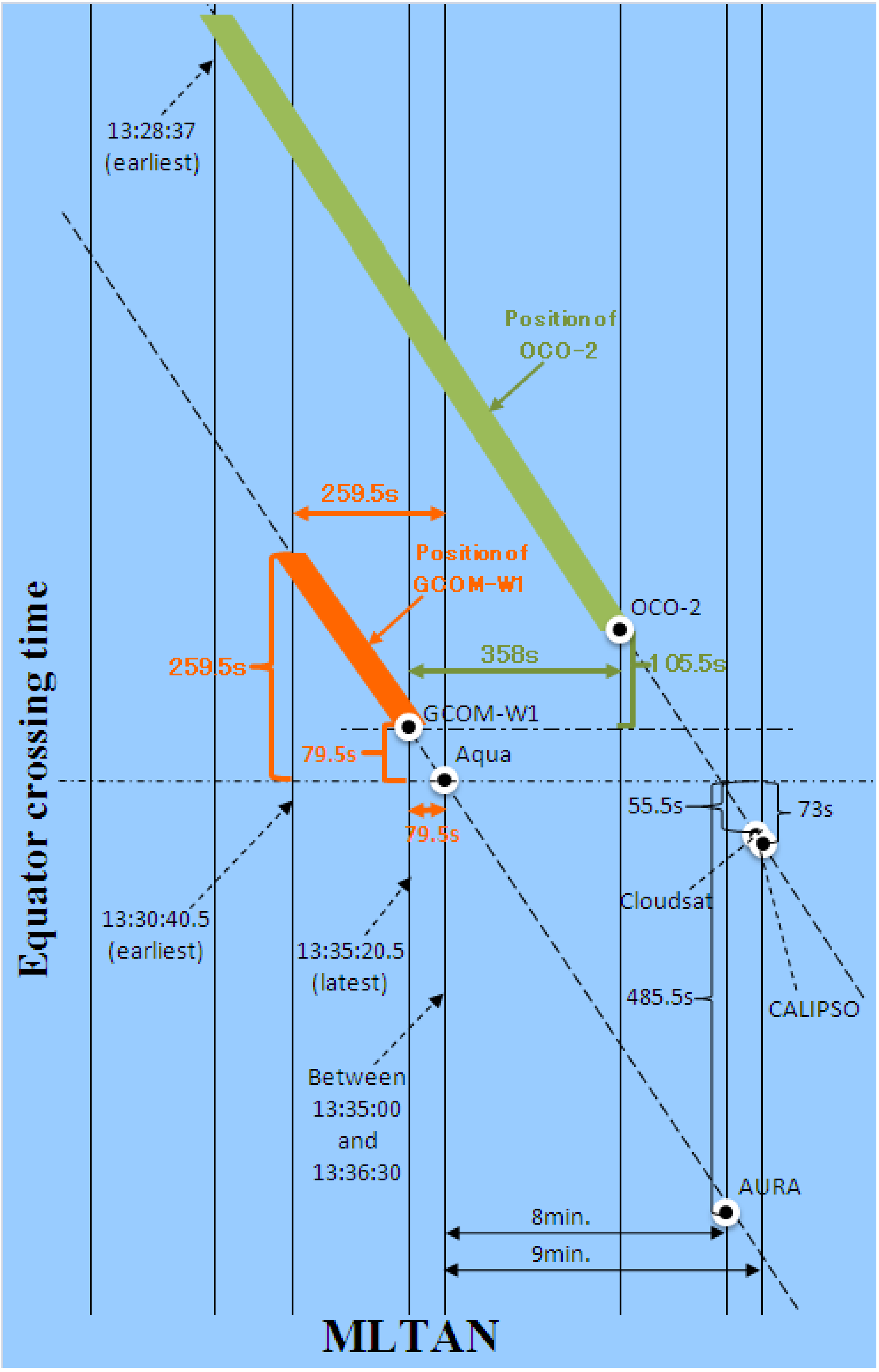


Figure 4.1-1 Position of GCOM-W1 in the A-Train

4.2 Ascent plan strategy

This section describes the ascent plan strategy for GCOM-W1. The guidelines of the ascent plan are introduced first, followed by the three fundamental strategies of the ascent plan design.

4.2.1 Guidelines of the ascent plan

JAXA considers the following guidelines important to the design of the GCOM-W1ascent plan:

- Determine dates of possible orbital maneuvers before the launch
- Complete the ascent operation as soon as possible
- Minimize fuel consumption
- Avoid deceleration maneuvers

The dates of possible orbital maneuvers should be determined before the launch so all tasks and key personnel can be allocated in advance. A shorter ascent operation will contribute quick start of mission operation in the A-Train and lower costs. Fuel consumption should be minimized since onboard fuel of GCOM-W1 is limited and is the key factor in extension of mission life. Deceleration maneuvers should be avoided since they require an attitude maneuver around the yaw axis by 180 degrees, which causes undesired ΔV.

4.2.2 Outline of ascent plan

The ascent plan was designed with the above guidelines taken into account. The ascent plan consists of three parts, called Steps 1, 2, and 3, as shown in Figure 4.2-1.

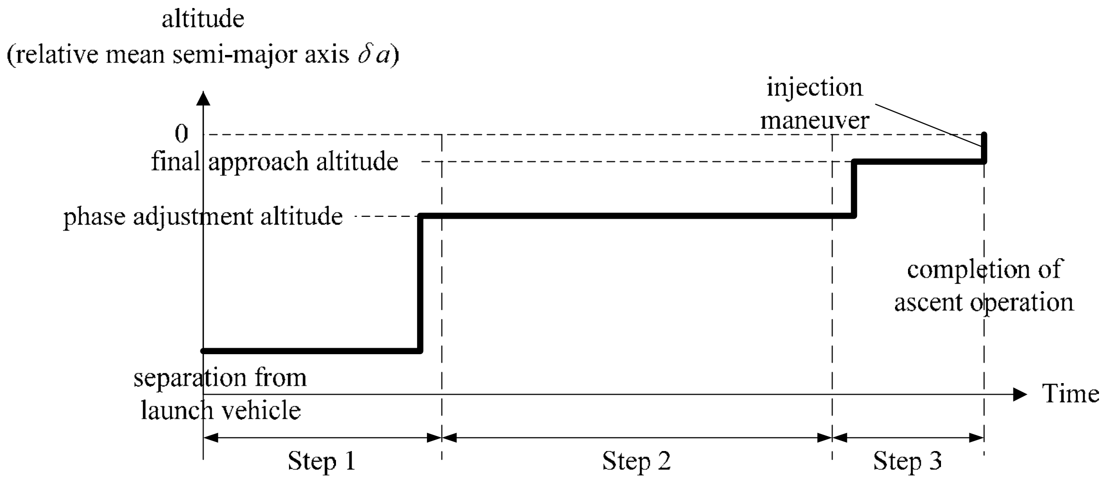


Figure 4.2-1 Basic structure of ascent operation

Each step includes its own objectives and tasks, as described below.

The objectives of Step 1 are checkout of the spacecraft functions necessary to perform maneuvers and compensation of rocket injection errors. Step 1 includes the following tasks:

- Test maneuvers
- Out-of-plane maneuvers for adjustment of inclination and RAAN to compensate for rocket injection errors
- In-plane maneuvers for raising GCOM-W1 from the injection altitude to its phase adjustment altitude

By selecting the proper "phase adjustment altitude," any change of relative phase angle caused by rocket injection errors in altitude can be absorbed during the subsequent Step 2.

The objective of Step 2 is "waiting" to catch up to the target position (target phase). During this step no maneuver is planned. The duration of Step 2 depends on the launch date and is basically unaffected by rocket injection errors.

The objectives of Step 3 are the safe approach and injection of GCOM-W1 to the A-Train. Step 3 includes the following tasks:

- In-plane maneuvers for raising GCOM-W1 from the "phase adjustment altitude" to the "final approach altitude"
- Final injection maneuvers

- Trim maneuvers to absorb small errors

GCOM-W1 performs an in-plane maneuver to raise its orbit from the phase adjustment altitude to the final approach altitude. The final approach altitude is 4 km below the A-Train. GCOM-W1 slowly approaches the target position. During Step 3, the relative eccentricity vector to the A-Train orbit is kept small by conducting pairs of in-plane maneuvers. GCOM-W1 is injected to the target position by the final injection maneuver and small errors due to the maneuver are adjusted by the subsequent trim maneuver.

4.2.3 Strategy of design

(1) How to adjust relative phase angle

The way to adjust the relative phase angle between GCOM-W1 and the target position is to follow the two guidelines discussed above:

- Complete the ascent operation as soon as possible
- Determine the dates of orbital maneuvers before the launch

Since mean argument of latitude ϕ is a function of the semi-major axis, any change of relative phase angle between GCOM-W1 and the target position can be expressed as follows by adopting linear approximation:

$$\dot{\phi} = n, \qquad \left(n = \sqrt{\frac{\mu}{a^3}} \right)$$

$$\delta\dot{\phi} = \frac{\partial \dot{\phi}}{\partial a} \delta a = -\frac{3}{2}\frac{n}{a} \delta a$$

$$\Delta\delta\phi = \frac{\partial \dot{\phi}}{\partial a} \int \delta a \, dt \equiv \Delta\delta\phi_a$$

where δ denotes the relative phase angle of GCOM-W1 with respect to the target position ($\delta\phi = \phi_{GCOM-W1} - \phi_{Target}$) and Δ denotes its changes over the passage of time. From the last equation, it is understood that the change of relative phase angle $\Delta\delta\phi$ is only dependent on the time series of relative semi-major axis δa.

Roughly speaking, we have to absorb two types of relative phase angle variation during ascent operation.

One is variation of an angle measured from the injection position of GCOM-W1 by the launch vehicle to the target position: $\Delta\delta\phi_0$ (total phase angle). The value of the total phase angle depends on the relative position of Aqua on the launch date. It has only 16 patterns since the orbit of Aqua is in a recurrent orbit with a 16-day cycle. The important point is that the value of $\Delta\delta\phi_0$ depends on the launch date and it is known before the launch operation.

The other is variation of relative phase angle caused by a rocket injection error in altitude: $\Delta\delta\phi_R$. After separation from the H-IIA rocket, GCOM-W1 has to perform several checkouts of the satellite functions, and only test maneuvers with small ΔV are performed prior to the first maneuver for ascent. Therefore, when the injection altitude of GCOM-W1 is different from the nominal one, an error of relative phase angle with respect to the nominal value is induced and accumulated during Step 1. The important point is that the value of $\Delta\delta\phi_R$ depends on the amount of rocket injection errors, and it is not known before the launch.

There are two methods to absorb these variations of relative phase angle. One is to adjust the altitude of Step 2. By this method, dates of maneuvers can be known in advance, and the period to complete the ascent operation is always constant, but the period is not minimized. The other is to adjust the duration of Step 2. By this method, the period to complete the ascent operation can be minimized, but the dates of maneuvers depend on the value of the relative phase angle to be absorbed. Figure 4.2-2 shows a simplified explanation of these two methods.

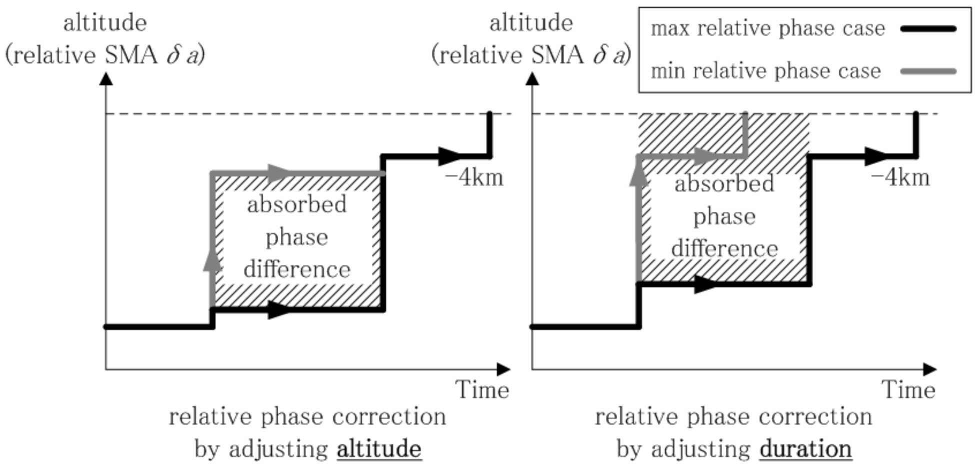


Figure 4.2-2 Simplified explanation of the methods
to absorb variation of relative phase angle

If $\Delta\delta\phi_R$ is absorbed by adjusting the duration of Step 2, the dates of the orbital maneuvers cannot be determined before the launch, since $\Delta\delta\phi_R$ depends on the results of the launch. Hence to follow the guidelines, $\Delta\delta\phi_R$ should be absorbed by changing the phase adjustment altitude of Step 2. On the contrary, $\Delta\delta\phi_0$ should be absorbed by changing the duration of Step 2 since it is known before the launch and can achieve an optimized (shorter) ascent operation.

The maneuver sequences in Step 1 and 3 are fixed, regardless of the launch date and the rocket injection errors. Only Step 2 changes depending on the launch date. Once a launch date is determined, a total phase angle is also determined. Then, we can also determine the necessary Step 2 period, that is to say the entire period for the ascent operation. The rocket injection error of the semi-major axis (±3σ) can be corrected by changing the phase adjustment altitude during Step 2 (the extra or insufficient area (phase angle) shown as green or blue in the Step 1 period of Figure 4.2-3 can be compensated by the same-colored area shown in the Step 2 period).

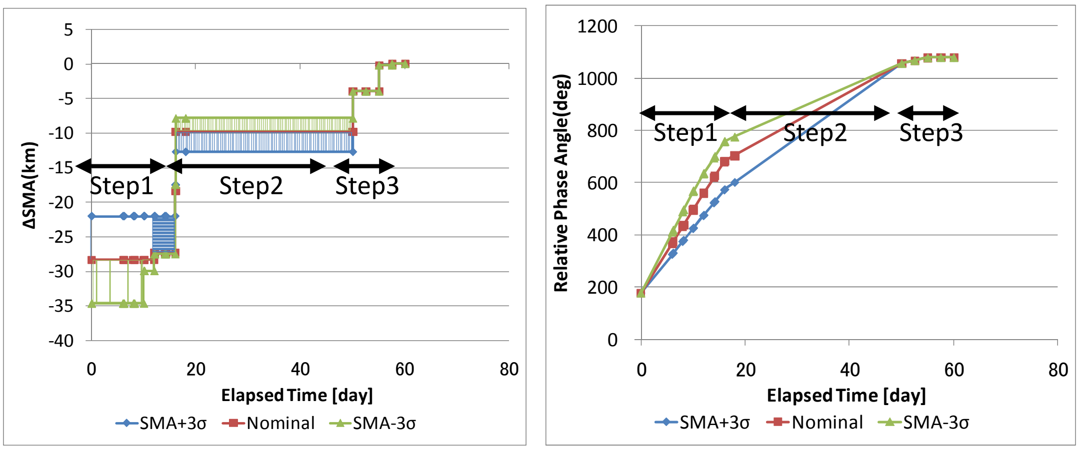


Figure 4.2-3 Example of ascent plan (plot of relative SMA and relative phase angle)

(2) How to adjust MLTAN

MLTAN adjustment is performed by shifting the launch time by the total amount of relative MLTAN drift during the ascent operation to minimize fuel consumption.

The variation of relative MLTAN ($\Delta\delta MLTAN$) during the ascent operation can be expressed as follows:

$$\dot{\Omega} = -\frac{3}{2}n\left(\frac{a_e}{a}\right)^2 J_2 \cos i$$

$$\delta\dot{\Omega} = \frac{\partial\dot{\Omega}}{\partial a}\delta a + \frac{\partial\dot{\Omega}}{\partial i}\delta i$$

$$\Delta\delta MLTAN = \Delta\delta\Omega = \frac{\partial\dot{\Omega}}{\partial a}\int \delta a\, dt + \frac{\partial\dot{\Omega}}{\partial i}\int \delta i\, dt$$
$$\equiv \Delta\delta\Omega_a + \Delta\delta\Omega_i$$

And the variation of $\delta\Omega$ induced by the difference of the semi-major axis: $\Delta\delta\Omega_a$ is proportional to the variation of relative phase angle $\Delta\delta\phi$, which is also induced by the difference of the semi-major axis as follows:

$$\frac{\Delta\delta\Omega_a}{\Delta\delta\phi} = -\frac{7}{2}\left(\frac{a_e}{a}\right)^2 J_2 \cos i = \frac{7}{3}\frac{\dot{\Omega}}{n} = constant.$$

Thus, $\Delta\delta\Omega_a$ can be known from the variation of relative phase angle $\Delta\delta\phi$ and $\Delta\delta\phi$ can be known from the position of Aqua on the rocket injection time. As a result, $\Delta\delta\Omega_a$ can be known before the launch.

On the other hand, the variation of $\delta\Omega$ induced by the difference of inclination: $\Delta\delta\Omega_i$ depends on the time series of relative inclination $\int \delta i\, dt$. It can be divided into two parts. One is the variation of $\delta\Omega$ induced by the difference between the nominal inclination of rocket injection and the target inclination of the operational orbit: $\Delta\delta\Omega_{i0}$. The other is the variation of $\delta\Omega$ induced by a rocket injection error in inclination: $\Delta\delta\Omega_{iR}$. Consequently, the total amount of variation $\Delta\delta\Omega_i$ can be expressed as follows:

$$\Delta\delta\Omega_i = \Delta\delta\Omega_{i0} + \Delta\delta\Omega_{iR}$$

The important point is that $\Delta\delta\Omega_{i0}$ can be known before the launch, and $\Delta\delta\Omega_{iR}$ cannot be known since it depends on rocket injection errors.

Therefore, $\Delta\delta\Omega_a$ and $\Delta\delta\Omega_{i0}$ in $\Delta\delta MLTAN$ can be estimated before the launch. Then the launch time can be properly selected by taking the estimated value into account so that relative MLTAN can be adjusted without unnecessary fuel consumption to absorb $\Delta\delta\Omega_a$ and $\Delta\delta\Omega_{i0}$.

On the contrary, $\Delta\delta\Omega_{iR}$ should be corrected by out-of-plane maneuvers since it cannot be determined before the launch. Similarly, the rocket injection error in RAAN should also be corrected by out-of-plane maneuvers.

This method enables a reduction of fuel consumption to correct $\Delta\delta\Omega_a$ and $\Delta\delta\Omega_{i0}$ by shifting the launch time properly. Figure 4.2-4 shows an example of an MLTAN adjustment based on this method.

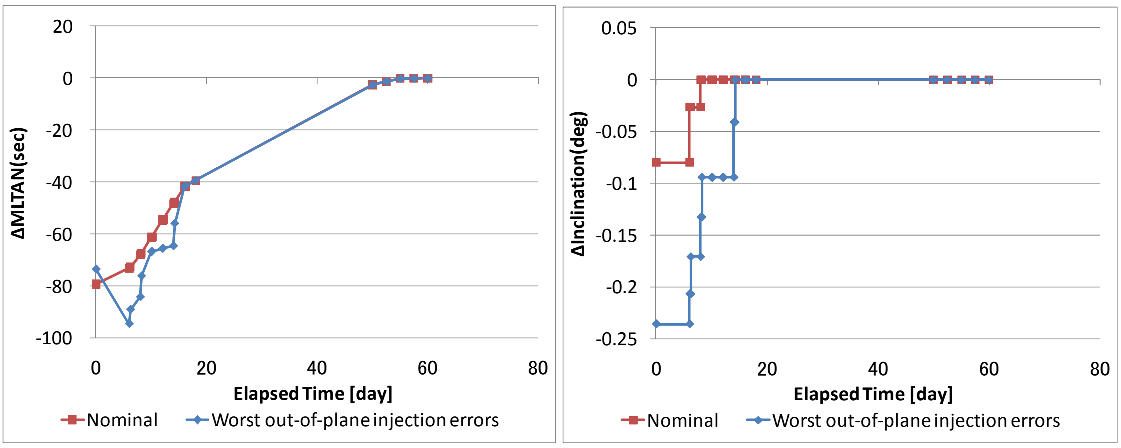


Figure 4.2-4 Example of ascent plan (plot of relative MLTAN and relative inclination)

In addition, when the launch time is delayed within its launch window, the change in RAAN due to the delay is not necessarily corrected. By adopting the original ascent plan, GCOM-W1 can be injected to the orbit that is shifted in the along-track direction and its ground track is on the WRS-2 grid.

(3) How to achieve a safe close approach and injection into the A-Train

The final injection maneuvers start at the orbit 4 km below Aqua. GCOM-W1 is not allowed to violate the Zone of Exclusion (ZOE) even during the ascent operation. The component of ZOE in radial direction is ±2 km. This means that even if the orbit is maintained as a frozen orbit, 2 km below the A-Train orbit (measured by the semi-major axis) is the highest limit that GCOM-W1 can fly before the final injection maneuvers.

Taking this restriction and the maneuver errors into account, the final approach altitude is selected to be 4 km below from the A-train orbit. The trajectory is kept as a frozen orbit in order not to violate the ZOE of Aqua by pairs of maneuvers. In addition, from the final approach altitude, GCOM-W1 can be injected into its control box even if a

±5% error of the final maneuver occurs. Figure 4.2-5 shows an example of the ascent plan during Step 3 operation.

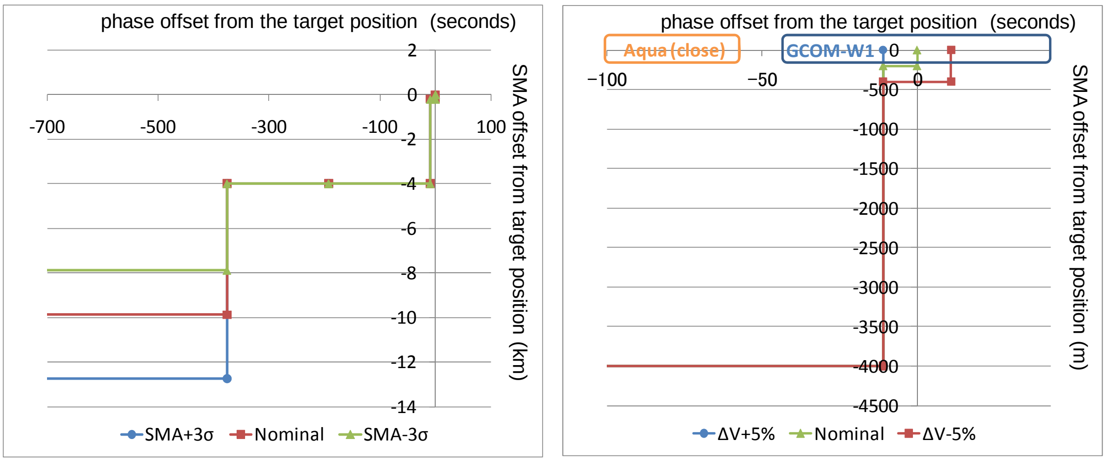


Figure 4.2-5 Example of ascent plan (Right: overall ascent plan of Step 3, Left: final injection maneuver and trim maneuver)

The ascent plan for GCOM-W1 with the three basic methods discussed above has the following four advantages:

- The date of maneuver can be determined before the launch, regardless of rocket injection errors
- The duration of the ascent operation can be minimized for the total phase angle of each launch date
- Fuel consumption can be minimized by selecting the proper launch time
- A safe close approach to the A-Train can be achieved by only acceleration maneuvers

The position of GCOM-W1's control box in the A-Train is decided by the time of launch according to this ascent plan. That means, when GCOM-W1 is launched at the beginning or end of the launch window (duration of 3 minutes), the equator crossing time and MLTAN of GCOM-W1 are 259.5 or 79.5 seconds earlier than that of Aqua, respectively.

