THE INSERTION OF GCOM-W1 INTO THE A-TRAIN CONSTELLATION

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Abstract: *The Afternoon Constellation, or "A-Train" is an Earth observation satellite constellation organized by NASA. The A-Train consists of multiple satellites which fly so that they follow the same ground track and observe the same locations on Earth at shift intervals. The GCOM-W1 is a JAXA Earth observation satellite. It joins the A-Train constellation for data continuity and enhancement of its scientific value by collaborative simultaneous measurements with various kinds of instruments on distinct satellites. A methodology for maneuver planning of the GCOM-W1 insertion into the A-Train constellation is studied for an efficient ascent operation. The key point of the methodology is the ability to determine dates of orbital maneuver operations before its launch date, regardless of launch injection errors. This means that maneuver operations can be scheduled before the launch and need not be changed, even in the event of a 3-sigma launch injection error. The GCOM-W1 was launched on May 17, 2012 and its ascent into the A-Train constellation was successfully completed on June 28, 2012. In this paper, the methodology of the GCOM-W1 maneuver planning is presented, the results of the actual ascent are shown, and lessons learned from the experiences are discussed.*

Keywords: *GCOM-W1, A-Train, constellation, maneuver planning, formation flying.*

1. Introduction

The Afternoon Constellation, or "A-Train" is an Earth observation satellite constellation organized by NASA, which consists of multiple satellites flying in close proximity in a 705 km sun-synchronous orbit with a 16-days repeat cycle, and 1:30 p.m. Mean Local Time of Ascending Node (MLTAN). The orbits of the satellites in the A-Train are controlled so that the satellites follow the same Worldwide Reference System-2 (WRS-2) ground track and observe the same locations on Earth virtually simultaneously. Currently, the A-Train consists of four satellites: Aqua (NASA), CloudSat (NASA), CALIPSO (NASA/CNES), Aura (NASA). PARASOL (CNES) was in the A-Train but moved to a lower orbit on December 2, 2009. OCO2 (NASA) will join the constellation in the near future.

JAXA runs what is known as the Global Change Observation Mission (GCOM) to observe the global environment, global water cycle mechanisms, and long-term climate change via multiple Earth observation satellites. The GCOM-W1 is the first satellite in the program. Its main science instrument is an Advanced Microwave Scanning Radiometer 2 (AMSR2), which is the successor to the AMSR-E installed on the Aqua. The GCOM-W1 joins the A-Train for data continuity from the AMSR-E on the Aqua and enhancement of its scientific value by collaborative simultaneous measurements with various kinds of instruments on distinct satellites in the constellation. Fig. 1 shows the GCOM-W1 and its propulsion system. It has a fully redundant propulsion system consisting of twelve thrusters with 4N thrust. Since thrust vectors for orbital maneuvers point in the anti-velocity direction (–X) of the GCOM-W1, an attitude maneuver around its yaw axis is needed before out-of-plane and deceleration maneuvers.