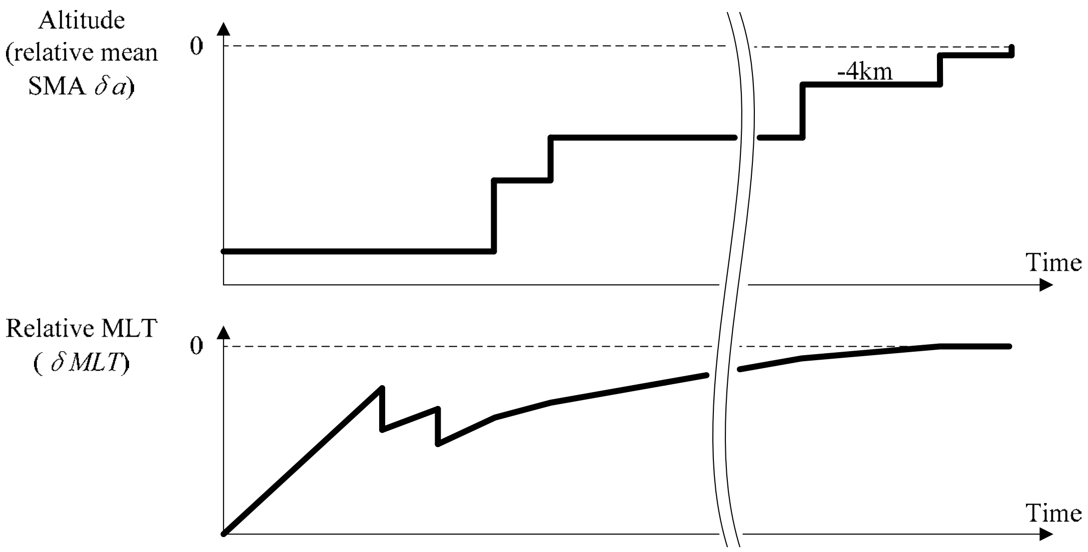
However, if a close approach to Aqua or Landsat 5 is detected during the ascent operation, GCOM-W1's MLTAN may be shifted from the nominal target ("MLTAN steering") in order to avoid a close approach, as described in Section 4.4.

4.3 Designed ascent plan

This section describes the detailed design of the GCOM-W1 ascent plan. The various constraints shown in Section 2 are considered in the design of the ascent plan. First, the overall ascent plan and time series of events are introduced. Second, the tasks and objectives of each event are explained.

(1) Overall ascent plan

Figure 4.3-1 shows the schematic of the overall ascent plan.



Phase	Step 1						Step 2	Step 3		
Duration [day]	6	2	2	2	2	2	N	2.5	2.5	2.5

Calibration Maneuver | #1 OP | #2 OP | #3 IP | #4 IP | #5 OP | #6 IP | #7 IP | #8 IP | #9 IP | #10 IP

Figure 4.3-1 Schematic of overall ascent plan
(OP: Out-of-plane maneuver, IP: In-plane maneuver)

The ascent plan consists of test maneuvers and ten maneuvers for in-plane and out-of-plane orbit adjustment.

After the separation of the GCOM-W1 from the H-IIA rocket, initial checkout operations and test maneuvers are performed.

Then, during Step 1, six time slots for out-of-plane maneuvers and in-plane (acceleration) maneuvers are allocated in the nominal time schedule. The interval between maneuver events is to be 48 hours (2 days). When the rocket injection errors are so small that a maneuver is unnecessary, the event is skipped and the time schedule is not changed.

During Step 2, no maneuver is planned. The duration of Step 2 depends on the launch date.

During Step 3, four time slots for in-plane maneuvers are allocated in the time schedule. The interval between maneuvers is to be 60 hours (2.5 days). Each maneuver event is basically executed as a pair of maneuvers to keep its eccentricity vector close to the value of the A-Train. In a manner similar to that of Step 1, an unnecessary maneuver is skipped and the time schedule is not changed.

(2) Step 1: Test maneuvers, adjustment of orbital plane, and altitude

The duration of Step 1 is 16 days. In this phase, two test maneuvers, three in-plane maneuvers, and three out-of-plane maneuvers are planned. Table 4.3-1 shows the list of planned maneuvers in Step 1. As mentioned above, the interval between maneuvers is to be 48 hours (2 days).

Table 4.3-1 List of planned maneuvers in Step 1

No.	Elapsed days from launch	Type of maneuver
	2	Test maneuver (In-plane)
	4	Test maneuver (Out-of-plane)
#1	6	1st out-of-plane maneuver
#2	8	2nd out-of-plane maneuver
#3	10	1st orbit raise
#4	12	2nd orbit raise
#5	14	3rd out-of-plane maneuver
#6	16	3rd orbit raise

On the second day from launch, a test maneuver for in-plane acceleration is performed. Then on the fourth day, a test maneuver for an out-of-plane orbit adjustment is performed. Both maneuvers are planned to be 60 seconds. These maneuvers are used to check the functionality/performance of the RCS system and to calibrate the thrust using the relationship between the burn duration and the generated ΔV.

Major maneuvers start from the sixth day. On the sixth and eighth day, out-of-plane maneuvers are performed. Using these maneuvers, the inclination is corrected to the target value, and the RAAN is adjusted so that the MLTAN reaches the target value at the time of injection of GCOM-W1 to the A-Train.

On the tenth and the twelfth day, in-plane maneuvers to raise the orbit are performed. Using these maneuvers, altitude (relative semi-major axis) is adjusted so that errors of relative phase angle induced by the rocket injection errors in altitude can be absorbed in Step 2.

On the fourteenth and sixteenth day, out-of-plane and in-plane maneuvers are planned. These slots for maneuvers are not used in many cases. If rocket injection errors are so large that they cannot be corrected by maneuvers until the twelfth day, the remaining necessary corrections are done using these slots. Otherwise, these maneuvers are skipped.

If possible conjunction with orbital debris is predicted during Step 1, it is avoided by changing the time of in-plane maneuvers.

(3) Step 2: Phasing, no burns

The duration of Step 2 depends on the launch date, and it is about 12–35 days. No maneuver event is planned in this phase.

The altitude (relative semi-major axis) of Step 2 is properly set so that errors of relative phase angle induced by rocket injection errors in altitude can be absorbed during this step. The descent rate of altitude caused by atmospheric drag is considered to set the initial altitude of Step 2. An error of relative phase angle due to an error of the predicted descent rate of altitude is absorbed by changing the duration of Step 2.

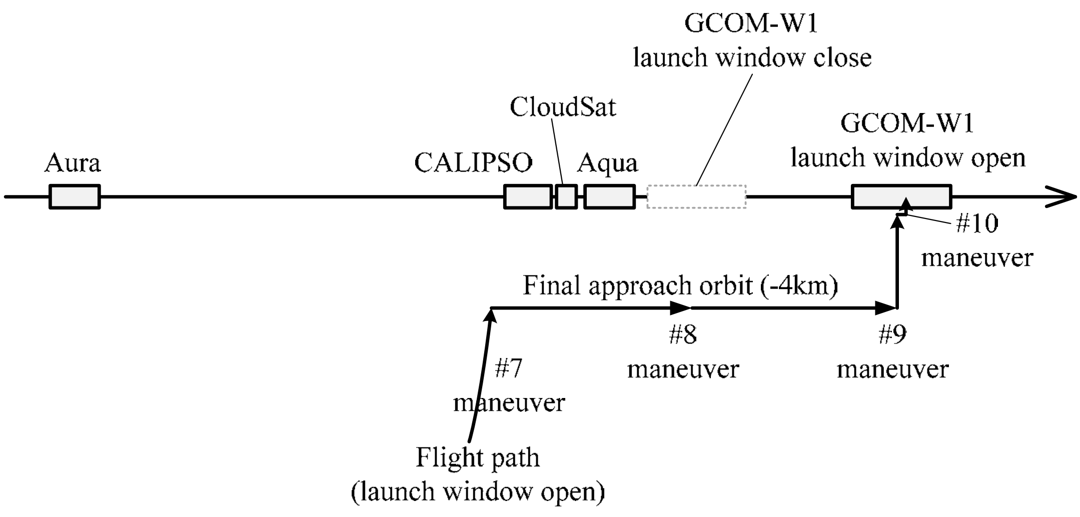
(4) Step 3: Orbit raising, adjustment of eccentricity vector, and final injection

The duration of Step 3 is 7.5 days. In this phase, four in-plane maneuvers are planned. Table 4.3-2 shows the list of planned maneuvers in Step 3. As mentioned above, the interval between maneuver events is to be 60 hours (2.5 days). Figure 4.3-2 shows the nominal flight path during Step 3.

Table 4.3-2 List of planned maneuvers in Step 3

No.	Elapsed days from launch	Type of maneuver
#7	16+N	4th orbit raise
#8	18.5+N	5th orbit raise
#9	21+N	6th orbit raise (final injection maneuver)
#10	23.5+N	7th orbit raise (trim maneuver)

(N denotes the duration of Step 2.)



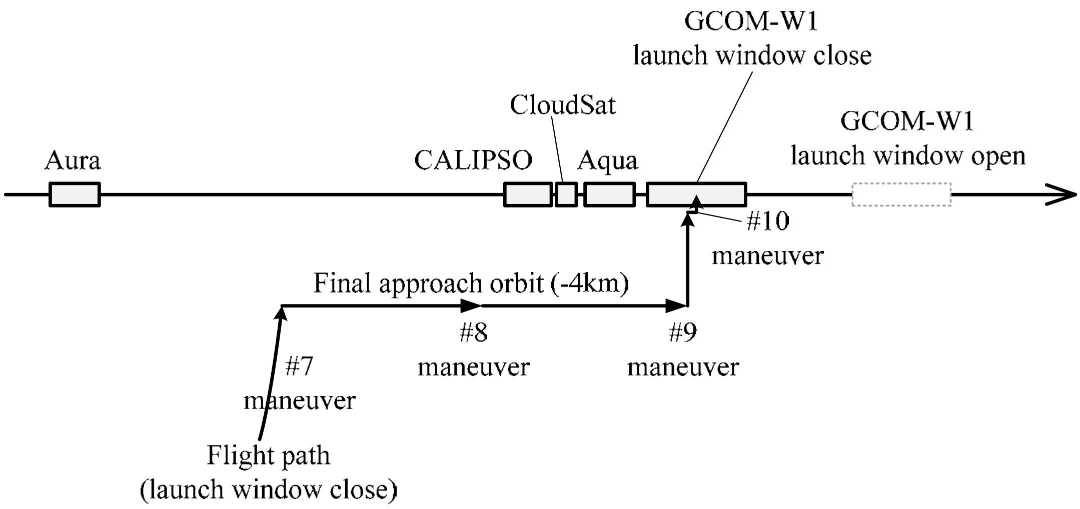


Figure 4.3-2 Step 3 nominal flight path (Top: launch window open, Bottom: launch window closed)

In Step 3, maneuvers should be executed carefully since the relative semi-major axis and the relative eccentricity vector have to be adjusted properly to prevent GCOM-W1 from invading the A-Train ZOE. Maneuvers are therefore performed as a pair of burns to keep the relative eccentricity vector. Furthermore, maneuvers are executed within visibility of the JAXA ground station in case of anomaly.

By the #7 maneuver (in-plane), GCOM-W1 reaches the “final approach orbit.” The altitude (semi-major axis) is 4 km below the A-Train. GCOM-W1 travels slowly through the final approach orbit under CALIPSO, CloudSat, and Aqua.

The size of the #7 maneuver should not be so large that it causes invasion of the ZOE due to an overburn. Therefore, the size of the #7 maneuver is designed to be less than 5 m/s by taking 5% errors of burns into account. On the other hand, the amount of altitude change by the #7 maneuver should not be too small, because the change of altitude is necessary for the adjustment of the relative eccentricity vector by acceleration maneuvers. The change of altitude of the #7 maneuver is then designed to be more than 5.32 km. With these upper and lower limitations of the #7 maneuver, invasion of the ZOE is avoided.

The #8 maneuver is the spare slot for fine tuning of the orbit. Small errors of altitude or eccentricity vector may be corrected by this maneuver.

The #9 maneuver is the “injection maneuver.” GCOM-W1 leaves the final approach orbit, which is 4 km below the A-Train, and goes up to the target position. Figure 4.3-3 shows the graphical explanation of the #9 injection maneuver and the #10 trim maneuver.

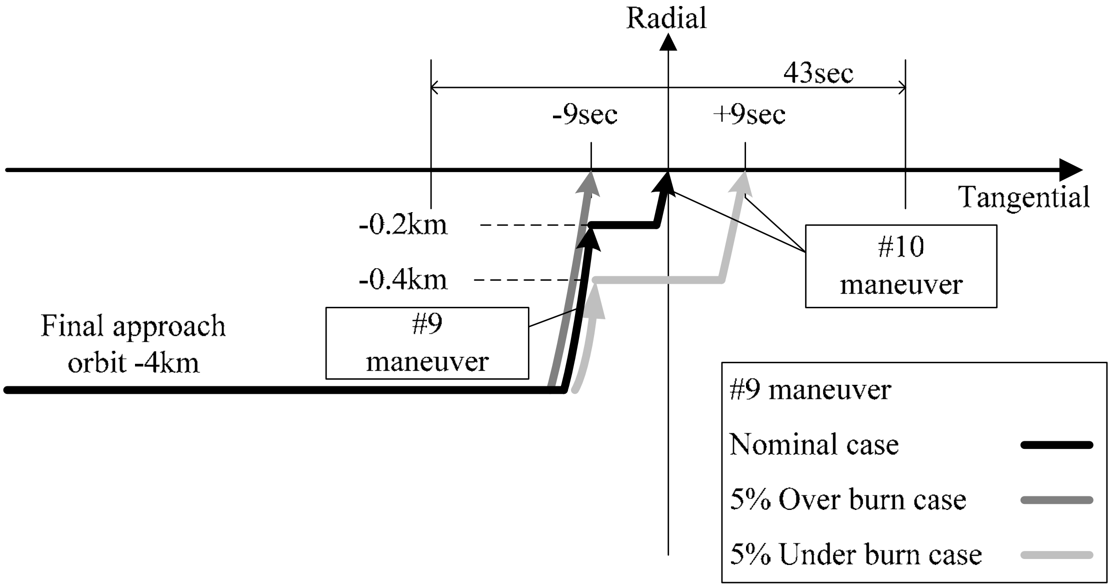


Figure 4.3-3 #9 injection maneuver and #10 trim maneuver

If the velocity of the #9 injection maneuver is greater than planned, then the subsequent #10 trim maneuver should inevitably be a deceleration maneuver. A deceleration maneuver is not accurate since it causes an attitude maneuver around the yaw axis, which possibly induces unexpected velocity increments. Therefore, to improve the accuracy of the final insertion of GCOM-W1, the target altitude of the #9 injection maneuver is designed to be lower than the altitude of the A-Train so that the achieved altitude does not exceed it even if ΔV of the maneuver is more than predicted. By taking a 5% error into account, the target altitude is designed to be 200 m below the A-Train orbit.

The #10 maneuver is the “trim maneuver.” Before this maneuver, GCOM-W1 is expected to be slightly (0 m–400 m) lower than the A-Train. The rest of the altitude difference is corrected by this maneuver and the ascent of GCOM-W1 to the A-Train is completed. GCOM-W1 is expected to be inserted within ±9 seconds from the target position by this acceleration maneuver.

4.4 Avoidance of close approach to Aqua control box during ascent operation

This section describes the operation methods to avoid a close approach to Aqua's control box during the ascent operation.

Figure 4.4-1 shows the MLTAN trend of Aqua, Forward Aqua, and the target of GCOM-W1. GCOM-W1 is required to maintain 15 seconds separation of equator crossing time between the control box of GCOM-W1 and that of Aqua for safety. The MLTAN difference between Forward Aqua and the target of GCOM-W1 is set to be 79.5 seconds so that the 15 seconds separation can be maintained.

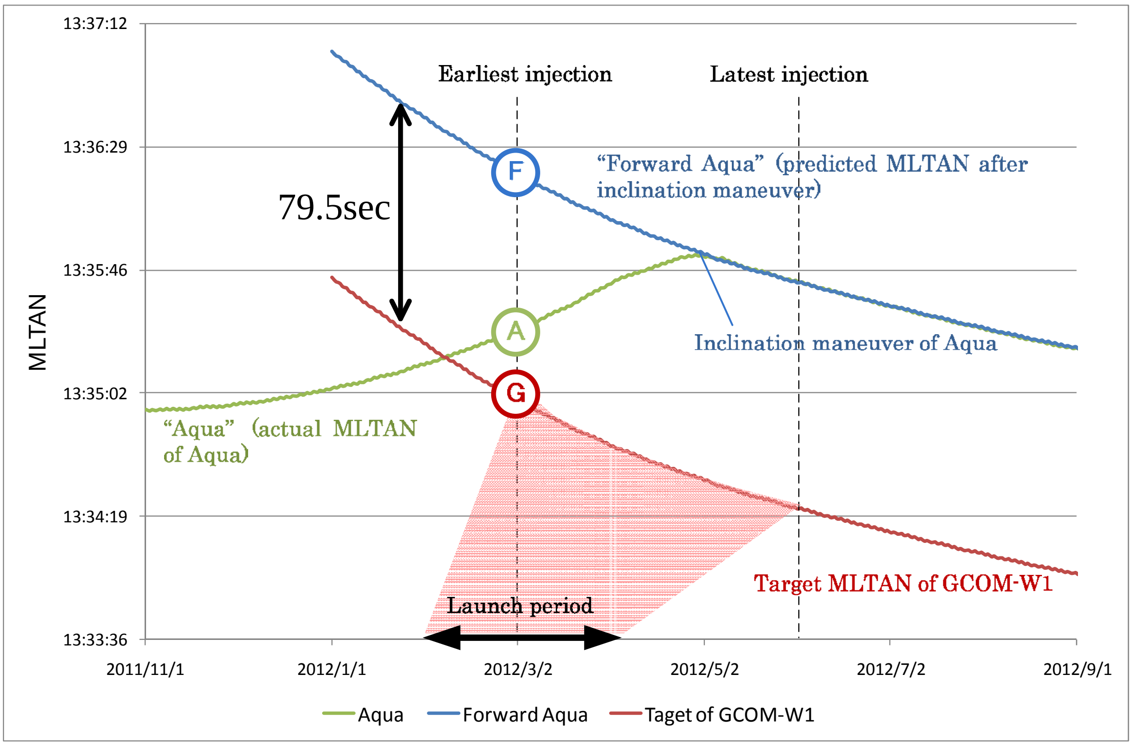


Figure 4.4-1 MLTAN of "Aqua," "Forward Aqua," and "Target of GCOM-W1"

As shown in Figure 4.4-1, before the inclination maneuver of Aqua, the difference of MLTAN between Aqua and GCOM-W1 is smaller than the difference between Forward Aqua and GCOM-W1.

In general, the difference of MLTAN is proportional to the difference of equator crossing time when the satellites maintain their ground track to follow the WRS-2. Therefore, a small difference of MLTAN means a small difference of equator crossing time.

Consequently, if injection of GCOM-W1 into A-Train is completed before the inclination maneuver of Aqua, then separation between the control box of GCOM-W1 and that of Aqua becomes smaller than 15 seconds. The worst case occurs when GCOM-W1 is launched at the beginning of the launch period and the ascent is completed in the shortest duration (shown as "Earliest injection" in Figure 4.4-1).

There are two operation methods to avoid a close approach to Aqua's control box during the ascent operation. One is a "Phase shift"; the other is "MLTAN steering." Figures 4.4-2 and 4.4-3 illustrate the worst case scenario. Figures 4.4-2 and 4.4-3 also show how to avoid a close approach to Aqua's control box using the "Phase shift" and "MLTAN steering," respectively.

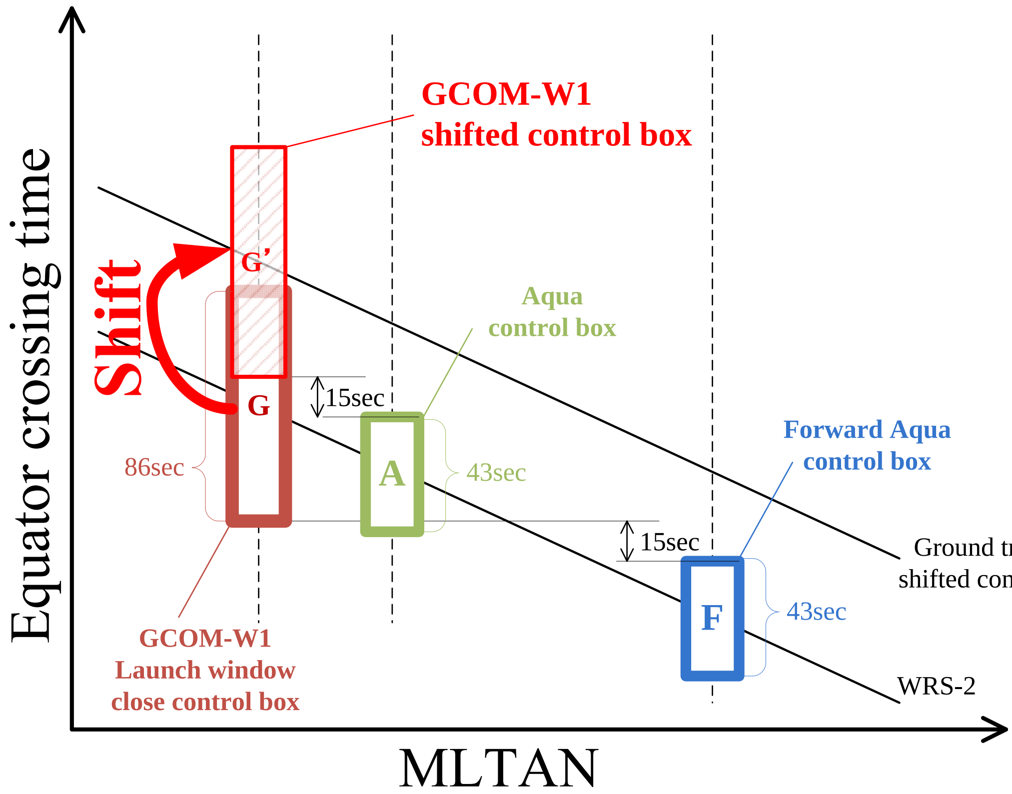


Figure 4.4-2 Phase shift ("A," "F," and "G" correspond to Figure 4.4-1)

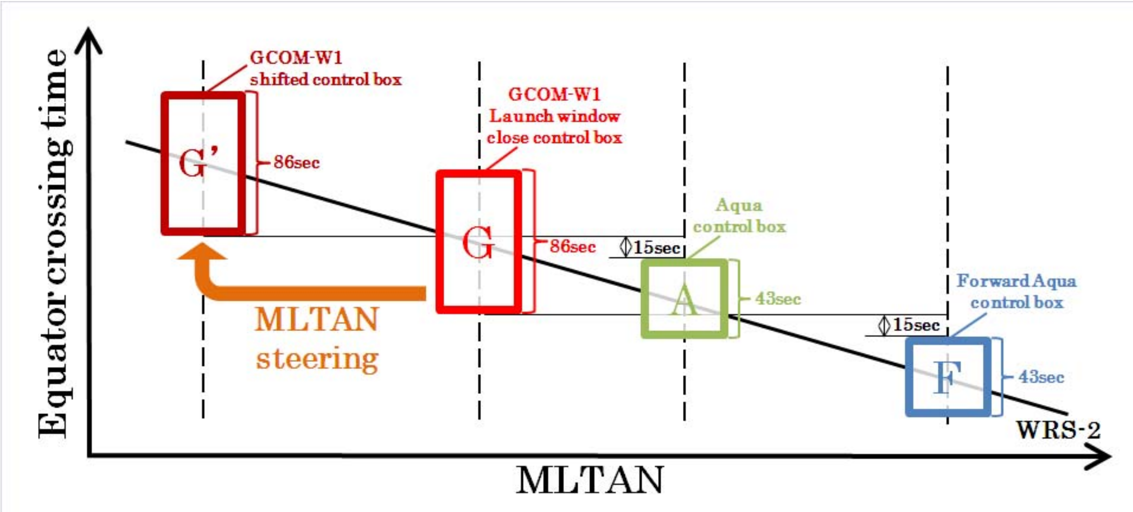


Figure 4.4-3 MLTAN steering ("A," "F" and "G" correspond to Figure 4.4-1)

If GCOM-W1 is injected into the original position, "G," then its control box does not have 15 seconds separation of equator crossing time to Aqua's control box. Furthermore, the equator crossing times of these two control boxes may overlap.

To avoid this situation, the position of the GCOM-W1 target control box is shifted from G to G' as shown in Figures 4.4-2 and 4.4-3. By shifting the target control box, the separation between the two control boxes is 15 seconds. In the earliest injection, the necessary amount of phase shift or MLTAN steering is 54 seconds.

The necessary amount of phase shift or MLTAN steering depends on the launch date, the duration of the ascent, and the date of the Aqua inclination maneuver. For simplification of operation, the amount is determined as a constant value for each launch month. According to the current best guess, the amount is 54 seconds for a launch in February and 23 seconds for a launch in March.

If GCOM-W1 is launched between February and March and the Aqua inclination maneuver is performed between April and May as planned, then a phase shift or MLTAN steering is necessary. On the contrary, if the launch period of GCOM-W1 or the date of the Aqua inclination maneuver is changed, which would allow GCOM-W1 to complete the ascent after the inclination maneuver, then a phase shift or MLTAN steering is no longer necessary. Therefore, it will be canceled in that case.

The shifted control box by "phase shift" is a temporary location for evacuation.

GCOM-W1 stays there until Aqua performs the inclination maneuver. After Aqua completes the maneuver and the original position of the control box **G** becomes safe, GCOM-W1 returns to the operational position. A backward phase shift can be achieved by drag make-up maneuvers. As shown in Figure 4.4-4, the mean altitude during the drag make-up maneuvers is to be higher than usual so that GCOM-W1 slowly drifts from the shifted target position **G'** to the original target position **G**.

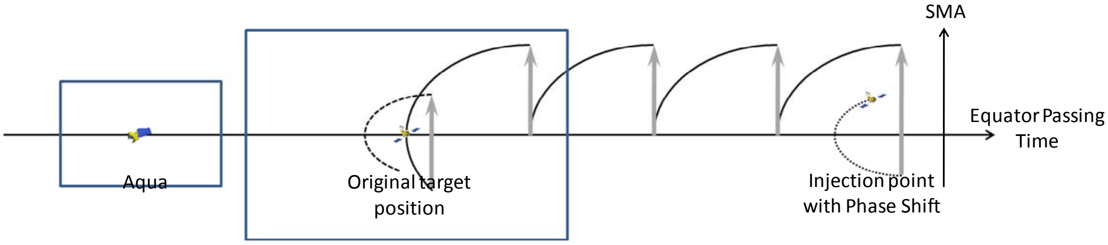


Figure 4.4-4 Phase shift operation of GCOM-W1 by drag make-up maneuvers

The ground track, after completion of MLTAN steering operation, follows the WRS-2, and the difference of MLTAN between Aqua and GCOM-W1 after that is from 79.5 seconds to 259.5 seconds. The position of the shifted control box by "MLTAN steering" meets the requirements of the AMSR2 science team and A-Train members. Therefore, special operations are not necessary after completion of the MLTAN steering operation.

4.5 Ascent maneuver simulations

4.5.1 Design result of the ascent maneuver sequence

According to the concept described in the previous sections, the actual ascent maneuver plans are simulated for the launch periods between Feb. 1, 2012 and Mar. 31, 2012. Here, a maneuver plan means a series of burns with their amounts and execution times during the ascent operation. The simulation results show the designed ascent plan in Section 4.3 has the capability to absorb the 3σ injection errors by the rocket. The initial relative phases of GCOM-W1 with respect to Aqua are shown in Figure 4.5-1. As described in Section 3, there are 16 patterns, since the orbit of Aqua is a recurrent orbit with a 16-day cycle. In this analysis, “Aqua_CCSDS_05082011_01012013.oem” received from NASA GSFC on May 10, 2011, is used as Aqua’s ephemeris.

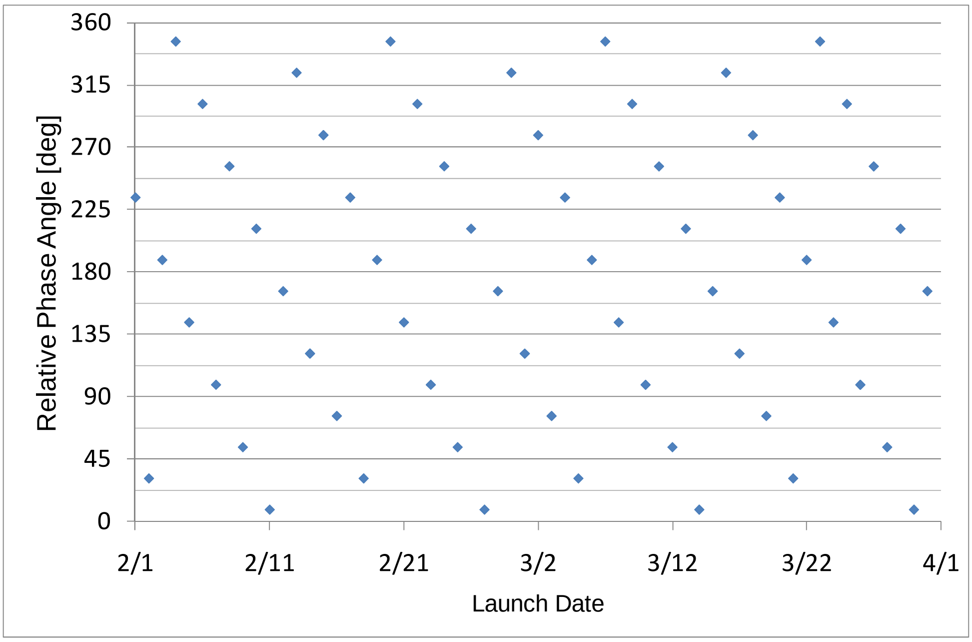


Figure 4.5-1 Initial relative phases of GCOM-W1 with respect to Aqua

Once the initial relative phase is determined, the overall ascent maneuvers sequence, especially the duration of Step 2, can be designed while taking launch vehicle injection errors into consideration. As a result, the total $\Delta\delta MLTAN$ during the ascent operation can be estimated. Because the total $\Delta\delta MLTAN$ corresponds to the shift of the launch time, the launch time of GCOM-W1 can be calculated. This analysis was done with reference to Forward Aqua. The results are shown in Table 4.5-1.

As described in Section 4.4, a “phase shift” and “MLTAN steering” to avoid a close approach with Aqua should be considered. In the analysis in Section 4.5, the amount of phase shift is determined individually in each month. The phase shift is 54 seconds for launch in February and 23 seconds for launch in March. This results in a slight difference in the values of $\Delta\delta MLTAN$ between the two months, even if the initial relative phase angle of GCOM-W1 with respect to Aqua is same. You can see from the same table, throughout the launch period, GCOM-W1 is injected to the operation position within 60 days. The launch time of GCOM-W1 is different for each launch date, as shown in Figure 4.5-2.

Table 4.5-1 The result of ascent maneuvers sequence design
(from Feb. 1, 2012 to Mar. 31, 2012)

Launch Time	16 petterns	First Phase Difference to the targe position [deg]	Time to Injection [days]	Total Δ δ MLT [seconds]	Launch Time (Open)
2/1	1	252.8	55.5	-83.1	16:39:02
2/2	2	50.3	45	-66.53	16:39:17
2/3	3	207.8	58.5	-87.83	16:38:56
2/4	4	5.3	48	-71.2	16:39:12
2/5	5	162.8	37.5	-54.65	16:39:27
2/6	6	320.3	51	-76	16:39:05
2/7	7	117.8	40.5	-59.39	16:39:21
2/8	8	275.3	54	-80.73	16:38:59
2/9	9	72.8	43.5	-64.13	16:39:15
2/10	10	230.3	57	-85.46	16:38:53
2/11	11	27.8	46.5	-68.87	16:39:09
2/12	12	185.3	60	-90.2	16:38:48
2/13	13	342.8	49.5	-73.63	16:39:03
2/14	14	140.3	39	-57.02	16:39:19
2/15	15	297.8	52.5	-78.36	16:38:57
2/16	16	95.3	42	-61.76	16:39:13
2/17	1	252.8	55.5	-83.1	16:38:51
2/18	2	50.3	45	-66.53	16:39:06
2/19	3	207.8	58.5	-87.83	16:38:45
2/20	4	5.3	48	-71.2	16:39:01
2/21	5	162.8	37.5	-54.65	16:39:17
2/22	6	320.3	51	-76	16:38:55
2/23	7	117.8	40.5	-59.39	16:39:10
2/24	8	275.3	54	-80.73	16:38:49
2/25	9	72.8	43.5	-64.13	16:39:05
2/26	10	230.3	57	-85.46	16:38:43
2/27	11	27.8	46.5	-68.87	16:38:59
2/28	12	185.3	60	-90.2	16:38:37
2/29	13	342.8	49.5	-73.63	16:38:53
3/1	14	138.4	39	-56.96	16:39:09
3/2	15	295.9	52.5	-78.3	16:38:47
3/3	16	93.4	42	-61.7	16:39:03
3/4	1	250.9	55.5	-83.04	16:38:41
3/5	2	48.4	45	-66.46	16:38:57
3/6	3	205.9	58.5	-87.77	16:38:35
3/7	4	3.4	48	-71.18	16:38:52
3/8	5	160.9	37.5	-54.59	16:39:07
3/9	6	318.4	51	-75.93	16:38:46
3/10	7	115.9	40.5	-59.33	16:39:01
3/11	8	273.4	54	-80.67	16:38:40
3/12	9	70.9	43.5	-64.07	16:38:56
3/13	10	228.4	57	-85.41	16:38:33
3/14	11	25.9	46.5	-68.8	16:38:50
3/15	12	183.4	60	-90.14	16:38:28
3/16	13	340.9	49.5	-73.57	16:38:44
3/17	14	138.4	39	-56.96	16:39:00
3/18	15	295.9	52.5	-78.3	16:38:39
3/19	16	93.4	42	-61.7	16:38:54
3/20	1	250.9	55.5	-83.04	16:38:33
3/21	2	48.4	45	-66.46	16:38:48
3/22	3	205.9	58.5	-87.77	16:38:27
3/23	4	3.4	48	-71.18	16:38:43
3/24	5	160.9	37.5	-54.59	16:38:59
3/25	6	318.4	51	-75.93	16:38:37
3/26	7	115.9	40.5	-59.33	16:38:53
3/27	8	273.4	54	-80.67	16:38:31
3/28	9	70.9	43.5	-64.07	16:38:48
3/29	10	228.4	57	-85.41	16:38:25
3/30	11	25.9	46.5	-68.8	16:38:42
3/31	12	183.4	60	-90.14	16:38:20

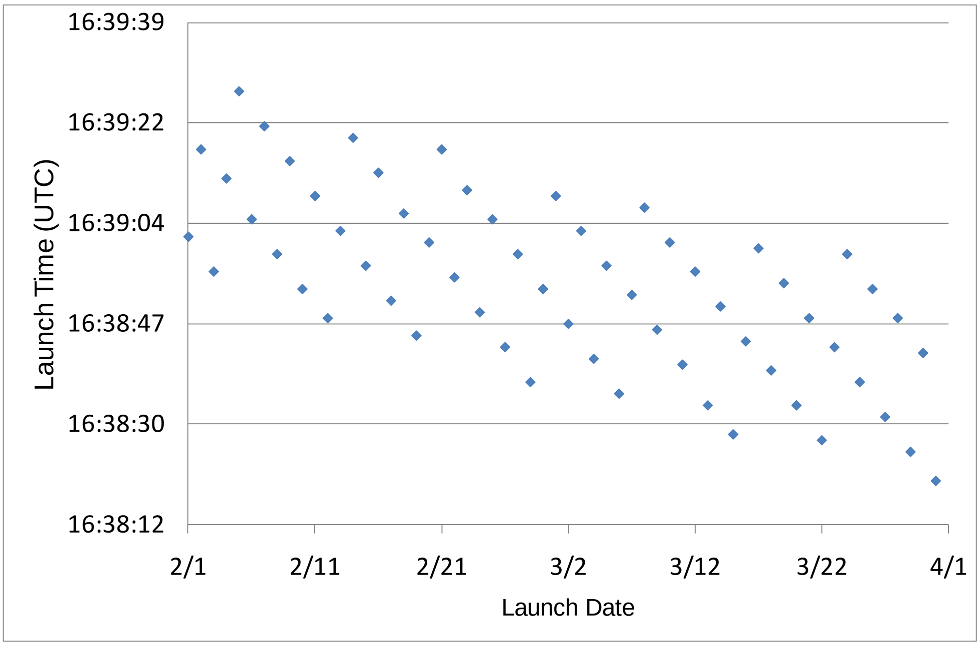


Figure 4.5-2 Launch time (Launch window open) of GCOM-W1

As discussed in the previous sections, the sequences of maneuvers do not have to be changed in spite of the launch injection errors. In other words, a maneuver sequence is designed so as to have the capability to absorb the 3σ launch injection errors. Therefore, in the process of designing a maneuver sequence, the total amount of ΔV required during the ascent operation is also estimated. The estimated total amount of maneuvers for the typical error cases are shown in Table 4.5-2. The maximum total amount of maneuvers for the ascent operation is less than 50 m/sec, which is acceptable for GCOM-W1 in terms of the fuel budget (See Section 2). The examples of designed maneuver plans are shown and simulated in the following section.

Table 4.5-2 Estimated total amount of maneuvers

Error case	Total amount of maneuvers
No injection error	18 m/sec
Worst out-of-plane error	38 m/sec
SMA+3σ Worst out-of-plane error	36 m/sec
SMA-3σ Worst out-of-plane error	41 m/sec

4.5.2 Ascent profile (launched on Feb. 1, 2012)

This section presents the simulation results of designed ascent maneuver plans (Feb. 1, 2012 (UTC) launch scenario). The designed ascent maneuver plans for cases with typical injection errors are shown in Table 4.5-3, Table 4.5-4, and Table 4.5-5. Table 4.5-3 shows a maneuver plan for the case without launch injection error, called the "nominal case," Table 4.5-4 and Table 4.5-5 indicate maneuver plans for the cases with launch injection errors in the semi-major axis (-3σ and $+3\sigma$, respectively) and in the orbital plane (worst correlated dispersion of inclination and RAAN), called the "-3σ case" and the "$+3\sigma$ case," respectively. As described in Sections 4.2 and 4.3, even if there are launch injection errors, the duration of the ascent operation and the sequences of maneuvers are never changed, although the amount of maneuvers are changed or some maneuvers are skipped depending on the launch injection errors.

Table 4.5-3 Designed maneuver plan in the case of a launch on Feb. 1, 2012 (without launch injection error)

	TIME (UTC) (Elapsed days from launch)	ΔV [m/sec]	Maneuver type
	Feb. 1 2012 16:39:02	-	Launch (Opening of Launch Window)
Step 1	7 Feb 2012 16:16:44 (6)	0.755	1st out-of-plane maneuver
	(8)	skip	2nd out-of-plane maneuver
	(10)	skip	1st orbit raise
	(12)	skip	2nd orbit raise
	15 Feb 2012 17:35:12 (14)	2.342	3rd out-of-plane maneuver
	17 Feb 2012 17:15:06 (16)	5.111	3rd orbit raise
	17 Feb 2012 19:42:44 (16)	5.115	
Step 2	(No maneuvers for 32 days)		(period for phase adjustment)
Step 3	20 Mar 2012 13:40:23 (48)	1.546	4th orbit raise
	20 Mar 2012 16:08:25 (48)	1.150	
	(50.5)	skip	5th orbit raise
	25 Mar 2012 15:07:42 (53)	1.005	6th orbit raise (final injection maneuver)
	25 Mar 2012 17:35:54 (53)	1.005	
	27 Mar 2012 23:07:23 (55.5)	0.110	7th orbit raise (trim maneuver)

Table 4.5-4 Designed maneuver plan in the case of a launch on 1 Feb. 2012
(with injection errors: SMA-3σ and worst out-of-plane error)

	TIME (UTC) (Elapsed days from launch)	ΔV [m/sec]	Maneuver type
	1 Feb 2012 16:39:02	-	Launch (Opening of Launch Window)
Step 1	7 Feb 2012 16:16:21 (6)	7.000	1st out-of-plane maneuver
	7 Feb 2012 22:49:07 (6)	7.000	
	9 Feb 2012 17:13:10 (8)	7.000	2nd out-of-plane maneuver
	9 Feb 2012 22:16:34 (8)	2.570	
	(10)	skip	1st orbit raise
	13 Feb 2012 17:18:16 (12)	4.530	2nd orbit raise
	13 Feb 2012 19:45:45 (12)	4.520	
	(14)	skip	3rd out-of-plane maneuver
	17 Feb 2012 17:19:35 (16)	3.541	3rd orbit raise
	17 Feb 2012 19:48:45 (16)	0.327	
Step 2	(No maneuvers for 32 days)		(period for phase adjustment)
Step 3	20 Mar 2012 13:48:44 (48)	1.400	4th orbit raise
	20 Mar 2012 16:16:44 (48)	1.150	
	(50.5)	skip	5th orbit raise
	25 Mar 2012 15:09:10 (53)	1.005	6th orbit raise (final injection maneuver)
	25 Mar 2012 17:37:22 (53)	1.005	
	28 Mar 2012 04:05:10 (55.5)	0.110	7th orbit raise (trim maneuver)

Table 4.5-5 Designed maneuver plan in the case of a launch on 1 Feb. 2012
(with injection errors: SMA+3σ and worst out-of-plane error)

	TIME (UTC) (Elapsed days from launch)	ΔV [m/sec]	Maneuver type
	1 Feb 2012 16:39:02	-	Launch (Opening of Launch Window)
Step 1	7 Feb 2012 16:33:51 (6)	7.000	1st out-of-plane maneuver
	7 Feb 2012 23:07:25 (6)	7.000	
	9 Feb 2012 17:36:37 (8)	7.000	2nd out-of-plane maneuver
	9 Feb 2012 22:40:40 (8)	2.550	
	(10)	skip	1st orbit raise
	(12)	skip	2nd orbit raise
	(14)	skip	3rd out-of-plane maneuver
	17 Feb 2012 17:13:33 (16)	4.196	3rd orbit raise
	17 Feb 2012 19:41:05 (16)	2.165	
Step 2	(No maneuvers for 32 days)		(period for phase adjustment)
Step 3	20 Mar 2012 13:14:44 (48)	2.845	4th orbit raise
	20 Mar 2012 15:42:51 (48)	1.150	
	(50.5)	skip	5th orbit raise
	25 Mar 2012 14:08:37 (53)	1.005	6th orbit raise (final injection maneuver)
	25 Mar 2012 16:36:46 (53)	1.005	
	28 Mar 2012 10:29:29 (55.5)	0.110	7th orbit raise (trim maneuver)

These ascent maneuver plans are simulated using precise orbit propagation. All planned maneuvers during the ascent operation are modeled in the ephemeris created by the orbit propagation. The results are shown in the following figures for each case. All the orbital parameters to be adjusted achieved the target values by the designed maneuvers in any case.

The semi-major axis (SMA) reaches the same value with Aqua (7077.7 km) in any case, as shown in Figure 4.5-3. As described in Section 4.3, the differences in time variation of SMA, especially in the altitude of Step 2, are intentionally introduced to absorb changes of relative phase angles caused by launch injection errors. Actually, at the end of Step 2, the relative phase angles with respect to the target position of the -3σ case and the +3σ case coincide with that of the nominal case (Figure 4.5-4). In any case, when the altitude of GCOM-W1 reaches the Afternoon Constellation altitude, GCOM- W1 also reaches the target position measured by the relative phase angle (Figure 4.5-5). The profiles of the relative phase angle versus apogee are almost the same in any case after the fourth orbit-raising maneuver, just as designed.