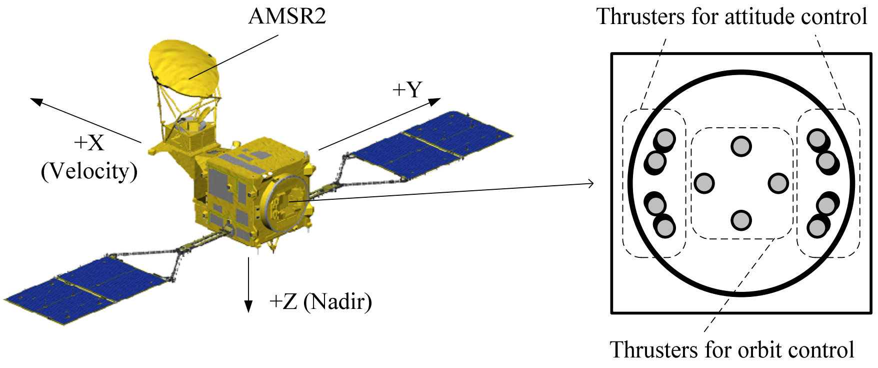
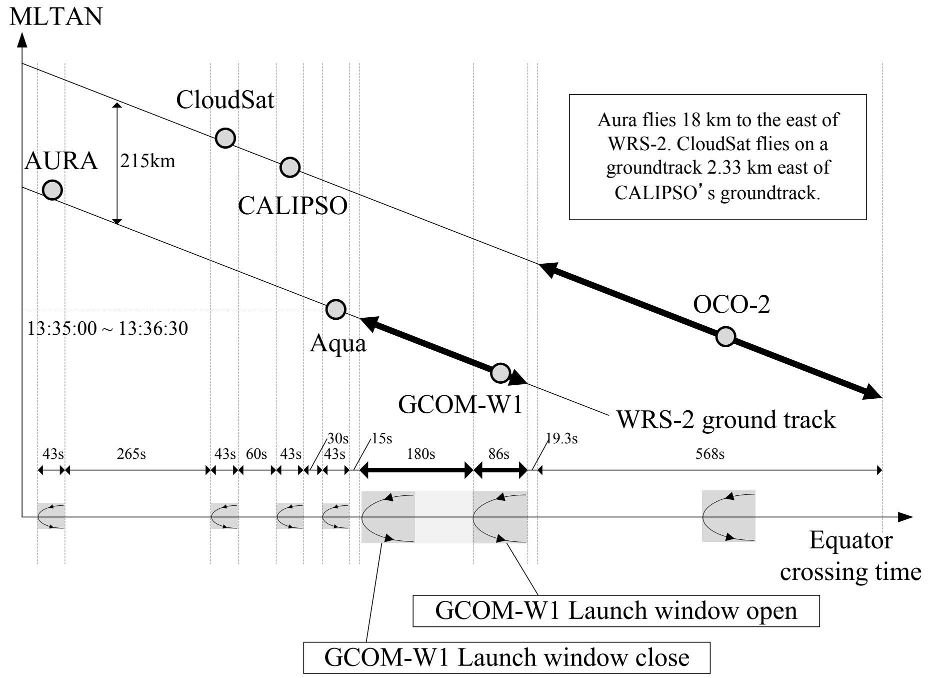


Figure 1. GCOM-W1 and its propulsion system

Fig. 2 shows the location of the GCOM-W1 control box in the A-Train. Each satellite in the A-Train is allowed to drift within its respective control box (seen in the figure as boxes with a hyperbolic line) until it approaches the boundary of its box. The satellite must them execute drag make-up maneuvers to maintain its equator crossing time within the control box.



Aura flies 18 km to the east of WRS-2. CloudSat flies on a groundtrack 2.33 km east of CALIPSO's groundtrack.

Figure 2. Location of GCOM-W1 control box in A-Train

The location of the GCOM-W1 control box is between 79.5 and 259.5 seconds ahead of the Aqua, depending on when GCOM-W1 launches within its 3-minute (180-second) launch window. The width of the control box is 86 seconds. The ground track of the GCOM-W1 follows that of Aqua and the WRS-2. This location of the control box is the goal position of the ascent of GCOM-W1 into the A-Train.

The AURA was launched on July 15, 2004 and inserted into the A-Train on August 9 [1]. The time schedule of the ascent maneuver plan was dependent on launch injection errors. If the 3-sigma error appears and results in a lower injection altitude, the plan would include an additional two ascent maneuvers and take an additional 6 days. Actually the launch injection error became so small that the ascent operation was performed following the nominal schedule.

The PARASOL is a microsatellite which was launched on December 18, 2004 [2]. Due to the limitation of a small fuel budget, its ascent maneuver plan strove to optimize fuel consumption. One method included the intentional offset of relative inclination to induce MLTAN drift. Another was control of multiple orbital parameters (such as semi-major axis and inclination) via a single maneuver. Despite the plan taking a long time (more than half a year) to arrive at the MLTAN target, it could help optimize fuel consumption.