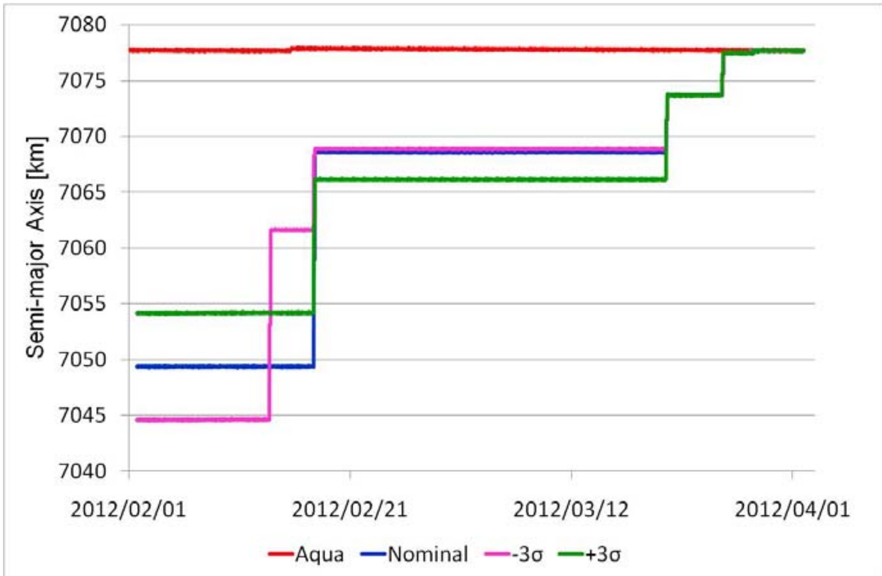


Figure 4.5-3 Time variation of mean semi-major axis (J2000)

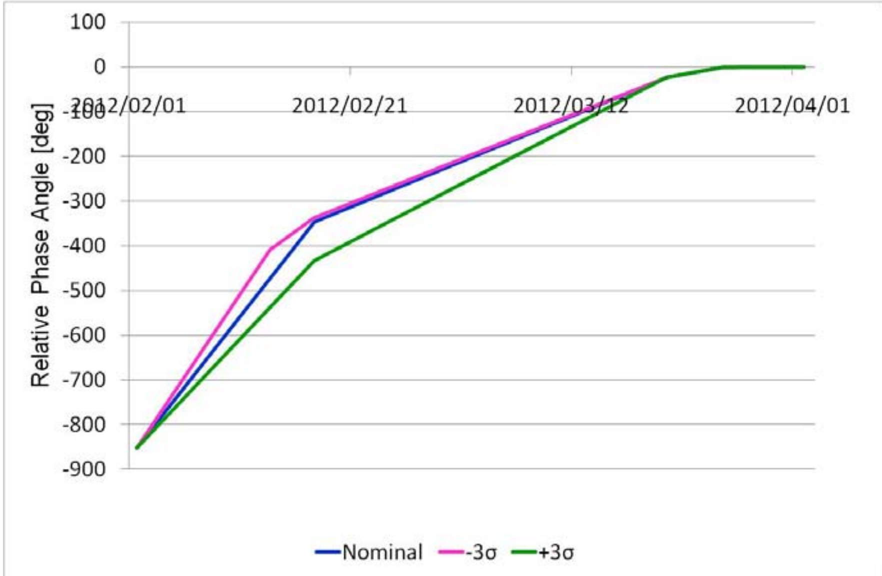


Figure 4.5-4 Time variation of relative phase angle wrt the target position

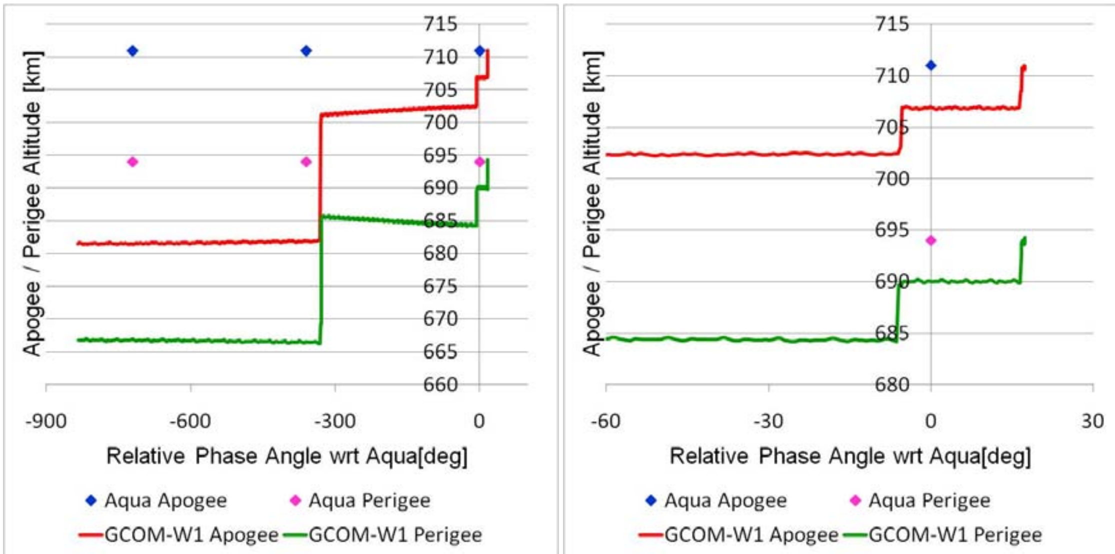


Figure 4.5-5 Relative phase angle vs. apogee/perigee altitude (Nominal)

(Right figure represents a profile around only Step 3)

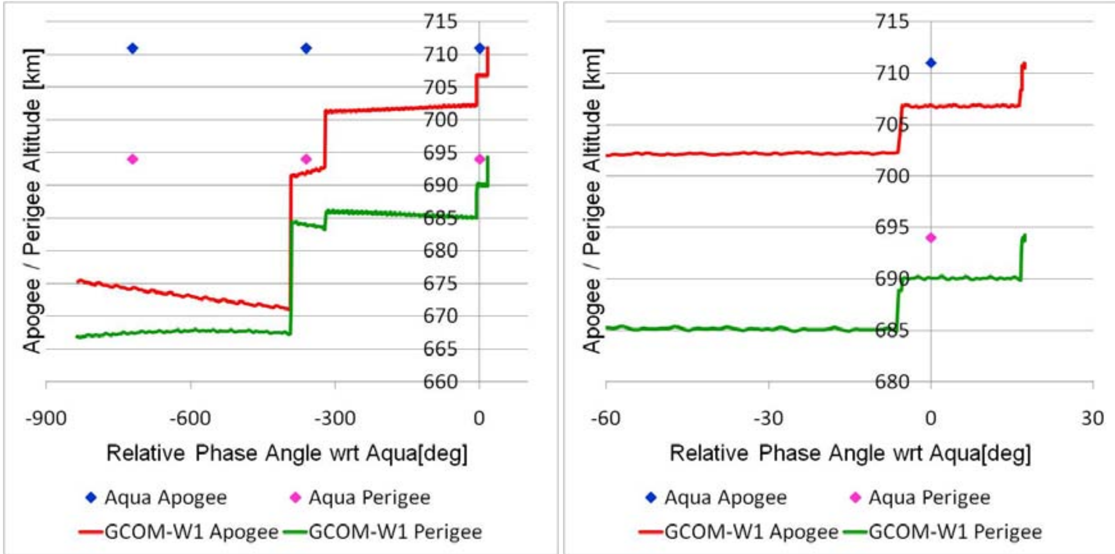


Figure 4.5-6 Relative phase angle vs. apogee/perigee altitude (-3**σ**)

(Right figure represents a profile around only Step 3)

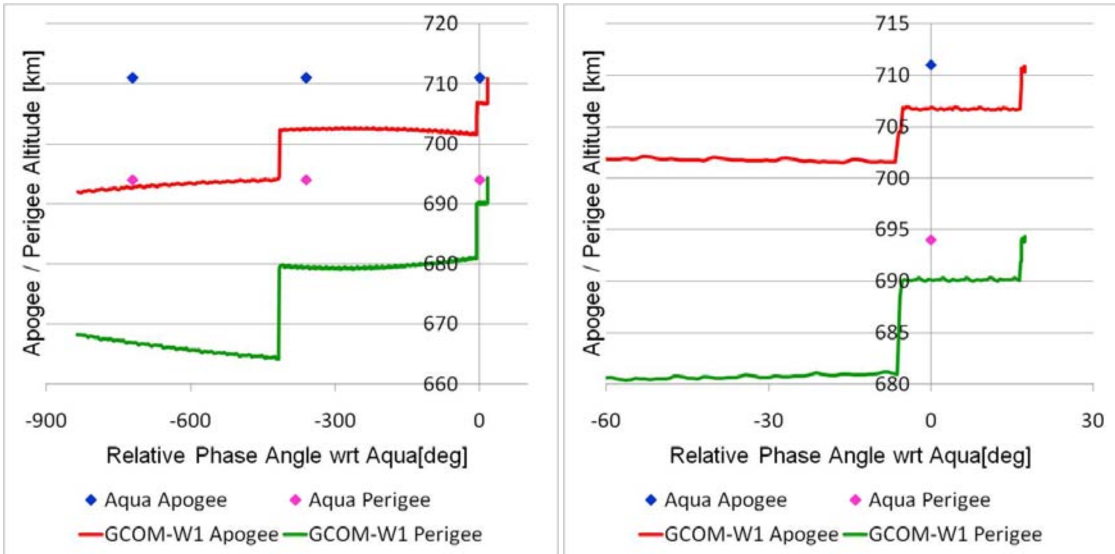


Figure 4.5-7 Relative phase angle vs. apogee/perigee altitude (+3**σ**)

(Right figure represents a profile around only Step 3)

The eccentricity vector reaches close to [0.0, 0.0118] in any case, which results in a frozen orbit. A spike in the profiles of eccentricity vector is caused by tentative dispersion during the period between pairs of burns in a maneuver. In cases with launch injection errors, the dispersion from the frozen point is comparatively large. However, the orbit is kept frozen after the maneuver to raise GCOM-W1 to the final approach altitude and there is no concern of close approach to the Afternoon Constellation satellites. The evaluation of the separation from Afternoon Constellation satellites is shown later.

Figure 4.5-8 Mean eccentricity vector (J2000) profile

(Top left: nominal, top right: -3σ, and bottom: +3σ)

In the nominal case, out-of-plane maneuvers are performed only to adjust the difference between the target inclination and the inclination of the injection orbit, as shown in Figure 4.5-9 (Nominal). The MLTAN becomes parallel to (Forward) Aqua's MLTAN without maneuvers for directly changing the MLTAN (RAAN) in the nominal case, as shown in Figure 4.5-10 (Nominal). In cases with launch injection errors (in the orbit plane), by conducting out-of-plane maneuvers for directly compensating launch injection errors, the inclination and MLTAN reach the target values.

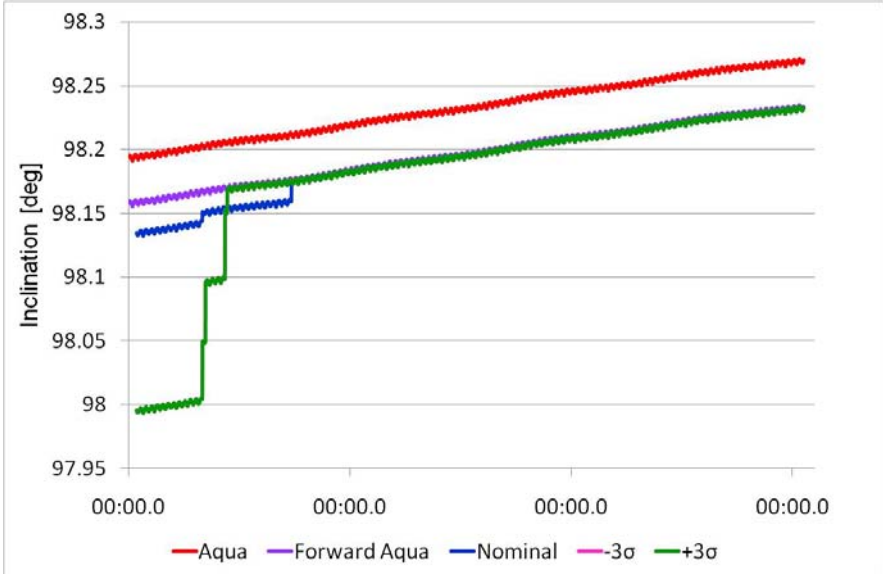


Figure 4.5-9 Time variation of mean inclination (J2000)

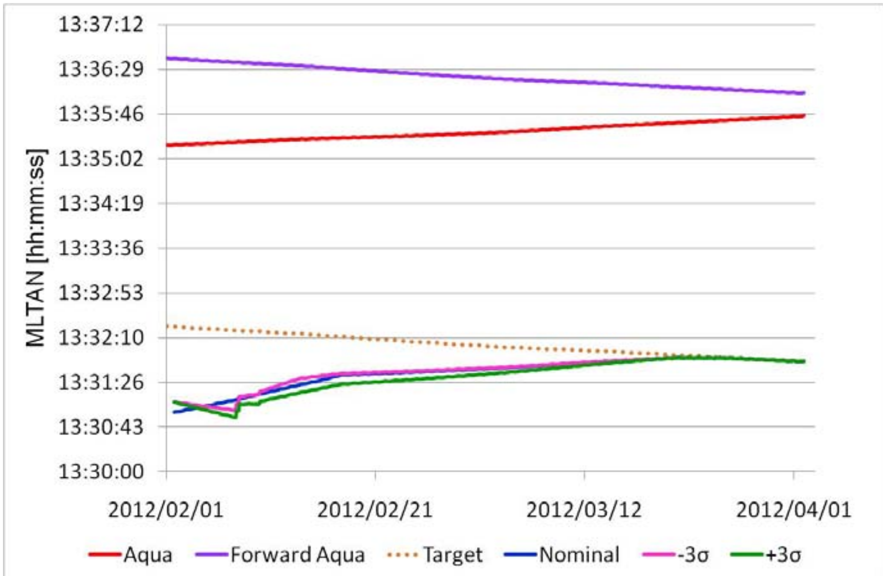


Figure 4.5-10 Time variation of MLTAN

An important point of the ascent profile is that GCOM-W1 never comes close to the Afternoon Constellation satellites. You can see from Figure 4.5-5 that the apogee and perigee altitudes of GCOM-W1 are more than 4 km below those of the Afternoon Constellation (711 km for apogee and 694 km for perigee) before the final injection maneuver. For more detailed evaluation, the separation of GCOM-W1 from Aqua is calculated during the ascent operation (See Figure 4.5-11, Figure 4.5-12, and Figure 4.5-13). The separation from Aqua (and the Afternoon Constellation) is enough to guarantee the safety of Aqua (more than 4 km) during the ascent operation. Especially when GCOM-W1 flies under Aqua (and the Afternoon Constellation), the radial separation is more than 4 km through the entire mean argument of latitude.

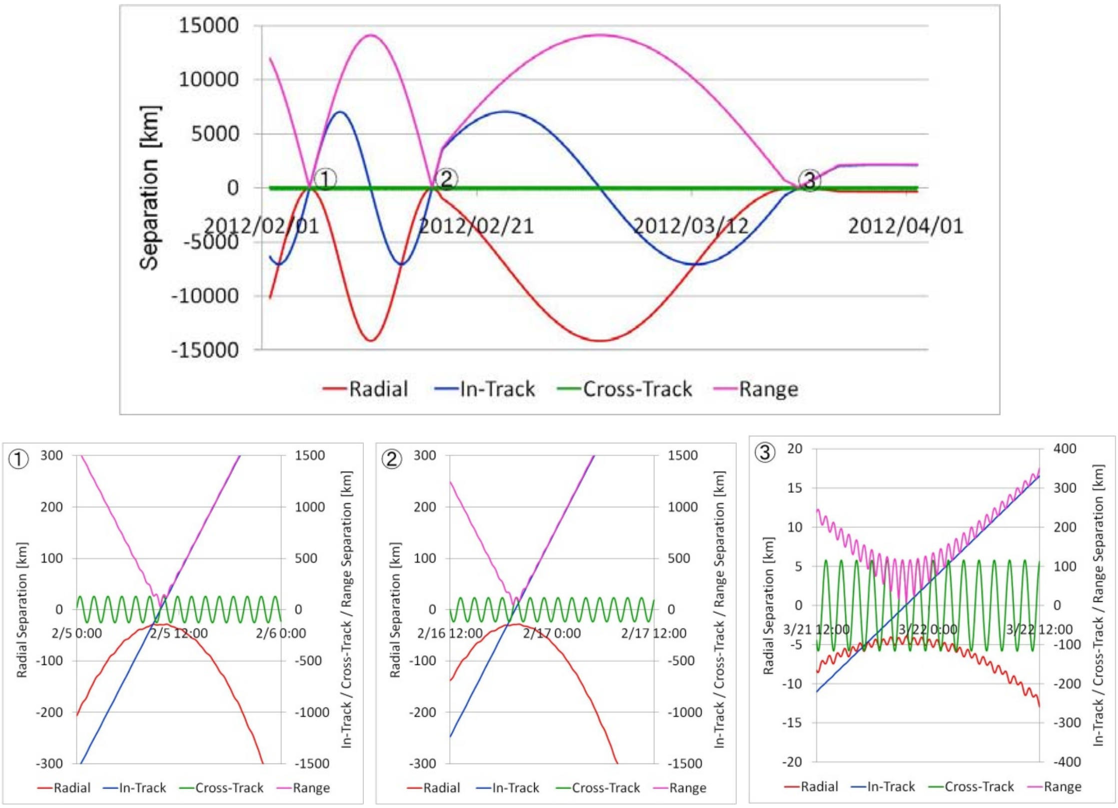


Figure 4.5-11 Separation of GCOM-W1 from Aqua (nominal case)

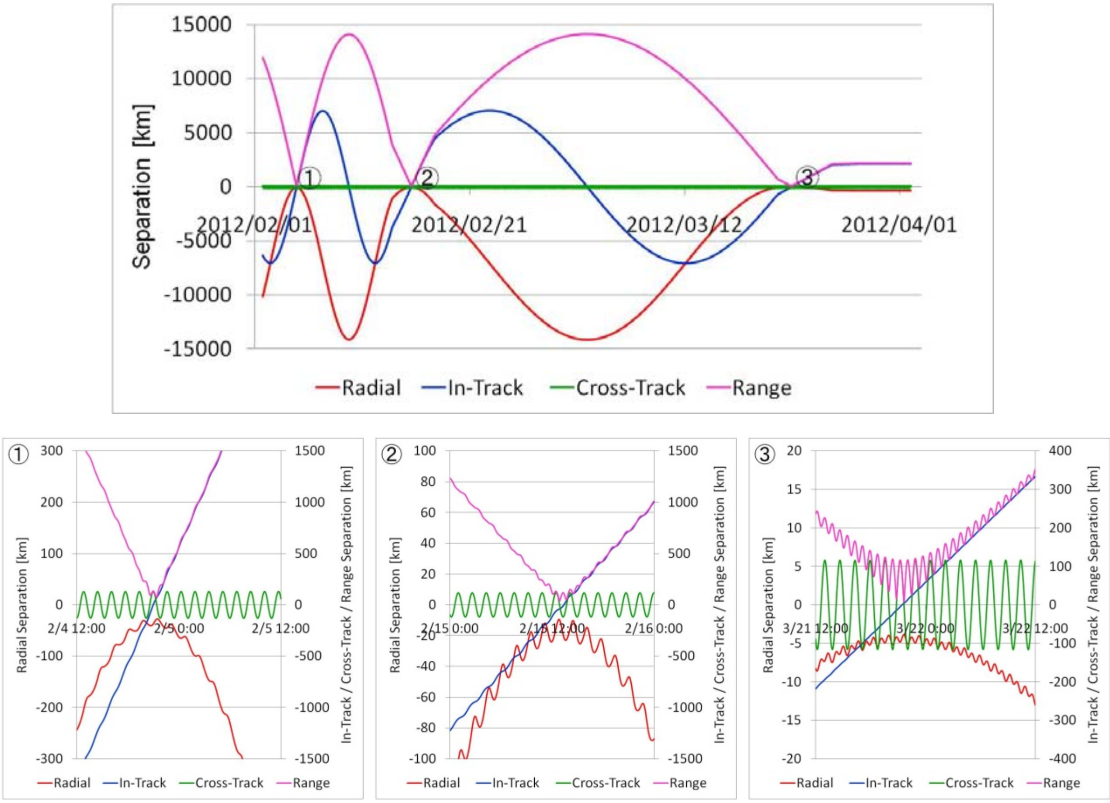


Figure 4.5-12 Separation of GCOM-W1 from Aqua (-3**σ** case)

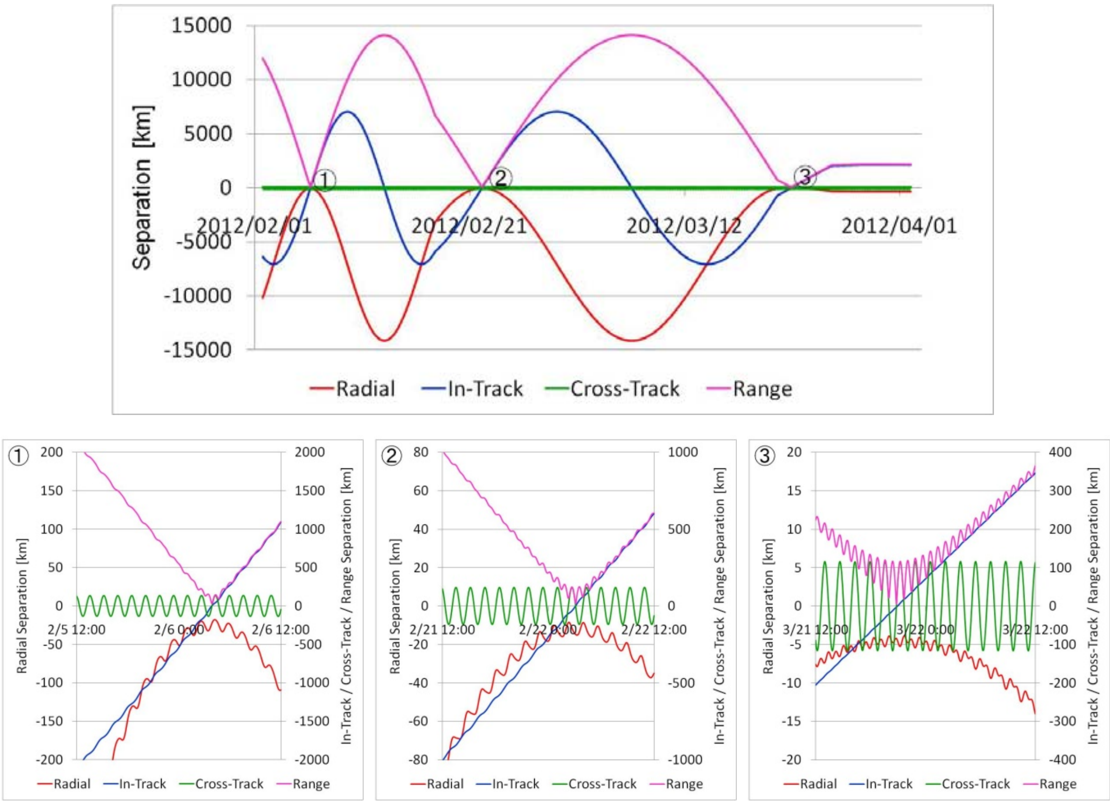


Figure 4.5-13 Separation of GCOM-W1 from Aqua (+3**σ** case)

4.5.3 Phase shift operations (start from 1 June 2012)

The simulations shown in Section 4.5.2 are performed from the launch to the trim maneuver and do not include the phase shift operation. This section presents a simulation result of phase shift operations that starts from 1 June 2012 with a 54-second phase shift. Let us assume that GCOM-W1

- is launched on 1 Feb. 2012,
- is injected to the Afternoon Constellation with a phase shift on 27 Mar. 2012,
- keeps its position as long as the risk of a close approach remains (1 June 2012),
- returns to the original target position (Aqua – 259.5 seconds).

In this simulation two maneuvers are planned, as shown in Table 4.5-6, in order to move GCOM-W1 backward. By using the upper part of the circulation orbit caused by the effect of atmospheric drag and two maneuvers, the backward phase shift of GCOM-W1 is successfully performed, as shown in Figure 4.5-14. As a result, GCOM-W1 flies along Aqua's ground track on the WRS-2 (See Figure 4.5-15).

Table 4.5-6 Maneuvers for phase shift

TIME (UTC)	ΔV [m/sec]
1 June 2012 01:18:42	0.115
19 June 2012 03:19:28	0.0527

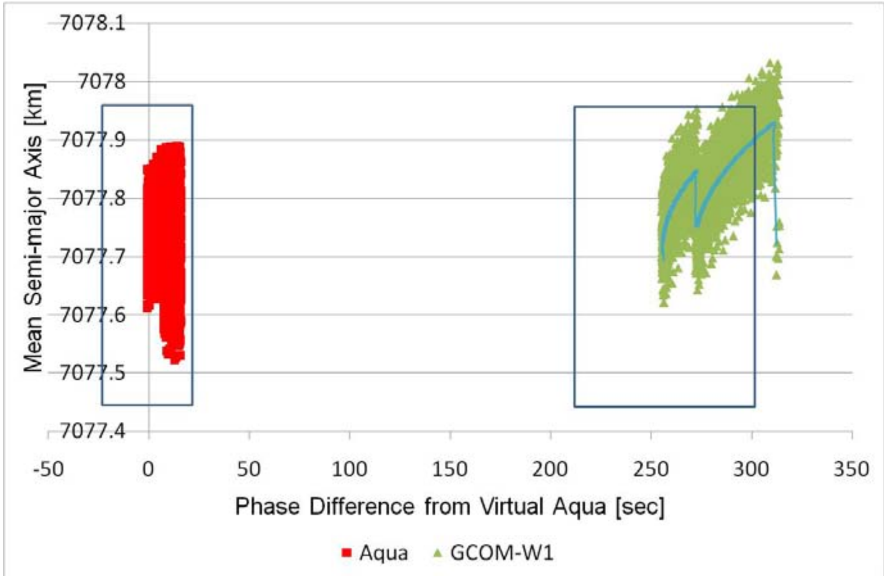


Figure 4.5-14 Phase shift operations (In-Track vs. Semi-major Axis)

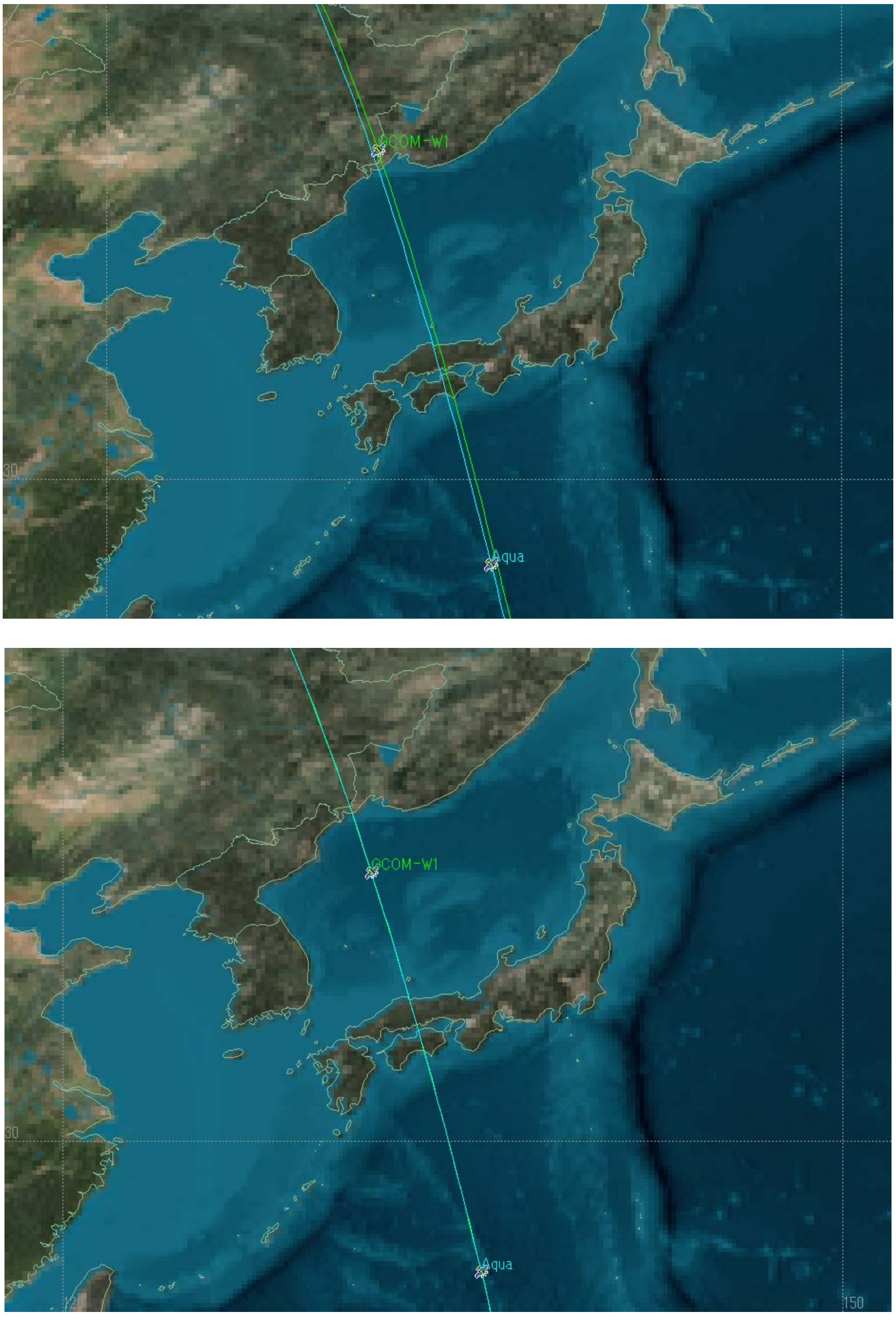


Figure 4.5-15 Ground track of GCOM-W1
Top: before phase shift (27 Mar. 2012)
Bottom: after phase shift (1 July 2012)

5 Contingency during ascent

5.1 Missed burn recovery plan

If anomalies that need recovery maneuvers happen during the ascent operation, the GCOM-W1 Mission Operations Team (MOT) replans the maneuver timing and the amount of ΔV to inject GCOM-W1 into the Afternoon Constellation. The simulation results of the recovery operations when a maneuver is missed in Step 1 or Step 3 are shown below.

(Scenario1) A maneuver in Step 1 is missed.

If a maneuver in Step 1 is missed, the relative phase angle with respect to Aqua and the total amount of $\Delta\delta MLTAN$ change from the planned values. The amount of change depends on how long it takes to restart maneuvers (the delay of the maneuver). The more delayed the maneuver is, the more the amount of change increases. According to the amount of change $\Delta\delta MLTAN$, the appropriate recovery plan should be selected from the following lists:

(a) Delay the maneuver schedule (date of maneuver execution) and change the amount of ΔVs
(b) Delay the maneuver schedule and change the amount of ΔVs and Step 2 duration
(c) Change the number and order of maneuvers in Step 1, the amount of ΔVs, and Step 2 duration (replanning of the maneuver sequences)

(Scenario 1-1) First (out-of-plane) maneuver in Step 1 is missed.

The change of $\Delta\delta MLTAN$ is greater when the first out-of-plane maneuver is missed or canceled. Analysis of the recovery operations is performed when the first maneuver in Step 1 is missed. The analysis condition is shown in Table 5.1-1.

Table 5.1-1 Analysis condition for (Scenario1-1)

<Anomaly case (recovery plan)> a) The semi-major axis error of rocket injection orbit is -3σ. b) The out-of-plane error of rocket injection orbit is +3σ. c) The recovery maneuvers start 3 days after the #1 maneuver cancelation.	
<Rocket injection orbit (Mean orbital element)>	
EPOCH (UTC)	2012/Feb/1 17:45:21
Semi-major axis	7044.613 (km)
Eccentricity	0.000809 (-)
Inclination	98.025 (deg.)
RAAN	334.125 (deg.)
Argument of perigee	98.169 (deg.)
Mean anomaly	262.015 (deg.)

The maneuver sequence planned in advance and the recovery plan due to the missed maneuver are shown in Table 5.1-2 and Table 5.1-3, respectively.

The total ΔV for the recovery plan increases by 3.318 m/s from the total ΔV for the planned sequence. This is because the out-of-plane maneuvers are necessary in order to cancel the MLTAN drift due to the #1 maneuver missing. The period for Step 2 shortens from 32 days (nominal plan) to 26 days (recovery plan) in order to adjust the relative phase angle and MLTAN behind the target position. Then this recovery plan is classified as Plan (b).

The results of the orbit propagation are shown in Figure 5.1-1 to Figure 5.1-4.

Table 5.1-2 Planned maneuver sequence (Scenario 1-1)

	TIME (UTC) (Elapsed days from launch)	ΔV [m/s]	Maneuver type
	1 Feb 2012 16:39:02	-	Launch (Opening of Launch Window)
Step 1	7 Feb 2012 16:16:21 (6)	7.000	1st out-of-plane maneuver
	7 Feb 2012 22:49:07 (6)	7.000	
	9 Feb 2012 17:13:10 (8)	7.000	2nd out-of-plane maneuver
	9 Feb 2012 22:16:34 (8)	2.570	
	(10)	skip	1st orbit raise
	13 Feb 2012 17:18:16 (12)	4.530	2nd orbit raise
	13 Feb 2012 19:45:45 (12)	4.520	
	(14)	skip	3rd out-of-plane maneuver
	17 Feb 2012 17:19:35 (16)	3.541	3rd orbit raise
	17 Feb 2012 19:48:45 (16)	0.327	
Step 2	(No maneuvers for 32 days)		(period for phase adjustment)
Step 3	20 Mar 2012 13:48:44 (48)	1.400	4th orbit raise
	20 Mar 2012 16:16:44 (48)	1.150	
	(50.5)	skip	5th orbit raise
	25 Mar 2012 15:09:10 (53)	1.005	6th orbit raise (final injection maneuver)
	25 Mar 2012 17:37:22 (53)	1.005	
	28 Mar 2012 04:05:10 (55.5)	0.110	7th orbit raise (trim maneuver)

Table 5.1-3 Maneuver sequence (recovery plan) (Scenario 1-1)

	TIME (UTC) (Elapsed days from launch)	ΔV [m/s]	Maneuver type
	1 Feb 2012 16:39:02	-	Launch (Opening of Launch Window)
Step 1	10 Feb 2012 16:16:51 (9)	7.000	1st out-of-plane maneuver
	10 Feb 2012 22:49:38 (9)	7.000	
	12 Feb 2012 17:28:58 (11)	7.000	2nd out-of-plane maneuver
	12 Feb 2012 22:17:05 (11)	5.899	
	14 Feb 2012 16:50:29 (13)	4.530	1st orbit raise
	14 Feb 2012 19:17:55 (13)	4.520	
	(15)	skip	2nd orbit raise
	(17)	skip	3rd out-of-plane maneuver
	20 Feb 2012 17:17:17 (19)	2.794	3rd orbit raise
	20 Feb 2012 19:45:08 (19)	1.366	
Step 2	(No maneuvers for 26 days)		(period for phase adjustment)
Step 3	17 Mar 2012 21:23:27 (45)	1.097	4th orbit raise
	17 Mar 2012 23:51:29 (45)	1.150	
	(47.5)	skip	5th orbit raise
	22 Mar 2012 23:10:17 (50)	1.005	6th orbit raise (final injection maneuver)
	23 Mar 2012 01:38:27 (50)	1.005	
	25 Mar 2012 15:24:11 (52.5)	0.110	7th orbit raise (trim maneuver)

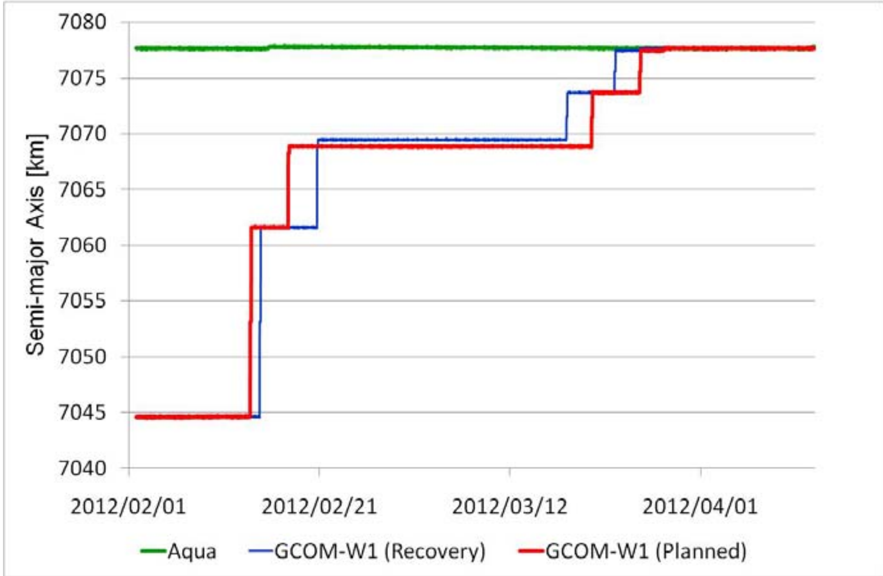


Figure 5.1-1 Change of semi-major axis (Mean element)
(Scenario 1-1)

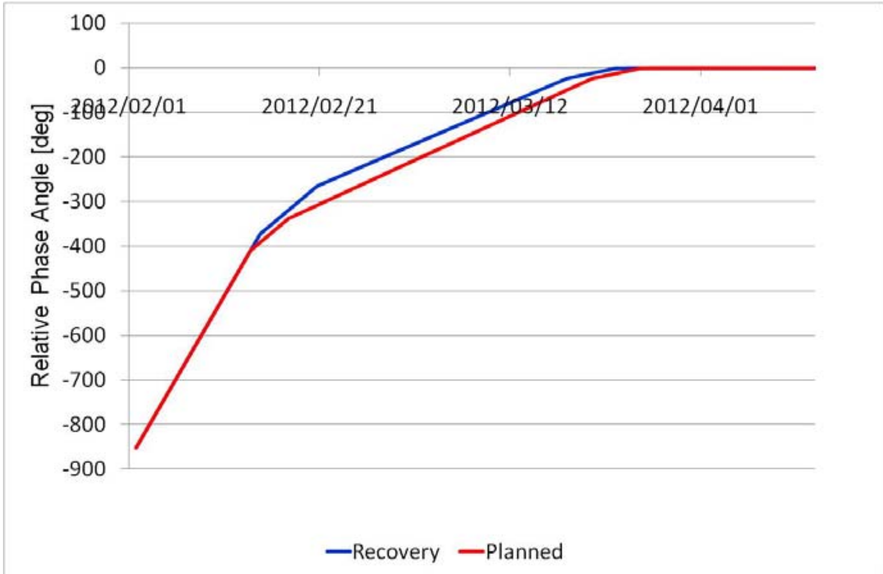


Figure 5.1-2 Change of relative phase angle (Mean element)
(Scenario 1-1)

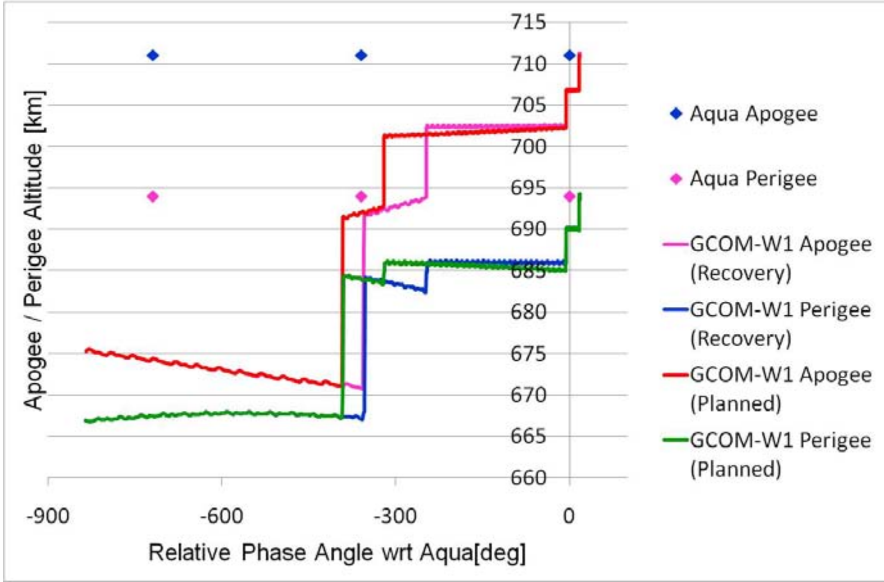


Figure 5.1-3 Relative phase angle vs. apogee/perigee altitude
(Scenario 1-1)

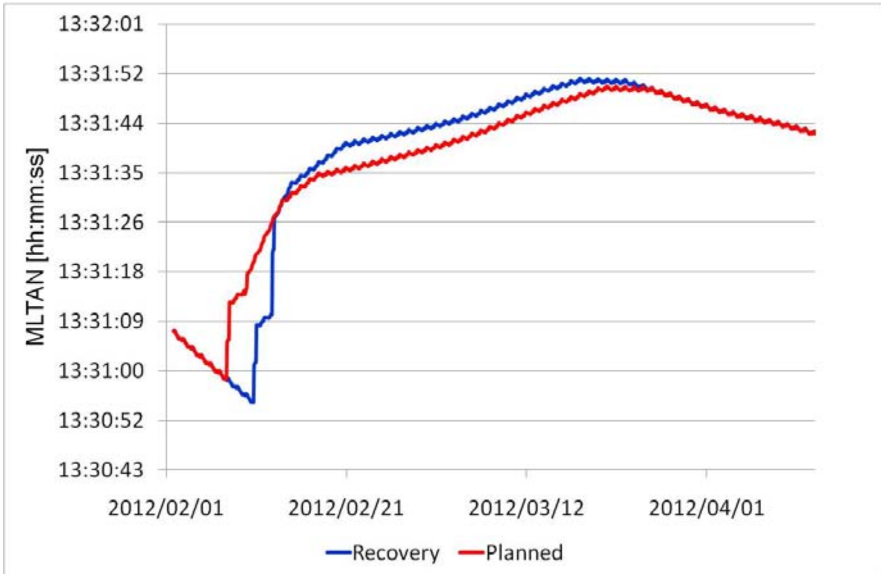


Figure 5.1-4 Change of MLTAN (Mean element)
(Scenario 1-1)

(Scenario 1-2) First orbit-raising maneuver in Step 1 is missed

By missing/canceling an orbit-raising maneuver during Step 1, the relative phase angle with respect to Aqua and the total amount of $\Delta\delta MLTAN$ change from planned values. The impact is greater when the first burn of a 2-burn pair during Step 1 is missed/canceled (especially the first burn of the first orbit-raise maneuver in Step 1). Therefore, we performed the simulations shown in Table 5.1-4 and checked whether the impact of missing/canceling a burn can be compensated by the recovery plan.

Table 5.1-4 Analysis condition for (Scenario 1-2)

	Simulation 1	Simulation 2
Launch injection errors in semi-major axis	-3 sigma	+3 sigma
Launch injection errors in out-of-plane	worst correlated dispersion of inclination and RAAN	worst correlated dispersion of inclination and RAAN
Nominal Maneuver Plan	Table 5.1-5	Table 5.1-7
Missed Burn	2nd orbit raise is delayed by 6 days (1st orbit raise is skipped in the nominal case)	3rd orbit raise is delayed by 6 days (1st and 2nd orbit raise are skipped in the nominal case)

The recovery maneuver plan for Simulation 1 is shown in Table 5.1-6. The recovery plan is classified as Plan (b). The results of the orbit propagation are shown in Figure 5.1-5 to Figure 5.1-9.

The recovery maneuver plan for Simulation 2 is shown in Table 5.1-8. The recovery plan is classified as Plan (c). The results of orbit propagation are shown in Figure 5.1-10 to Figure 5.1-14.

The results of simulations show that the recovery plan has the capability to compensate the impact of missing/canceling a first orbit-raising burn.

Table 5.1-5 Nominal maneuver plan in case of the launch on 1 Feb. 2012
(with injection errors: SMA-3σ and worst out-of-plane error)
(Scenario 1-2 Simulation1)

	TIME (UTC) (Elapsed days from launch)	ΔV [m/s]	Maneuver type
	1 Feb 2012 16:39:02	-	Launch (Opening of Launch Window)
Step 1	7 Feb 2012 16:16:21 (6)	7.000	1st out-of-plane maneuver
	7 Feb 2012 22:49:07 (6)	7.000	
	9 Feb 2012 17:13:10 (8)	7.000	2nd out-of-plane maneuver
	9 Feb 2012 22:16:34 (8)	2.570	
	(10)	skip	1st orbit raise
	13 Feb 2012 17:18:16 (12)	4.530	2nd orbit raise
	13 Feb 2012 19:45:45 (12)	4.520	
	(14)	skip	3rd out-of-plane maneuver
	17 Feb 2012 17:19:35 (16)	3.541	3rd orbit raise
	17 Feb 2012 19:48:45 (16)	0.327	
Step 2	(No maneuvers for 32 days)		(period for phase adjustment)
Step 3	20 Mar 2012 13:48:44 (48)	1.400	4th orbit raise
	20 Mar 2012 16:16:44 (48)	1.150	
	(50.5)	skip	5th orbit raise
	25 Mar 2012 15:09:10 (53)	1.005	6th orbit raise (final injection maneuver)
	25 Mar 2012 17:37:22 (53)	1.005	
	28 Mar 2012 04:05:10 (55.5)	0.110	7th orbit raise (trim maneuver)

Table 5.1-6 Recovery maneuver plan in case of the launch on 1st Feb. 2012 (Scenario 1-2 Simulation 1)

	TIME (UTC) (Elapsed days from launch)	ΔV [m/s]	Maneuver type
	1 Feb 2012 16:39:02	-	Launch (Opening of Launch Window)
Step 1	7 Feb 2012 16:16:21 (6)	7.000	1st out-of-plane maneuver
	7 Feb 2012 22:49:07 (6)	7.000	
	9 Feb 2012 17:13:10 (8)	7.000	2nd out-of-plane maneuver
	9 Feb 2012 22:16:34 (8)	2.570	
	(10)	skip	1st orbit raise
	6days delay		
	19 Feb 2012 15:35:53 (18)	4.000	2nd orbit raise
	19 Feb 2012 18:03:19 (18)	7.000	
	21 Feb 2012 15:27:24 (20)	0.367	3rd out-of-plane maneuver
	23 Feb 2012 15:41:41 (22)	1.990	3rd orbit raise
	23 Feb 2012 18:09:38 (22)	0.854	
Step 2	(No maneuvers for 14 days)		(period for phase adjustment)
Step 3	8 Mar 2012 11:54:25 (36)	0.469	4th orbit raise
	8 Mar 2012 14:22:26 (36)	1.150	
	(38.5)	skip	5th orbit raise
	13 Mar 2012 12:43:59 (41)	1.005	6th orbit raise (final injection maneuver)
	13 Mar 2012 15:12:10 (41)	1.005	
	16 Mar 2012 11:33:02 (43.5)	0.110	7th orbit raise (trim maneuver)

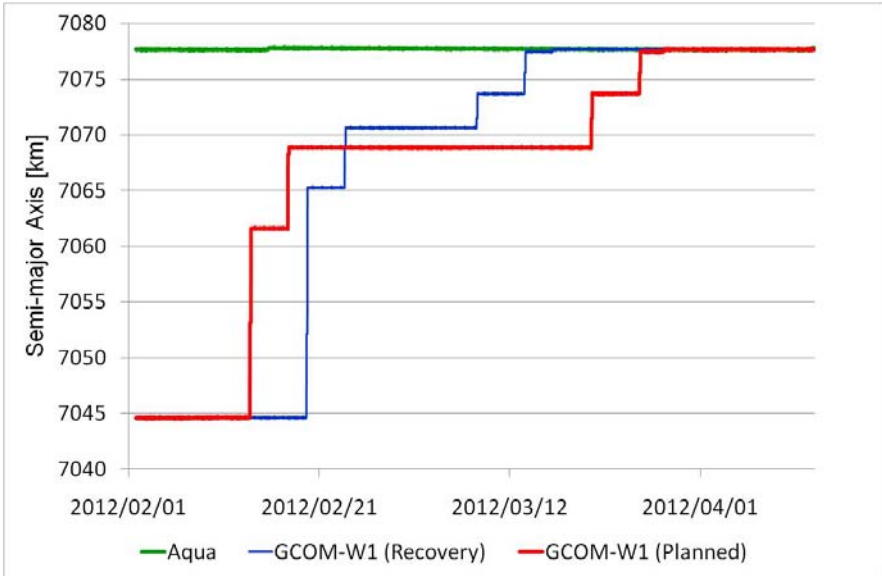


Figure 5.1-5 Time variation of mean semi-major axis (J2000)
(Scenario 1-2 Simulation 1)