The CALIPSO and CloudSat were launched on a dual launch configuration on April 28, 2006 [3][4][5] and completed a coordinated ascent on June 3. The ascent maneuver was designed with safety in mind to prevent the close approach between the two spacecrafts even in contingencies. The time schedule of the ascent maneuver plan was dependent on launch injection errors.

The main topic of this paper is the methodology of GCOM-W1 maneuver planning to insert it into the goal position in the A-Train. The methodology is studied so that the ascent can be performed efficiently in terms of planning tasks, schedules, and human resources. The key point of the methodology is the ability to determine dates of orbital maneuver operations before the launch date, regardless of launch injection errors. This means that maneuver operations can be scheduled before the launch and need not be changed, even in the event of a 3-sigma launch injection error. The GCOM-W1 was launched on May 17, 2012 and its ascent into the A-Train was successfully completed on June 28, 2012. In this paper, the methodology of the GCOM-W1 maneuver planning is presented, and the results of the actual ascent are shown and discussed.

2. Constraints and Conditions

The ascent operation should be planned considering various kinds of constraints and a priori conditions. In this section these constraints and conditions are summarized to understand the problem of the GCOM-W1 insertion into the A-Train. .

2.1. Duration of ascent

The GCOM-W1 should be inserted into the target control box within 60 days.

2.2. Delta-V Budget

The maximum total delta-V of the entire ascent should be less than 50 m/s.

2.3. Fleet Envelope

The fleet envelope is defined as the region between the perigee and apogee limits of the A-Train, namely 694 and 711 km respectively. The apogee of the rocket injection orbit should be a minimum of 2 km from the perigee limit, even taking 3-sigma launch injection errors into consideration. The launch injection altitude must be selected considering this restriction.

2.4. Zone Of Exclusion (ZOE)

The concept of a Zone of Exclusion (ZOE) is defined to guarantee an acceptable separation distance between two satellites. The ZOE is a rectangular volume in space, centered on each of the satellites in the A-Train. No satellite in the A-Train is allowed to enter the ZOE of other member satellites. The size of the ZOE is ±2km in radial, ±25 km in along-track, and ±25 km in cross-track respectively. The GCOM-W1 should not enter the ZOEs of other A-Train satellites.

2.5. Target Orbit of the Secondary Payload

The GCOM-W1 was not the sole payload of its launch vehicle, but was shared with the other secondary payload. The target rocket injection orbit of the GCOM-W1 should be determined considering not only the requirements of the GCOM –W1 but also that of the secondary payload.

2.6. Maneuver Duration and Interval

There are constraints in terms of the maneuver duration and interval, which are listed in Tab. 1.

Table 1. Constraints on maneuver duration and interval

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

2.7. Rocket Injection Orbit

The rocket injection orbit was determined as Tab. 2 considering the constraints of the fleet envelope and the requirement of the secondary payload described above. The semi-major axis is designed to be 29km below the A-Train and is selected so that the propagated orbit of the GCOM-W1 after separation from the launch vehicle does not violate the fleet envelope constraint even if 3-sigma launch injection orbit errors appear. The inclination is selected considering the predicted inclination trend of the Aqua and the requirement of the secondary payload. Due to the latter constraint, the selected inclination is slightly shifted from that of the Aqua. Therefore execution of inclination maneuvers is mandatory even if the launch is performed without any injection errors.

2.8. Initial Relative Phase Angle

The launch time is around 13:30 local time to inject the GCOM-W1 into its target orbital plane. The repeat cycle of the A-Train is 16 days, 233 revolutions. meaning the Aqua rotates around the Earth at 233/16 = 14 9/16 times in 24 hours. Therefore, the argument of latitude of the Aqua at the launch time changes 9/16 revolutions day by day, and returns to the original position in 16 days. Consequently, as shown in Fig. 4, the initial relative phase angle of the Aqua with respect to the GCOM-W1 has 16 patterns and changes depending on the launch date.