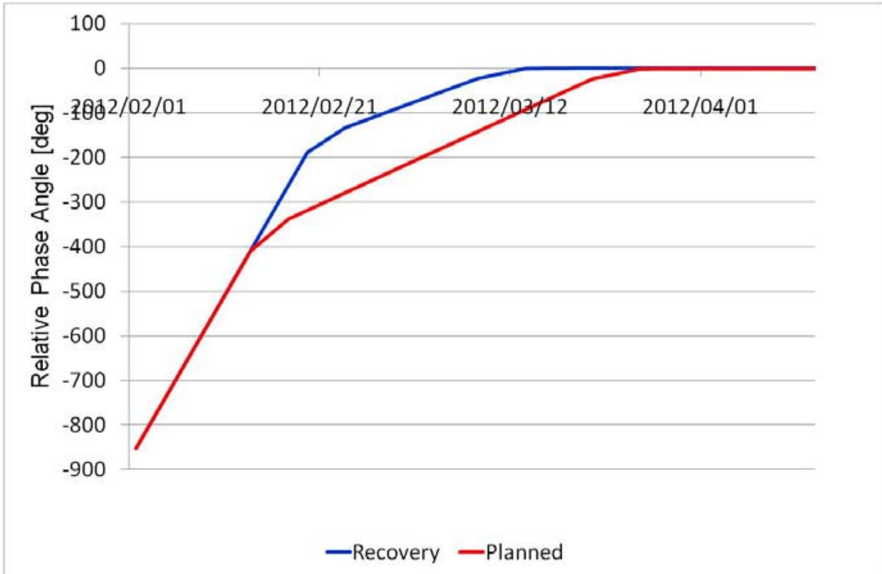


Figure 5.1-6 Time variation of relative phase angle wrt the target position
(Scenario 1-2 Simulation 1)

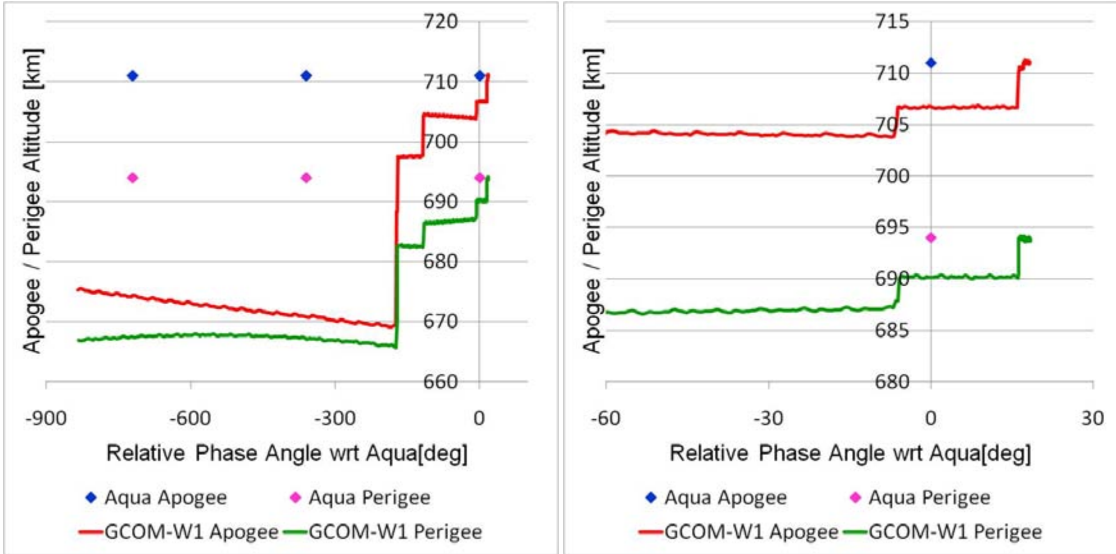


Figure 5.1-7 Relative phase angle vs. apogee/perigee altitude

(Right figure represents a profile around only Step 3)

(Scenario 1-2 Simulation 1)

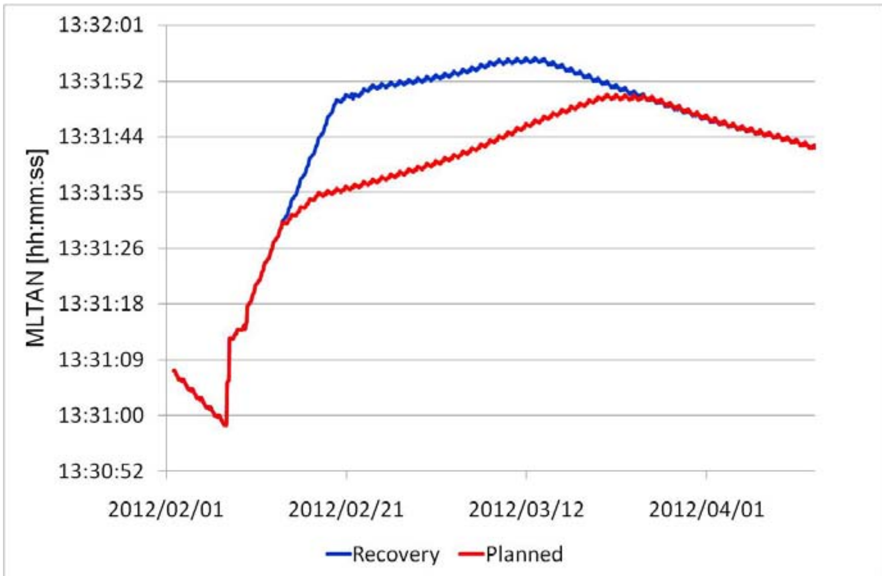


Figure 5.1-8 Time variation of MLTAN

(Scenario 1-2 Simulation 1)

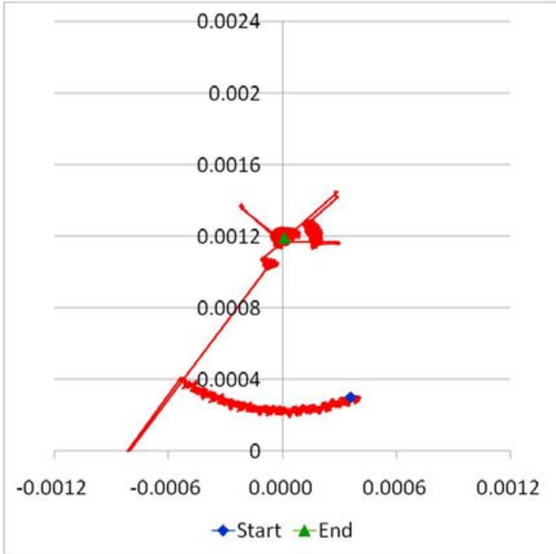


Figure 5.1-9 Mean eccentricity vector (J2000) profile
(Scenario 1-2 Simulation 1)

Table 5.1-7 Nominal maneuver plan in the case of a launch on 1 Feb. 2012
(with injection errors: SMA+3σ and worst out-of-plane error)
(Scenario 1-2 Simulation2)

	TIME (UTC) (Elapsed days from launch)	ΔV [m/s]	Maneuver type
	1 Feb 2012 16:39:02	-	Launch (Opening of Launch Window)
Step 1	7 Feb 2012 16:33:51 (6)	7.000	1st out-of-plane maneuver
	7 Feb 2012 23:07:25 (6)	7.000	
	9 Feb 2012 17:36:37 (8)	7.000	2nd out-of-plane maneuver
	9 Feb 2012 22:40:40 (8)	2.550	
	(10)	skip	1st orbit raise
	(12)	skip	2nd orbit raise
	(14)	skip	3rd out-of-plane maneuver
	17 Feb 2012 17:13:33 (16)	4.196	3rd orbit raise
	17 Feb 2012 19:41:05 (16)	2.165	
Step 2	(No maneuvers for 32 days)		(period for phase adjustment)
Step 3	20 Mar 2012 13:14:44 (48)	2.845	4th orbit raise
	20 Mar 2012 15:42:51 (48)	1.150	
	(50.5)	skip	5th orbit raise
	25 Mar 2012 14:08:37 (53)	1.005	6th orbit raise (final injection maneuver)
	25 Mar 2012 16:36:46 (53)	1.005	
	28 Mar 2012 10:29:29 (55.5)	0.110	7th orbit raise (trim maneuver)

Table 5.1-8 Recovery maneuver plan in the case of a launch on 1 Feb. 2012 (Scenario 1-2 Simulation 2)

	TIME (UTC) (Elapsed days from launch)	ΔV [m/s]	Maneuver type
	1 Feb 2012 16:39:02	-	Launch (Opening of Launch Window)
Step 1	7 Feb 2012 16:33:51 (6)	7.000	1st out-of-plane maneuver
	7 Feb 2012 23:07:25 (6)	7.000	
	9 Feb 2012 17:36:37 (8)	7.000	2nd out-of-plane maneuver
	9 Feb 2012 22:40:40 (8)	2.550	
	(10)	skip	1st orbit raise
	(12)	skip	2nd orbit raise
	(14)	skip	3rd out-of-plane maneuver
	6-day delay		
	23 Feb 2012 17:26:57 (22)	4.878	3rd orbit raise
	23 Feb 2012 19:54:42 (22)	1.315	
	25 Feb 2012 15:26:17 (24)	0.099	Recovery out-of-plane maneuver
Step 2	(No maneuvers for 17 days)		(period for phase adjustment)
Step 3	13 Mar 2012 18:11:28 (41)	2.168	4th orbit raise
	13 Mar 2012 20:39:30 (41)	2.000	
	(43.5)	skip	5th orbit raise
	18 Mar 2012 19:49:47 (46)	1.005	6th orbit raise (final injection maneuver)
	18 Mar 2012 22:18:00 (46)	1.005	
	21 Mar 2012 03:49:33 (48.5)	0.110	7th orbit raise (trim maneuver)

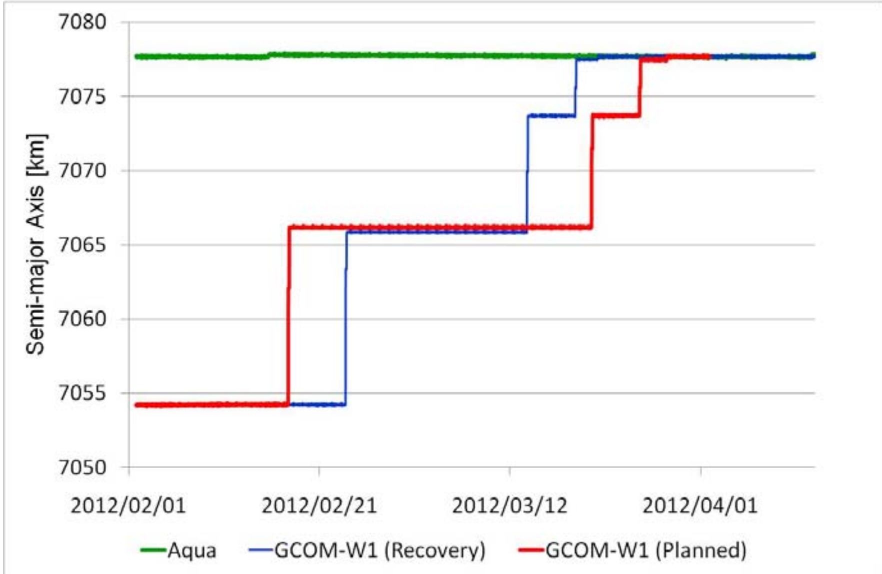


Figure 5.1-10 Time variation of mean semi-major axis (J2000)
(Scenario 1-2 Simulation 2)

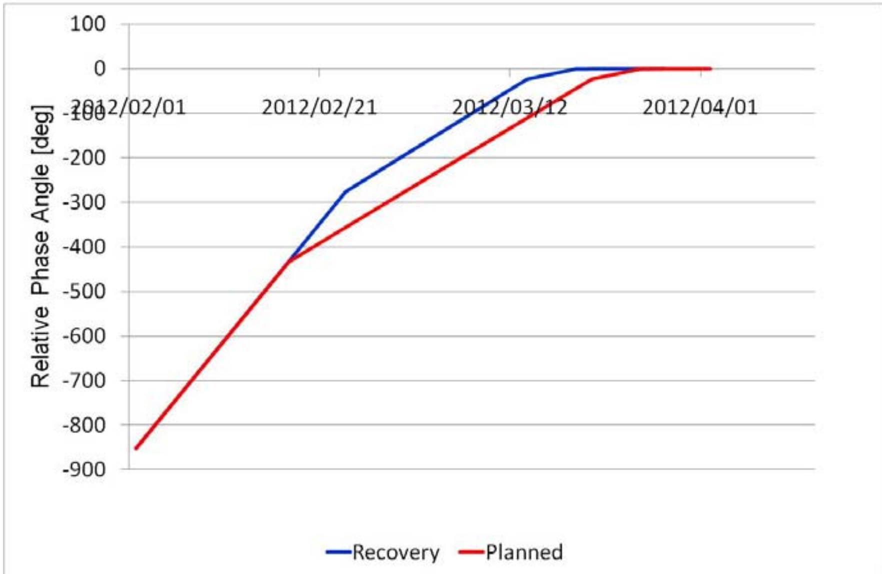


Figure 5.1-11 Time variation of relative phase angle wrt the target position
(Scenario 1-2 Simulation 2)

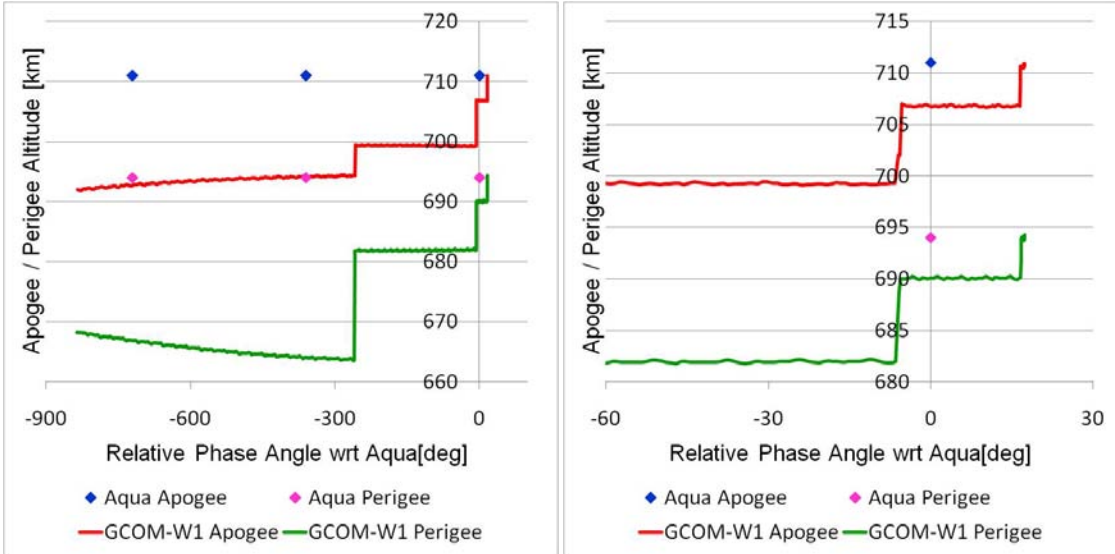


Figure 5.1-12 Relative phase angle vs. apogee/perigee altitude

(Right figure represents a profile around only Step 3)

(Scenario 1-2 Simulation 2)

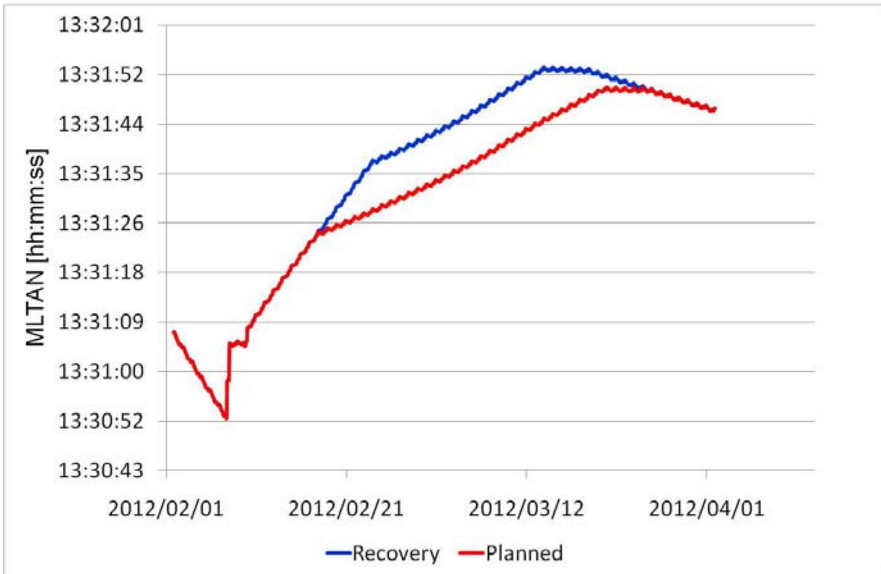


Figure 5.1-13 Time variation of MLTAN

(Scenario 1-2 Simulation 2)

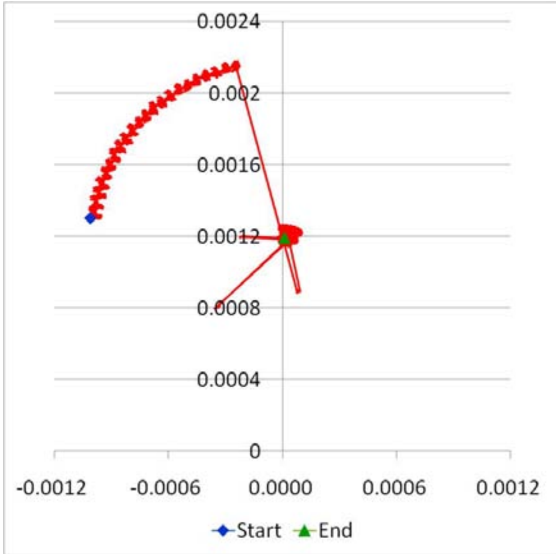


Figure 5.1-14 Mean eccentricity vector (J2000) profile
(Scenario 1-2 Simulation 2)

(Scenario 2) A maneuver in Step 3 is missed.

If a maneuver in Step 3 is missed, it is possible that GCOM-W1 may pass through the target position. Depending on the phase angle relative to the target position at the next available time slot to perform a maneuver, an appropriate recovery operation should be performed based on the following policy:

(Case 1)

If GCOM-W1 recovers its ability to perform maneuvers relatively behind the target position, GCOM-W1 should be injected by properly adjusting the amount of ΔVs in Step 3 and avoid passing through the target position.

(Case 2)

If GCOM-W1 passes through the target position because of the missed maneuver in Step 3, various recovery operations are required. The details of recovery operations will be selected according to the distance between GCOM-W1 and the target position (or the relative phase angle ahead of the target position).

(Case 2-1)

If the overrun is small, GCOM-W1 will return to the control box using drag make-up maneuvers. This is the same method as used in the phase shift operations described in Section 4.4.

(Case 2-2)

If the overrun is too large to be recovered by only drag make-up maneuvers (it takes too much time*), GCOM-W1 will return to the target position by acceleration and deceleration maneuvers. Injection from an altitude higher than the Afternoon Constellation is performed through the following steps for safety:

- Perform acceleration maneuvers. The amount of maneuvers changes depending on the overrun distance.
- Inject GCOM-W1 into the target position while the launch window is open, regardless of the actual launch time, in order to have a sufficient distance from Aqua. The deceleration maneuver is performed to inject GCOM-W1 into the orbit 200 m lower than the Afternoon Constellation. Finally, the trim maneuver is performed to inject it into the target position while the launch window is open.
- GCOM-W1 returns to the original target position derived from the actual

launch time using drag make-up maneuvers.

*) As shown in Section 4.5, GCOM-W1 is inserted to the operation position within the overall launch period of 60 days. Sixty days is the maximum allotted time for the insertion of GCOM-W1 into A-Train in the nominal case. If an anomaly happens, however, a maximum of 90 days can be used for the insertion. Therefore, if the overrun is so large that it takes more than 90 days to insert GCOM-W1 into A-Train by recovery operation "Case 2-1," then recovery operation "Case 2-2" is selected.

(Case 2-3)

If the overrun is larger than those in the above two cases, GCOM-W1 should be injected after one more revolution with out-of-plane maneuvers compensating the extra $\Delta\delta MLTAN$. The estimated extra $\Delta\delta MLTAN$ during the full synodic period is about 38 seconds. The amount of out-of-plane maneuvers for compensating the $\Delta\delta MLTAN$ is about 21 m/s.

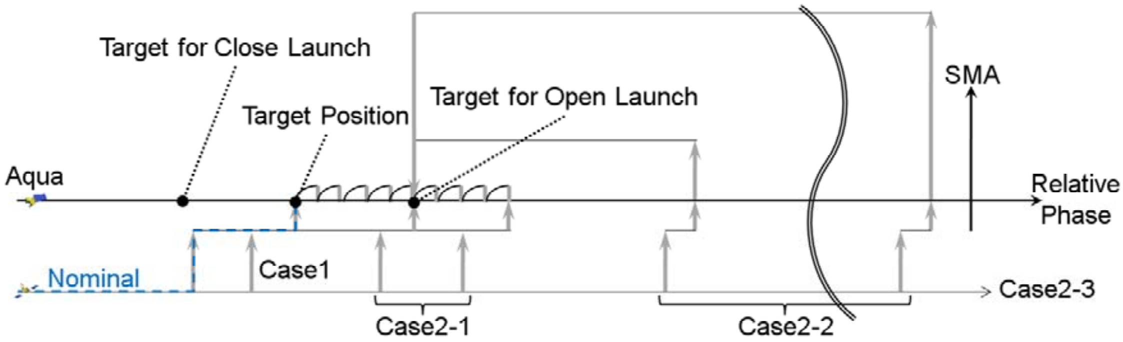


Figure 5.1-15 Recovery plan in case of missed burn in Step 3

The analysis of recovery operations is performed when the first maneuver in Step 3 (#7 maneuver) is missed. The analysis condition is shown in Table 5.1-9.

Table 5.1-9 Analysis condition for (Scenario 2)

<Anomaly case> a) The #7 maneuver in which GCOM-W1 is inserted in Step 3 is canceled. b) The recovery maneuvers start 6 days after the #7 maneuver cancelation.	
<Rocket injection orbit (Mean orbital element)>	
EPOCH (UTC)	2012/Feb/1 17:45:21
Semi-major axis	7044.613 (km)
Eccentricity	0.000809 (-)
Inclination	98.025 (deg.)
RAAN	334.125 (deg.)
Argument of perigee	98.169 (deg.)
Mean anomaly	262.015 (deg.)

The maneuver sequences of the nominal plan and the recovery plan after an anomaly occurs in the #7 maneuver are shown in Table 5.1-2 and Table 5.1-10. The total ΔV for the recovery plan increases by 4.289 m/s from the total ΔV in the nominal plan. This is because the acceleration maneuvers are necessary to perform the backward phase shift, and the deceleration maneuvers are performed in order to stop the backward phase shift and insert GCOM-W1 into the Afternoon Constellation. This recovery plan is classified as “Case 2-2.”

The results of the orbit propagation are shown in Figure 5.1-16 to Figure 5.1-19.

By missing/canceling the second burn of the #9 or #10 maneuvers, GCOM-W1 drifts forward. The impact of this kind of missed burn should also be evaluated. The drift speed is 2.2 deg./day (relative phase angle with respect to Aqua) if the second burn of the #9 maneuver is missed and 0.22 deg./day if the #10 maneuver is missed. The impact is verified from several points of view. Note that the final injection (#9) maneuver will be started at 4 km below the Afternoon Constellation and the trim (#10) maneuver will be started at 200 m below the Afternoon Constellation (see Section 4).

- Injection to the Afternoon Constellation

  The simulation shown in Section 5.1 shows that the recovery plan has the capability to compensate the impact of missing/canceling the first orbit-raising burn in Step 3 (1st burn of #7 maneuver). In terms of recovery operations, the impact is greater if the first burn of the #7 maneuver is missed/canceled than if the second burn of the #9 or #10 maneuvers is missed/canceled. Therefore, the recovery plan surely has the capability to compensate the impact of missing/canceling the second burn of the #9 or #10 maneuvers.
- Safety of Aqua (A-Train satellites)

  Because GCOM-W1 drifts "forward," there is no risk of endangering Aqua.
- Safety of Terra

  There is enough space between Terra and GCOM-W1's target position. It takes more than 14 days to overtake Terra if the second burn of the #9 maneuver is missed (See appendix). These periods will allow us to recover the ability to perform maneuvers or coordinate respective plans for resolution with ESMO and Terra.
- Safety of Landsat 5

  GCOM-W1 might endanger Landsat 5 depending on its target position. Coordination with ESMO and Landsat 5 is necessary. Developing the coordination plan will be our future work.

Table 5.1-10 Maneuver sequences (recovery plan)
(Scenario 2)

	TIME (UTC) (Elapsed days from launch)	ΔV [m/s]	Maneuver type
	1 Feb 2012 16:39:02	-	Launch (Opening of Launch Window)
Step 1	7 Feb 2012 16:16:21 (6)	7.000	1st out-of-plane maneuver
	7 Feb 2012 22:49:07 (6)	7.000	
	9 Feb 2012 17:13:10 (8)	7.000	2nd out-of-plane maneuver
	9 Feb 2012 22:16:34 (8)	2.570	
	(10)	skip	1st orbit raise
	13 Feb 2012 17:18:16 (12)	4.530	2nd orbit raise
	13 Feb 2012 19:45:45 (12)	4.520	
	(14)	skip	3rd out-of-plane maneuver
	17 Feb 2012 17:19:35 (16)	3.541	3rd orbit raise
	17 Feb 2012 19:48:45 (16)	0.327	
Step 2	(No maneuvers for 38 days)		(period for phase adjustment)
Step 3	26 Mar 2012 14:17:20 (54)	3.473	4th orbit raise
	26 Mar 2012 16:45:30 (54)	3.235	
	(56.5)	skip	5th orbit raise
	4 Apr 2012 04:19:55 (59)	-1.061	6th orbit raise (final injection maneuver)
	4 Apr 2012 06:48:14 (59)	-1.080	
	6 Apr 2012 20:34:05 (61.5)	0.110	7th orbit raise (trim maneuver)

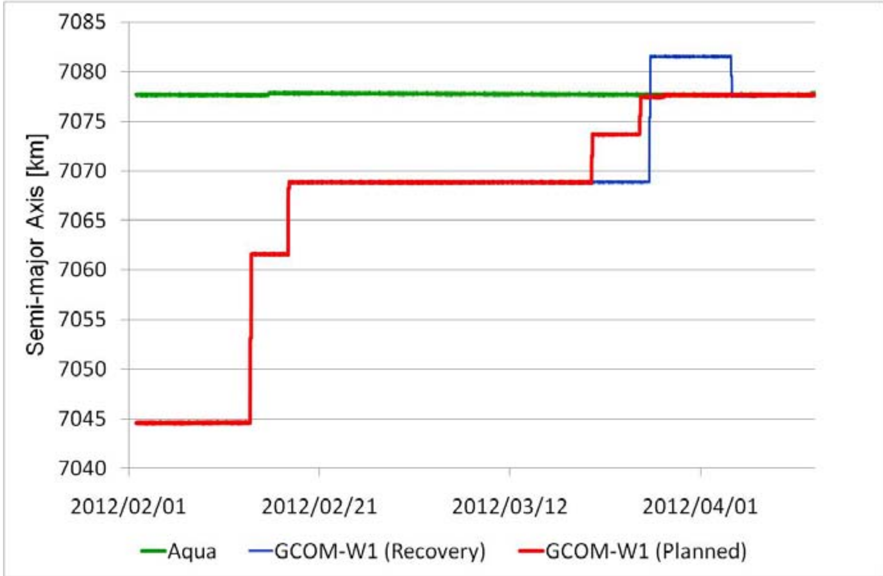


Figure 5.1-16 Change of semi-major axis (Mean element)
(Scenario 2)

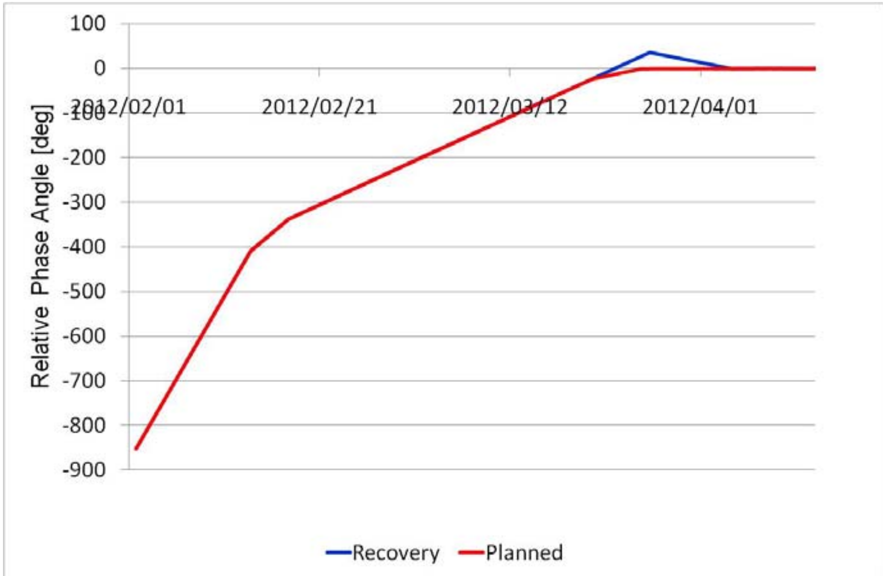


Figure 5.1-17 Change of relative phase angle (Mean element)
(Scenario 2)

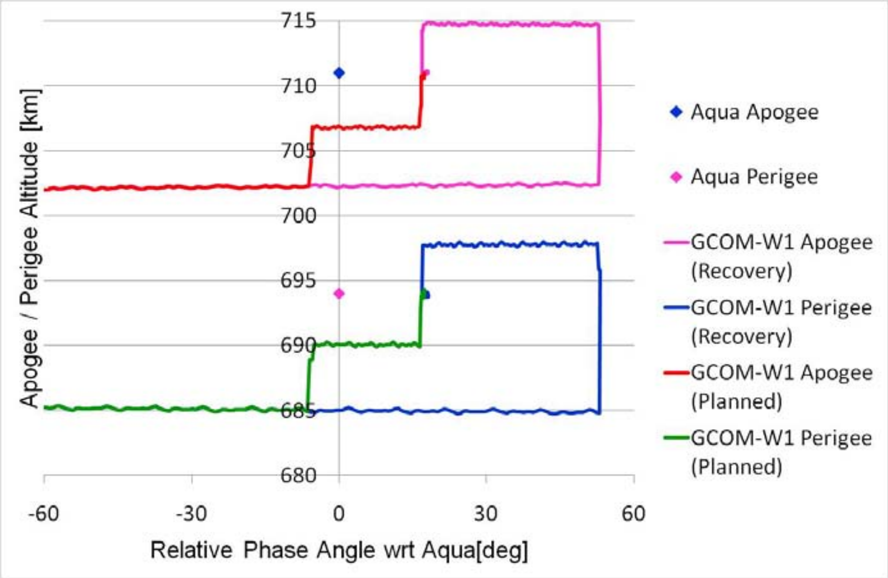


Figure 5.1-18 Relative phase angle vs. apogee/perigee altitude (Scenario 2)

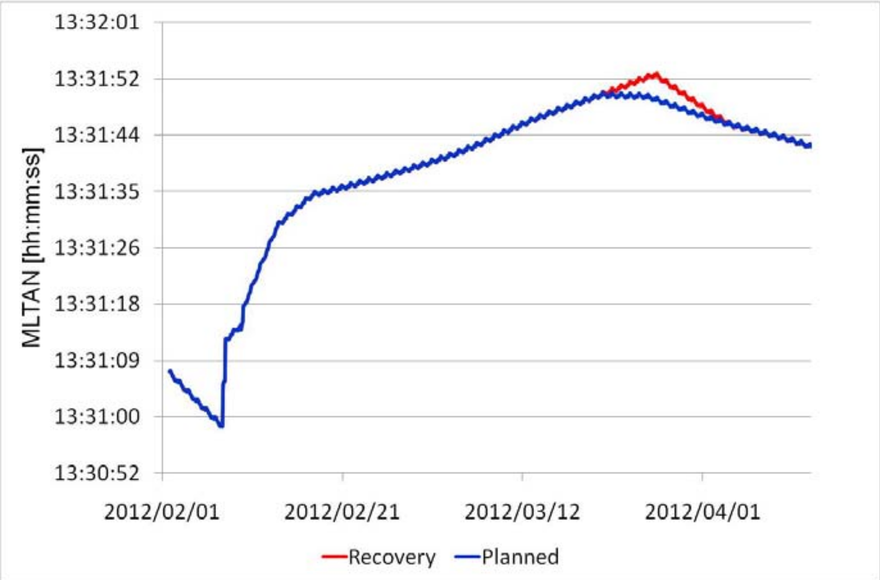


Figure 5.1-19 Change of MLTAN (Mean element) (Scenario 2)

5.2 AMSR2 rotation anomaly

If a rotation anomaly of AMSR2 occurs, the altitude of GCOM-W1 will increase due to the burns of the attitude control thrusters. The rotation speed of AMSR2 will be controlled at less than 11 rpm during the ascent operation. In this condition, the altitude of GCOM-W1 is raised less than 1 km.

The highest altitude of GCOM-W1 when GCOM-W1 flies under the A-Train satellites in Step 3 is 3.5 km below the nominal altitude of the A-Train satellites. If an AMSR2 rotation anomaly occurs during the ascent operation, the altitude of GCOM-W1 will stay more than 2.5 km below the nominal altitude of the A-Train satellites. The altitude of GCOM-W1 in Steps 1 and 2 is less than the altitude in Step 3. Therefore, there is no risk that GCOM-W1 enters the alert ZOE of the A-Train satellites during the ascent operation.

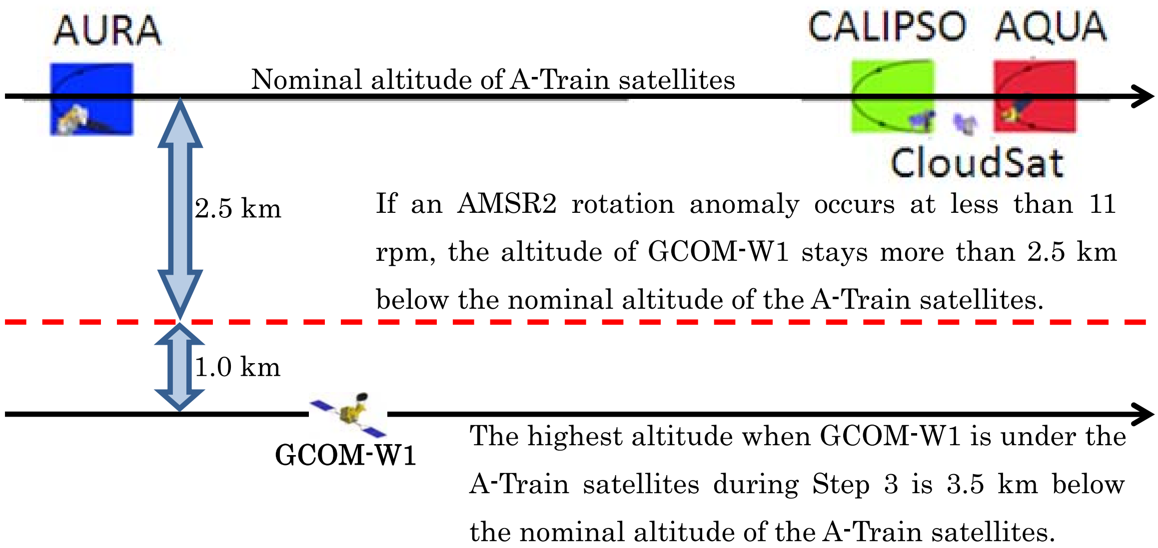


Figure 5.2-1 Altitude of GCOM-W1 in Step 3

5.3 Avoidance of Landsat 5 and PARASOL

(1) Potential close approach to Landsat 5 and PARASOL during ascent operation

Figure 5.3-1 shows the region where a close approach to Landsat 5 and PARASOL is concerned.

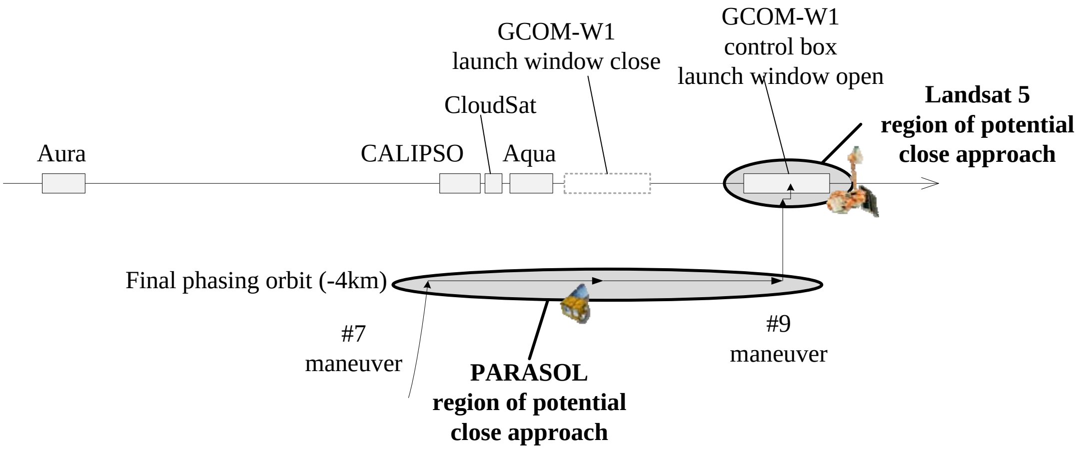


Figure 5.3-1 Region of potential close approach to Landsat 5 and PARASOL

Landsat 5 and the A-Train satellites all follow similar 705-km orbits that intersect near the poles. Since these satellites maintain their ground tracks on the WRS-2 grid, the relative phase angle of the crossing point slowly moves along the line of the A-Train constellation. During the ascent operation of GCOM-W1, the crossing point is supposed to stay in a region near the target position, as shown in Figure 5.3-1.

On the other hand, PARASOL has already left the A-Train constellation and is currently 4 km below the rest of the A-Train satellites. GCOM-W1 raises its altitude from the separation orbit to the A-Train orbit and intersects the altitude of PARASOL during the ascent operation. Furthermore, the “final approach orbit” of GCOM-W1 is designed to be 4 km below the A-Train and its altitude is close to that of PARASOL, as shown in Figure 5.3-1. Then, investigation of a potential close approach to PARASOL is also necessary.

(2) Analysis of Landsat 5 close approach

Figure 5.3-2 shows the characteristics of the relative orbit between Aqua and Landsat 5 during the ascent operation.

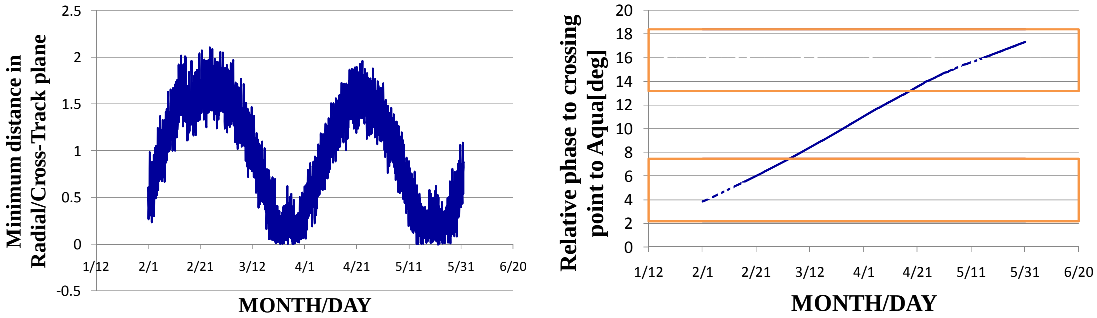


Figure 5.3-2 Relative orbit of Aqua and Landsat 5 during ascent operation
(Left: Minimum distance between two satellites in Radial/Cross-Track plane, Right: Relative phase of crossing point to Aqua)

Landsat 5 maintains a loosely frozen orbit, which causes its apogee and perigee to oscillate above and below the A-Train spacecraft. On the other hand, satellites in the A-Train maintain very strict frozen orbits. These oscillations mean that there are short periods of time where radial separation between the orbits is zero, as shown in the left plot of Figure 5.3-2.

The relative phase angle of the control box of GCOM-W1 with respect to Aqua is located from 13 to 19 deg. when the launch window is open and 2 to 8 deg. when the launch window is closed. Then, from the right plot of Figure 5.3-2, it can be understood that the crossing point with Landsat 5 is supposed to stay in these control boxes during the ascent operation. Figure 5.3-3 shows how the crossing point travels along the trail of the A-Train.

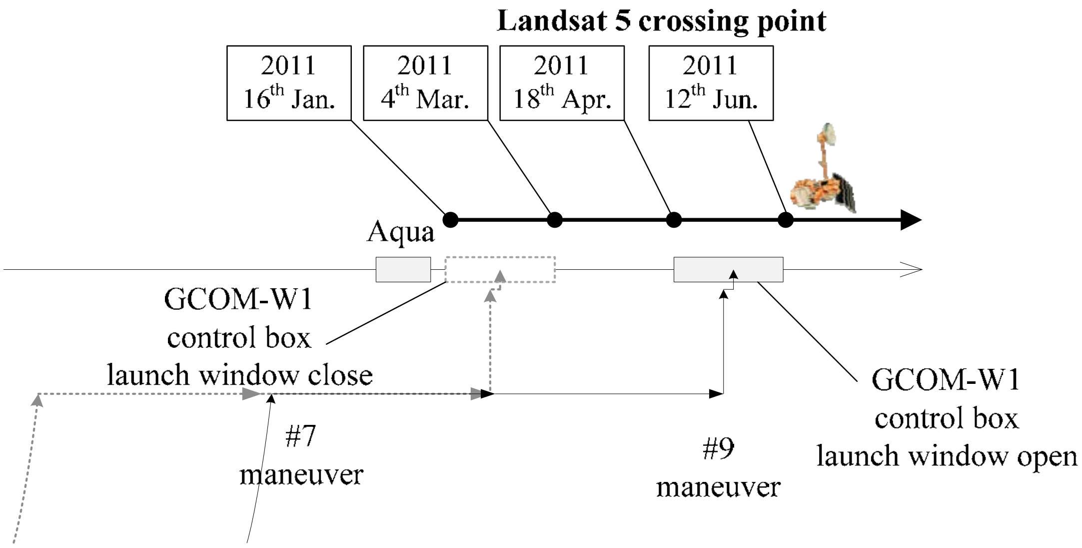


Figure 5.3-3 Landsat 5 crossing point and control box of GCOM-W1

As shown in Figure 5.3-3, the crossing point stays in the control box while the launch window is closed from 16 January to 4 March, and it stays in the control box when the launch window is open from 18 April to 12 June. Therefore, some countermeasures should be considered. In nominal operation, GCOM-W1 can avoid conflict with Landsat 5 by adjusting its location in advance to keep radial separation large enough during the passage of Landsat 5. However, if Landsat 5 stays near the target position of the injection maneuver, then it should be avoided by changing the target position. Figure 5.3-4 shows how to avoid Landsat 5.

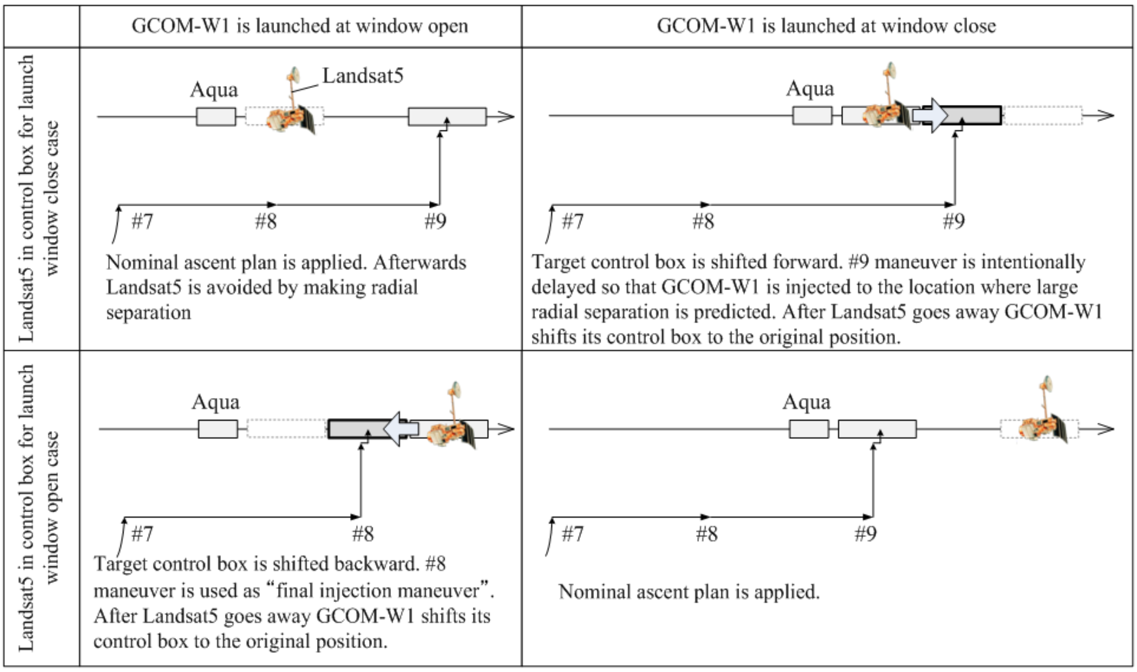


Figure 5.3-4 Avoidance of Landsat 5 crossing point by shifting GCOM-W1’s control box

If GCOM-W1 is launched at the open of the launch window and Landsat 5 is in the control box for the launch window close case at the time of the injection maneuver (left–top of Figure 5.3-4), then it is not necessary to change the target position. The nominal ascent plan can be applied. In a like manner, if GCOM-W1 is launched at the close of the launch window and Landsat 5 is in the control box for the launch window open case (right–bottom of Figure 5.3-4), then the nominal ascent plan can also be applied.