Table 2. Rocket injection orbit of the GCOM-W1 at the first ascending node

	Osculating, True Of Date	Mean, True Of Date
Semi-major axis a[km]	7058.484	7049.301
Eccentricity e	0.001150	0.001050
Inclination i[deg]	98.158	98.164
Right ascension of ascending node Ω[deg]	Depending on launch date	
Argument of perigee ω[deg]	66.013	89.641
Mean anomaly M[deg]	294.138	270.510

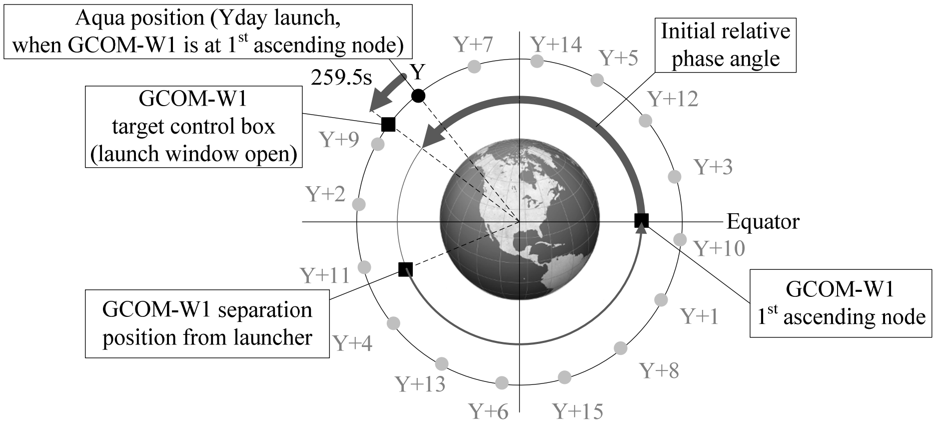


Figure 4. Discrete patterns of the initial relative phase angle of Aqua with respect to GCOM-W1

3. Methodology of Maneuver Planning

This section describes the methodology of ascent maneuver planning for the GCOM-W1 insertion into the A-Train. First, the policies we adopted for the methodology design are described, followed by an introduction to the basic structure of the GCOM-W1 ascent. Third, adjustment of MLTAN of the GCOM-W1 to the target value is presented, before finally showing the core idea of the methodology to adjust the relative phase angle.

3.1. Policies to design methodology

The following policies are considered important for the methodology to plan the GCOM-W1 ascent to the A-Train:

(a) Dates of orbital maneuvers should be determined before the launch date regardless of launch injection errors.
(b) All specified constraints related to collision risk mitigation should be strictly respected.
(c) The ascent should be completed by the specified deadline, and its duration should be minimized as much as possible.
(d) Fuel consumption should be less than specified amount and minimized as much as possible.

(e) Deceleration maneuvers should be avoided as much as possible.

In general, after an Earth observation satellite is launched, ground operators must perform not only operations related to orbital maneuvers, but also other necessary tasks, such as health checks of the satellite bus system (attitude, communication, thermal, power, and so on), initial functional checks of payload instruments, and so on. It is necessary to define all of these tasks, prepare procedures and documents, allocate tasks on the predicted visible paths of ground stations, and manage the working time of the personnel in charge of these tasks in advance. All these preparations should be done before the launch operation. If the dates of orbital maneuvers are not determined before the launch operation, and are subject to change depending on the results of launch injection errors, then it is not possible to assign tasks and personnel deterministically. This means additional workload in preparing for multiple cases and various resulting launch injection errors. Furthermore, the prepared tasks and schedules are subject to change depending on the results of the launch injection errors. Consequently, variable maneuver dates depending on the results of launch injection errors can result in inefficient ground operations in terms of their preparation and execution. For this reason, we deem it important to ensure the dates of orbital maneuvers can be determined before the launch date, regardless of launch injection errors. This feature is expected to contribute to the efficient preparation and execution of the GCOM-W1 ground operations.