On the contrary, if GCOM-W1 is launched at the open of the launch window and Landsat 5 is in the control box for the launch window open case (left–bottom of Figure 5.3-4), then the target control box is shifted backward, and the #8 maneuver is used as the injection maneuver in place of the #9 maneuver.

Similarly, if GCOM-W1 is launched at the close of the launch window and Landsat 5 is in the control box for the launch window close case (right–top of Figure 5.3-4), then the target control box is shifted forward, and the #9 maneuver is delayed to adjust the relative phase to the shifted target position.

After the crossing point of Landsat 5 passes, GCOM-W1 performs small maneuvers to change the control box from the shifted position to the original position. Then the ground track of GCOM-W1 follows along the WRS-2 grid.

(3) Analysis of PARASOL close approach

Figure 5.3-5 shows the characteristics of a relative orbit between Aqua and PARASOL during the ascent operation.

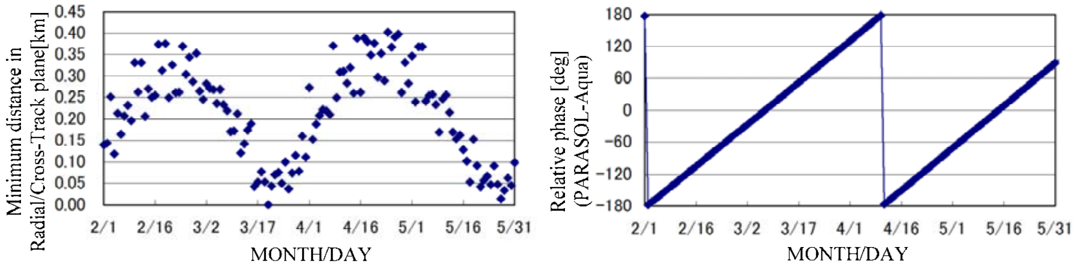


Figure 5.3-5 Relative orbit of Aqua and PARASOL during ascent operation (Left: Minimum distance between two satellites in Radial/Cross-Track plane (orbit of Aqua is shifted to the altitude of PARASOL), Right: Relative phase of PARASOL wrt Aqua)

As shown in the left plot, the relative eccentricity vector of PARASOL and Aqua is so close that the minimum distance in radial/cross-track plane is less than 500 m and remains small. This means that the preferable way to avoid conflicts is by adjusting the altitude. The right plot shows that Aqua passes through the intercept point quickly and the period of concern is short.

The rate of relative phase angle change of PARASOL with respect to Aqua is about 5.2 deg./day, and as such the relative location repeats in a period of about 70 days. Therefore, whether the close approach with PARASOL occurs or not depends upon the launch date. If GCOM-W1 is unfortunately launched on the date when a close approach occurs, then the altitude of the final phasing orbit is slightly shifted to keep the difference of altitude between GCOM-W1 and PARASOL, as shown in Figure 5.3-6.

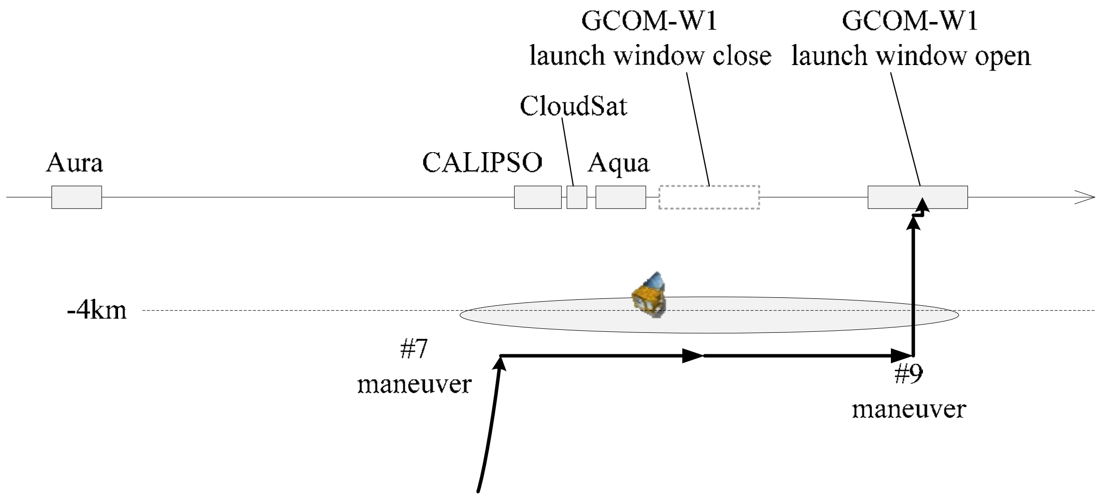


Figure 5.3-6 Avoidance of close approach to PARASOL by adjusting altitude of final phasing orbit

5.4 Cancelation of Aqua's inclination maneuvers in 2012

If Aqua's inclination maneuvers in 2012 are canceled up until 2 months before the launch of GCOM-W1, the launch window based on the ephemeris of the real Aqua is adopted to achieve constellation with Aqua.

If Aqua's inclination maneuvers in 2012 are canceled after L-2 months, the launch window is not changed and GCOM-W1 is launched within the launch window, which targets the Forward Aqua. In this case, GCOM-W1 is not inserted into the position 259.5 seconds to 79.5 seconds in front of Aqua with regard to equator crossing time and MLTAN. The countermeasure against this problem is decided based on the status of Aqua.

(1) If Aqua is able to perform recovery maneuvers afterward.

GCOM-W1 maintains its orbit and waits for the recovery maneuvers of Aqua. GCOM-W1 does not perform special maneuvers.

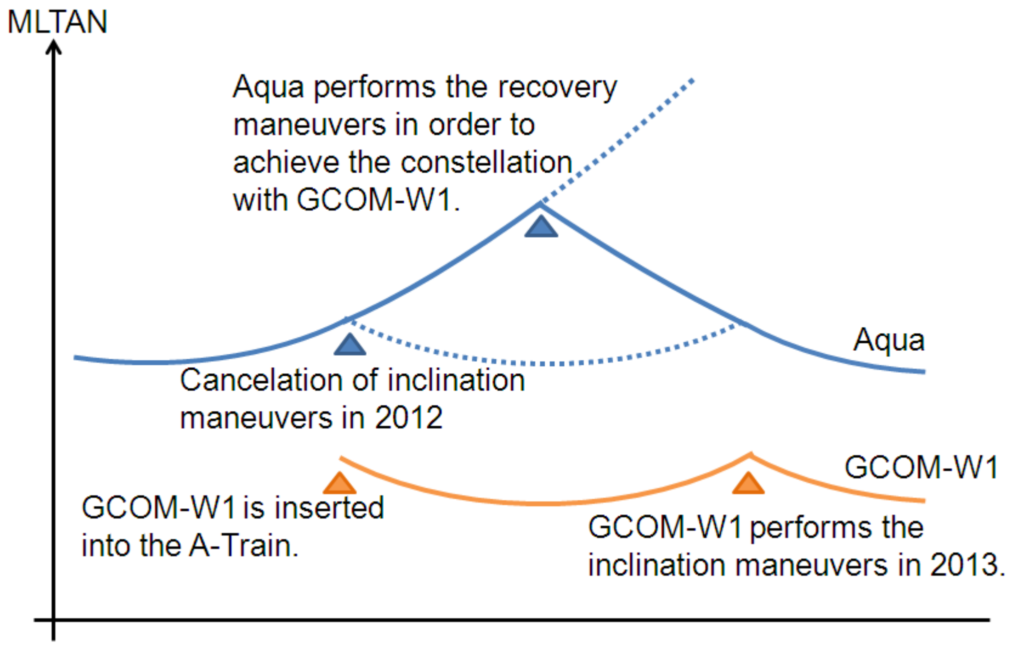


Figure 5.4-1 Cancelation of Aqua's inclination maneuvers in 2012 (If Aqua is able to perform recovery maneuvers afterward)

(2) If Aqua is unable to perform recovery maneuvers.

If the catch-up maneuvers intended to achieve the constellation with Aqua are feasible, GCOM-W1 performs the maneuvers.

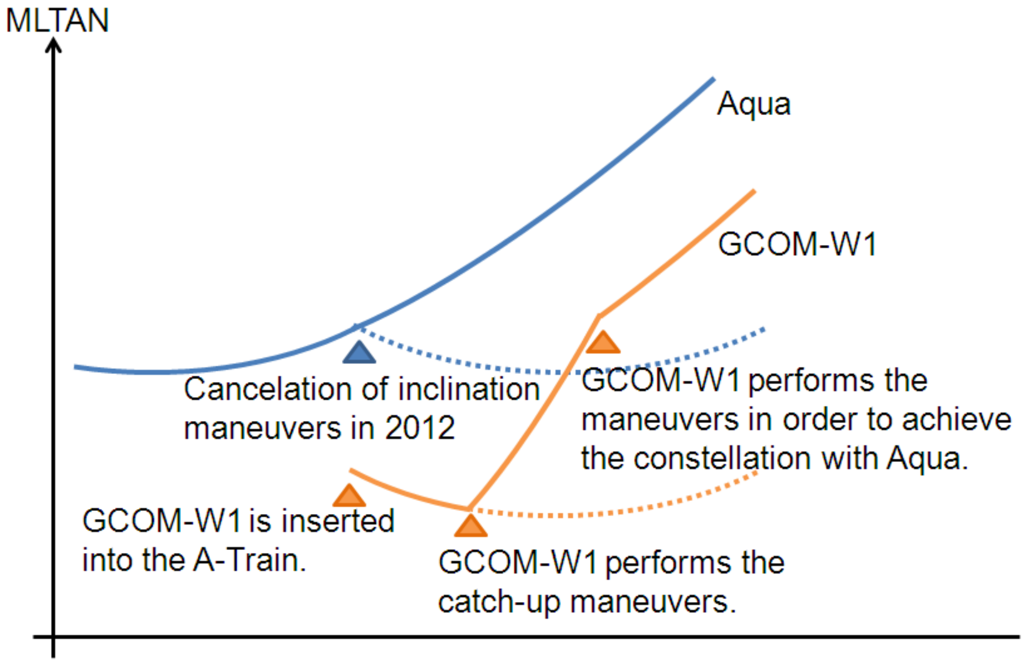


Figure 5.4-2 Cancelation of Aqua's inclination maneuvers in 2012 (If Aqua is unable to perform the recovery maneuvers)

6. GCOM-W1 operations during ascent

After separation from the H-IIA rocket, GCOM-W1 performs attitude rate dumping, solar array paddle deployment, and achieves the Local Vertical Local Horizontal (LVLH) attitude. The main events of GCOM-W1 within 1 day after launch are shown in Table 6-1.

Table 6-1 Main events of GCOM-W1 within 1 day after launch

Elapsed time from launch	Event
0 min.	H-IIA rocket lifts off
23 min.	GCOM-W1 separates from the rocket
From 24 min. to 31 min.	Attitude rate is dumped
From 31 min. to 36 min.	Solar array paddles are deployed
From 36 min. to 66 min.	Attitude acquisition mode (attitude control by thrusters)
66 min.	Rotation of solar array paddles starts
6.5 hours	Normal attitude control mode starts (attitude control by RWAs)
11 hours	Main reflector of AMSR2 is deployed
12.5 hours	Launch lock of AMSR2 sensor unit is released
21 hours	Rotation of AMSR2 starts (0 rpm -> 4 rpm)

The test maneuvers for ascent are performed at L+2 days (acceleration) and L+4 days (out-of-plane), and the ascent maneuver starts from 6 days after launch. GCOM-W1 is inserted into the Afternoon Constellation within 60 days after launch. During the ascent operation, the rotation speed of AMSR2 is maintained at less than 11 rpm. The main in-orbit check items of GCOM-W1 from L+1 day to 2 months after launch are shown in Table 6-2.

Table 6-2 Main events of GCOM-W1 from L+1 day to 2 months after launch

Ascent status	Event
Step 1	Acceleration test maneuver
	Checkout of the redundant thrusters for attitude control
	Inclination test maneuver
	From #1 ascent maneuver to #6 ascent maneuver
Step 2	AMSR2 run-up from 4 rpm to 11 rpm
	Checkout of X-band communication
	Checkout of the normal AOCS mode
Step 3	From #7 ascent maneuver to #10 ascent maneuver
A-Train orbit	AMSR2 run-up to 40 rpm and observation performance check

7. Orbit maintenance after entering A-Train

(1) In-plane orbit maintenance

GCOM-W1 is phased with Aqua such that GCOM-W1 flies over Aqua's ground track on the WRS-2 grid. GCOM-W1 is operated within a pre-defined ground-track control box of ±20 km measured at the descending node (corresponding to ±43 seconds in equator crossing time) around the reference point. The trailing edge of its control box varies with its launch time within a 3-minute launch window. It is at least 15 seconds ahead of the Aqua control box. To keep an operation margin, the target of the station keeping is ±8 km.

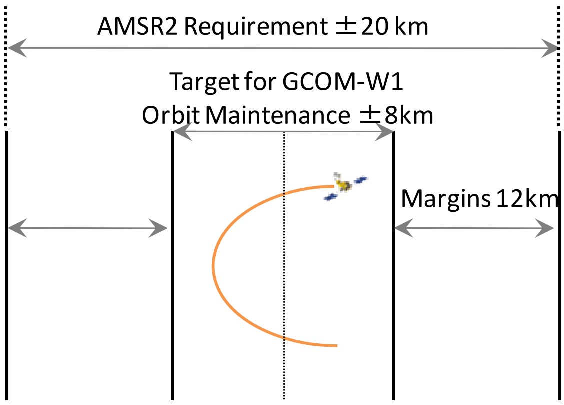


Figure 7-1 Target for GCOM-W1 orbit maintenance

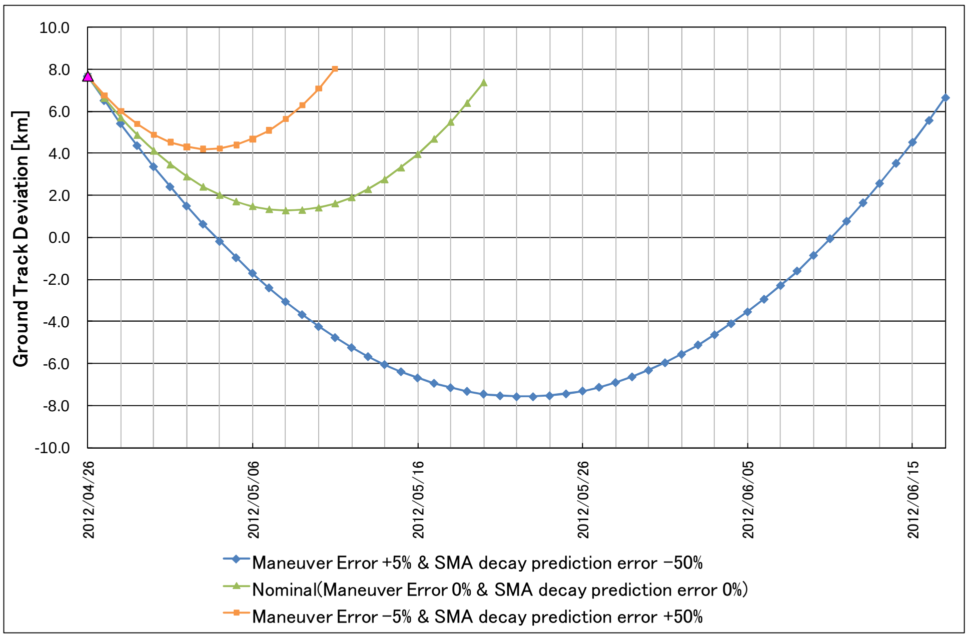
Drag make-up (DMU) maneuvers are planned with two factors in mind: the decay of the SMA of GCOM-W1 owing to atmospheric drag and maneuver errors. The basic concept of in-plane orbit maintenance for GCOM-W1 is shown below.

(a) A DMU maneuver is performed in a certain week when GCOM-W1 is expected to pass though the eastern edge (+8 km) before the next window for a DMU maneuver (Wednesday of the next week) in a worst-case situation. The worst case means that the future decay in SMA of GCOM-W1 is 50% larger than expected.

(b) A DMU maneuver is planned in order to keep GCOM-W1 within ±8 km, assuming the worst scenario, which means -50% prediction errors in the decay of SMA and +5% maneuver error. In other words, the amount of ΔV is determined so that the western edge of the circulation orbit after the DMU maneuver reaches -8 km inside its control box in the worst scenario.

(c) A DMU maneuver is planned roughly 10 days before and precisely 2 days before the execution (on Monday).

(d) The future decay in SMA of GCOM-W1 is predicted using the actual decay in SMA for the past 30 days, not using any predictions on solar activity. This prediction of the decay in SMA is used only for the planning of DMU maneuvers, not for creating a predictive ephemeris (modeling maneuvers). The atmospheric density model based on the solar activity prediction is used to create a predictive ephemeris (orbit propagation).



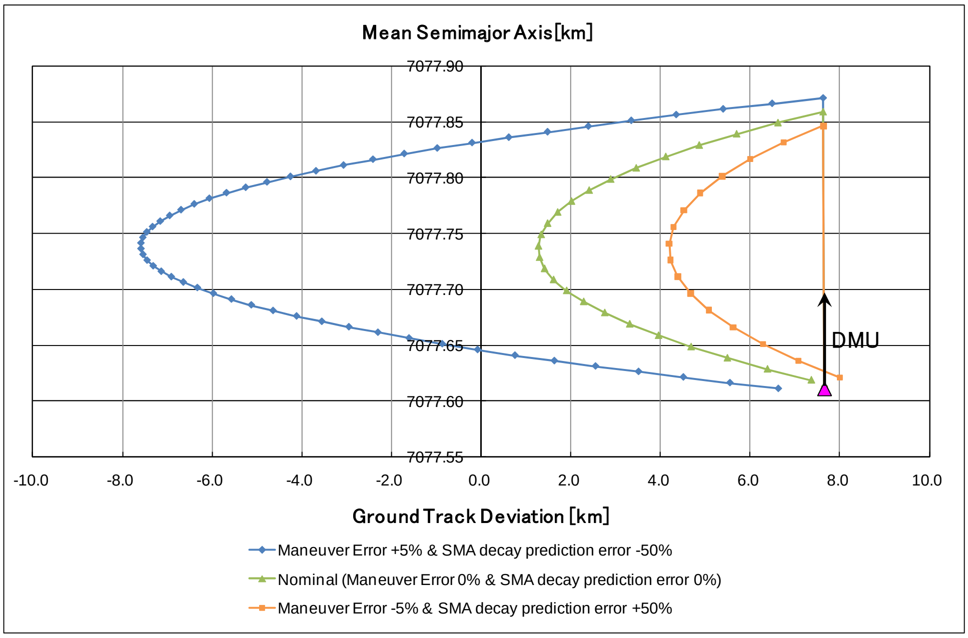


Figure 7-2 Analysis result of orbit maintenance

(2) Inclination maneuver concept

GCOM-W1 maintains a mean local time of ascending node (MLTAN) between 79.5 and 259.5 seconds earlier than Aqua's, depending on when GCOM-W1 launches within its 3-minute launch window. To keep a fixed offset from the MLTAN of Aqua, inclination maneuvers should be performed in coordination with Aqua's around the same time (annually). The basic concept of inclination adjustment maneuvers for GCOM-W1 is shown below.

(a) The MLTAN of GCOM-W1 is planned so that the future MLTAN trend of GCOM-W1 becomes parallel to that of Aqua. The amount of ΔV is determined to target an inclination similar to Aqua's.

(b) The inclination maneuver plan for GCOM-W1 is updated after each actual inclination maneuver of Aqua based on the definitive results from ESMO.

(c) Inclination maneuvers are performed in coordination with A-Train members.

(d) If the difference between the MLTAN of GCOM-W1 and that of Aqua is going to exceed the limit, correction burns are performed.

(e) After performing inclination maneuvers, the delta SMA induced during the maneuvers are evaluated. The results of the evaluations are used for the planning of the next inclination maneuvers. The delta SMA induced by the out-of-plane maneuvers in Step 1 are also evaluated and used for the planning of the inclination maneuvers in the following spring.

8. Conclusion and way forward

JAXA studied the ascent plan with consideration given to satellite design, constraints on maneuvers, rocket injection errors, and anomalies, and achieved the following conclusions:

- GCOM-W1 does not enter the ZOE of other A-Train satellites during ascent operation even in contingency cases
- GCOM-W1 is inserted into the A-Train within 60 days after launch
- The position of GCOM-W1 in the A-Train meets the requirements of the AMSR2 science team and A-Train members
- The estimated total amount of fuel consumption is smaller than the requirement
- Even when a maneuver is missed in Step 1 or Step 3, GCOM-W1 is inserted into the A-Train within 90 days after launch
- GCOM-W1 is able to avoid a close approach to Landsat 5 and PARASOL during the ascent operation
- GCOM-W1 is able to maintain its position within the control box and its MLTAN of between 79.5 and 259.5 seconds earlier than Aqua's MLTAN

The study of the ascent plan was carried out under the condition that GCOM-W1 is launched between 1 February 2012 and 31 March 2012. Therefore, the ascent plan that is used for the actual ascent operation is updated using the latest conditions.

Appendix A Definition of terms

Term	Definition
Acceleration maneuver	A maneuver performed in the flight direction to increase its semi-major axis
Altitude	Geocentric distance subtracted by equatorial radius of the Earth (6378.137 km)
Deceleration maneuver	A maneuver performed in reverse of the flight direction to decrease its semi-major axis
Eccentricity vector	A vector directing toward the perigee with a magnitude equal to the eccentricity
Final approach altitude	An altitude in Step 3 that is 4 km lower than the altitude of the Afternoon Constellation
Maneuver	An execution of velocity increment using the satellite propulsion system to control orbit. The maneuver consists of a single burn or multiple burns.
Maneuver plan	A series of burns including their amounts and execution times during the ascent operation
Maneuver sequence	A series of maneuvers with the execution days elapsed after launch and types (out-of-plane, orbit-raising) during the ascent operation
Phase adjustment altitude	An altitude in Step 2 that is lower than the altitude of the Afternoon Constellation to eliminate the relative phase angle from GCOM-W1 to the target position
Phase shift	Intentional offset of the phase angle to the target position on the Afternoon Constellation to avoid a close approach of GCOM-W1 to Aqua during the ascent phase
Relative phase angle	Any difference of phase angle between two satellites. The virtual position may be a substitute for the satellite. It is measured by the difference in their argument of latitude along the orbit of the satellite.
Total phase angle	A variation of the relative phase angle between the target position of GCOM-W1 on the Afternoon Constellation and the position injected by the launch vehicle