Satisfaction of constraints related to collision risk mitigation, such as the fleet envelope and ZOE constraints, is the top priority when designing the ascent trajectory and its error analysis. The duration of the GCOM-W1 ascent should follow the constraint described above. In addition, a shorter ascent is preferable since it facilitates swifter mission operations and more economical ground operations. Similarly, the predicted fuel consumption should follow the above constraint, and preferably be minimized, since the onboard fuel of the GCOM-W1 is the key factor to extending the GCOM-W1 mission life. Deceleration maneuvers should be avoided since they require an attitude maneuver around the yaw axis by 180 degrees, which potentially induces undesired velocity increments and may cause an unexpected close approach to other A-Train satellites.

3.2. Structure of the Ascent Operation

The GCOM-W1 ascent plan was designed with the above policies taken into account consists of three parts, Steps 1, 2, and 3, as shown in Fig. 5.

The objectives of Step 1 are checkout of the spacecraft functions necessary to perform maneuvers and compensation of rocket injection errors. Step 1 includes test maneuvers, out-of-plane maneuvers to adjust an orbital plane, and in-plane maneuvers to raise the GCOM-W1 to phase adjustment altitude. By selecting the proper phase adjustment altitude, any change in relative phase angle caused by rocket injection errors at 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 the GCOM-W1 to the A-Train. Step 3 includes in-plane maneuvers to raise the GCOM-W1 to final approach altitude, a final injection maneuver, and a trim maneuver. The GCOM-W1 performs an in-plane maneuver to raise its orbit from the phase adjustment altitude to the final approach altitude, which is 4 km below the A-Train. The GCOM-W1 slowly approaches the target position. During Step 3, the relative eccentricity vector to the A-Train orbit is minimized by conducting pairs of in-plane maneuvers. The GCOM-W1 is injected to the target position by the final injection maneuver and small errors are adjusted by the subsequent trim maneuver.

The order and interval of maneuver events in Step 1 and 3 are fixed and independent from the launch date and the launch injection errors, which contributes to efficient preparation of maneuver operation procedures. Only the duration of Step2 changes depending on the launch date. Therefore the launch injection errors does not have an influence on the dates of maneuvers in all steps. This feature contributes to the efficient preparation and execution of the entire GCOM-W1 operational works.

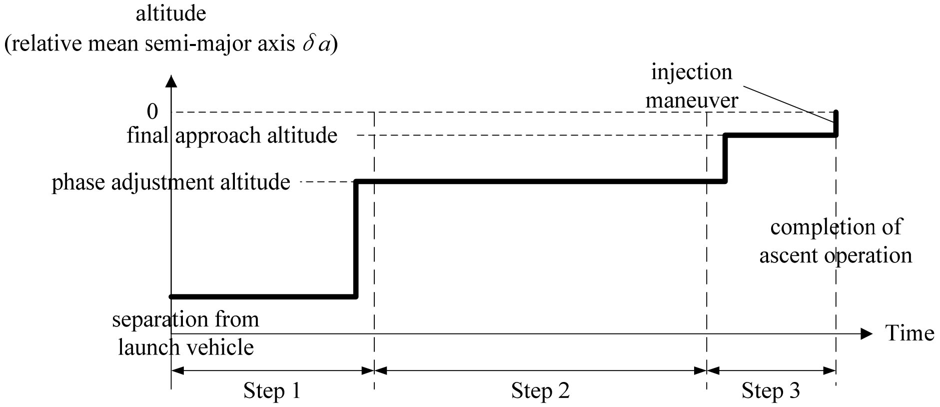


Figure 5. Structure of the GCOM-W1 ascent

3.3. MLTAN Adjustment

The GCOM-W1 should be inserted into an orbital plane of the specified MLTAN as shown in Fig. 2. The rocket injection orbit is not sun-synchronous since its altitude is lower than the A-Train orbit. Therefore if the orbital plane of the rocket injection orbit is identical to that of the target orbit, the resulting MLTAN after the ascent differs from the target value. To compensate for this difference without consuming fuel, the launch time is intentionally shifted. The variation in relative MLTAN of the GCOM-W1 with respect to the Aqua (denoted as $\Delta\delta MLTAN$) is expressed as follows by adopting a linear approximation:

$$\dot{\Omega} = -\frac{3}{2} n \left(\frac{a_e}{a}\right)^2 J_2 \cos i \tag{1}$$

$$\delta\dot{\Omega} \approx \frac{\partial \dot{\Omega}}{\partial a} \delta a + \frac{\partial \dot{\Omega}}{\partial i} \delta i \tag{2}$$

$$\begin{aligned} \mathit{\Delta}\delta MLTAN &= \mathit{\Delta}\delta\mathit{\Omega} \\ &= \int \delta\dot{\mathit{\Omega}}\, dt + \mathit{\Delta}\delta\mathit{\Omega}_R \\ &= \frac{\partial\dot{\mathit{\Omega}}}{\partial a}\int \delta a\, dt + \frac{\partial\dot{\mathit{\Omega}}}{\partial i}\int \delta i\, dt + \mathit{\Delta}\delta\mathit{\Omega}_R \\ &\equiv \mathit{\Delta}\delta\mathit{\Omega}_a + \mathit{\Delta}\delta\mathit{\Omega}_i + \mathit{\Delta}\delta\mathit{\Omega}_R \end{aligned} \tag{3}$$

where δ denotes the relative value of GCOM-W1 with respect to that of the target, $\mathit{\Delta}$ denotes its variation, and $\mathit{\Delta}\delta\mathit{\Omega}_R$ denotes the rocket injection error in $\mathit{\Omega}$. Variation in $\delta\mathit{\Omega}$ induced by the difference in inclination: $\mathit{\Delta}\delta\mathit{\Omega}_i$ is divided into two parts as follows:

$$\mathit{\Delta}\delta\mathit{\Omega}_i = \mathit{\Delta}\delta\mathit{\Omega}_{inom} + \mathit{\Delta}\delta\mathit{\Omega}_{iR} \tag{4}$$

where $\mathit{\Delta}\delta\mathit{\Omega}_{inom}$ is variation in $\delta\mathit{\Omega}$ induced by difference between the nominal inclination of rocket injection and the target inclination, and $\mathit{\Delta}\delta\mathit{\Omega}_{iR}$ is variation in $\delta\mathit{\Omega}$ induced by perturbation due to the rocket injection error in inclination. Key is the fact that $\mathit{\Delta}\delta\mathit{\Omega}_{inom}$ can be known before the launch, but $\mathit{\Delta}\delta\mathit{\Omega}_{iR}$ cannot be known since it depends on the rocket injection errors.

Similarly, change in the relative phase angle can be expressed as follows by adopting a linear approximation:

$$\dot{\phi} = n = \sqrt{\mu/a^3} \tag{5}$$

$$\delta\dot{\phi} \approx \frac{\partial\dot{\phi}}{\partial a}\delta a \tag{6}$$

$$\begin{aligned} \mathit{\Delta}\delta\phi &= \int \delta\dot{\phi}\, dt + \mathit{\Delta}\delta\phi_R = \frac{\partial\dot{\phi}}{\partial a}\int \delta a\, dt + \mathit{\Delta}\delta\phi_R \\ &\equiv \mathit{\Delta}\delta\phi_a + \mathit{\Delta}\delta\phi_R \end{aligned} \tag{7}$$

where ϕ denotes the GCOM-W1 argument of latitude , n denotes the mean motion, and $\mathit{\Delta}\delta\phi_R$ denotes the rocket injection error in ϕ. Thus variation in $\delta\mathit{\Omega}$ induced by the difference in the semi-major axis: $\mathit{\Delta}\delta\mathit{\Omega}_a$ is proportional to the variation in the relative phase angle during ascent:

$$\frac{\mathit{\Delta}\delta\mathit{\Omega}_a}{\mathit{\Delta}\delta\phi_a} = -\frac{7}{2}\left(\frac{a_e}{a}\right)^2 J_2 \cos i = \frac{7}{3}\frac{\dot{\mathit{\Omega}}}{n} = constant. \tag{8}$$

Therefore $\mathit{\Delta}\delta\mathit{\Omega}_a$ can be computed from $\mathit{\Delta}\delta\phi_a$, which can be known before the launch from the predicted initial relative phase angle between the GCOM-W1 and the Aqua on the launch date.

Consequently, $\Delta\delta\Omega_a$ and $\Delta\delta\Omega_{inom}$ in $\Delta\delta MLTAN$ can be known before the launch, whereupon the launch time shift can be computed as the sum of both. Conversely, unknown $\Delta\delta\Omega_R$ and $\Delta\delta\Omega_{iR}$ should be corrected by out-of-plane maneuvers of the spacecraft.

3.4. Phase Adjustment

As described in Fig. 4, the initial relative phase angle of the Aqua with respect to the GCOM-W1 has 16 patterns and changes depending on the launch date. The GCOM-W1 should absorb this date-dependent initial relative phase angle and rocket injection errors to reach the target location in A-Train. The change in the relative phase angle can be divided as follows:

$$\begin{aligned}\Delta\delta\phi &= \Delta\delta\phi_a + \Delta\delta\phi_R \\ &= \Delta\delta\phi_{anom} + \Delta\delta\phi_{aR} + \Delta\delta\phi_R \\ &= \Delta\delta\phi_{a0} + \Delta\delta\phi_{ats} + \Delta\delta\phi_{aR} + \Delta\delta\phi_R\end{aligned} \tag{9}$$

Variation in the angle measured from the nominal injection position of GCOM-W1 by the launch vehicle to the target position: $\Delta\delta\phi_{anom}$ is divided into two parts.

One is the nominal initial phase angle without considering the launch time shift: $\Delta\delta\phi_{a0}$, which depends on the relative position of Aqua on the launch date. It has 16 patterns. It roughly changes from 0 to 360 deg depending on the launch date.

The other is relative phase angle change in the Aqua due to launch time shift: $\Delta\delta\phi_{ats}$. As described in the last section, launch time is shifted to compensate for the variation in relative MLTAN during the ascent. When the launch time is shifted, the initial relative phase angle of the Aqua with respect to the GCOM-W1 is also changed. This effect may be significant when this is a rendezvous problem to International Space Station (ISS), since the nodal regression rate of the ISS orbit far exceeds that of a sun-synchronous orbit. Furthermore, since the sign of the nodal regression rate of the ISS is positive, the launch time should be delayed, whereupon the relative phase angle of the ISS with respect to the rendezvous spacecraft increases. This means the spacecraft needs additional phase adjustment capability. Conversely, in a sun-synchronous orbit case, a sign of the nodal regression rate is negative, meaning the launch time is shifted earlier. This means additional phase adjustment capability is not needed. Consequently, the impact of $\Delta\delta\phi_{ats}$ on the required phase adjustment capability is small in the GCOM-W1 case. Besides, its value can be known before the launch since it is proportional to the launch time shift.

The variation in relative phase angle caused by a rocket injection error in altitude: $\Delta\delta\phi_{aR}$ is dependent on launch injection errors and cannot be known before the launch. After separation from the H-IIA rocket, GCOM-W1 must perform several checkouts of the satellite functions, and only small maneuvers are performed prior to the first maneuver for ascent. Therefore, when the injection altitude of GCOM-W1 differs from the nominal figure, an error of relative phase angle with respect to the nominal value is induced and accumulated during Step 1.

Consequently, $\Delta\delta\phi_{a0}$ and $\Delta\delta\phi_{ats}$ can be known before the launch, whereas $\Delta\delta\phi_{aR}$ and $\Delta\delta\phi_R$ are dependent on launch injection errors and cannot be known before the launch. In the case of

GCOM-W1, the sum of $\Delta\delta\phi_{a0}$ and $\Delta\delta\phi_{ats}$ is about 360 deg, and that of $\Delta\delta\phi_{aR}$ and $\Delta\delta\phi_R$ is about 140 deg.

There are two methods to absorb these variations of relative phase angle, one of which is to adjust altitude of Step 2. By this method, dates of maneuvers can be known in advance, and the period to complete the ascent is always constant, but duration for the ascent is not minimized. The other is to adjust duration of Step 2. By this method, the period to complete the ascent can be minimized, but dates of maneuvers depend on value of relative phase angle to be absorbed. Fig. 6 shows a simplified explanation of these two methods.

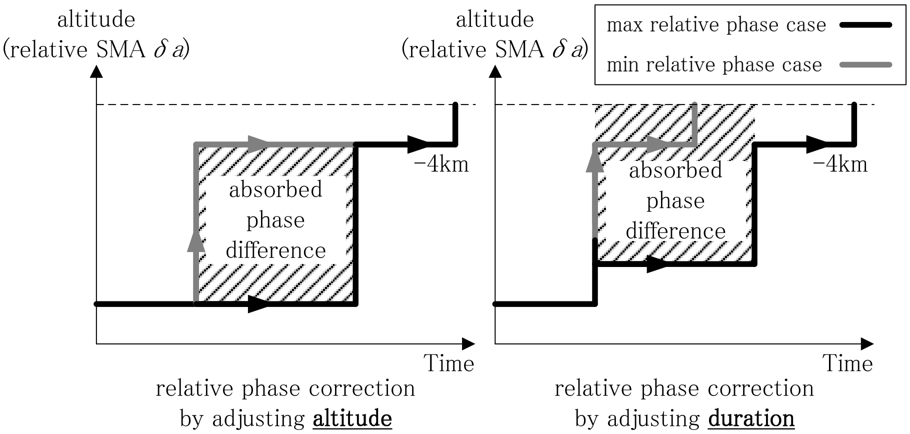


Figure 6. Simplified explanation of the methods to absorb variation in relative phase angle

If $\Delta\delta\phi_{aR}$ and $\Delta\delta\phi_R$ are absorbed by adjusting the duration of Step 2, the dates of the orbital maneuvers cannot be determined before the launch, since they depend on the results of the launch. Accordingly, to follow the policies, they should be absorbed by changing the phase adjustment altitude of Step 2. Conversely, $\Delta\delta\phi_{a0}$ and $\Delta\delta\phi_{ats}$ should be absorbed by changing the duration of Step 2 since they are known before the launch and taking this approach can achieve a shorter ascent. The maneuver sequences in Steps 1 and 3 are fixed, regardless of the launch date and rocket injection errors. Only Step 2 changes depending on the launch date. Once a launch date is determined, the sum of $\Delta\delta\phi_{a0}$ and $\Delta\delta\phi_{ats}$ is also determined. Then we can also determine the necessary Step 2 period, whereupon the entire period for the ascent can be computed. The rocket injection error of the semi-major axis and the phase angle (±3σ of $\Delta\delta\phi_{aR}$ and $\Delta\delta\phi_R$) can be corrected by changing the phase adjustment altitude during Step 2.

4. Maneuver Plan

In this section the GCOM-W1 ascent maneuver plan is shown. The various constraints described in Section 2 and the methodology developed in Section 3 are also considered in the design of the plan. Fig. 7 shows a schematic of the overall ascent plan, while Tab. 3 shows a list of maneuvers.

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

After the GCOM-W1 separates from the H-IIA rocket, initial checkout operations and test maneuvers are performed to check the functionality and performance of the RCS system and also calibrate the thrust using the relationship between the burn duration and the generated ΔV.

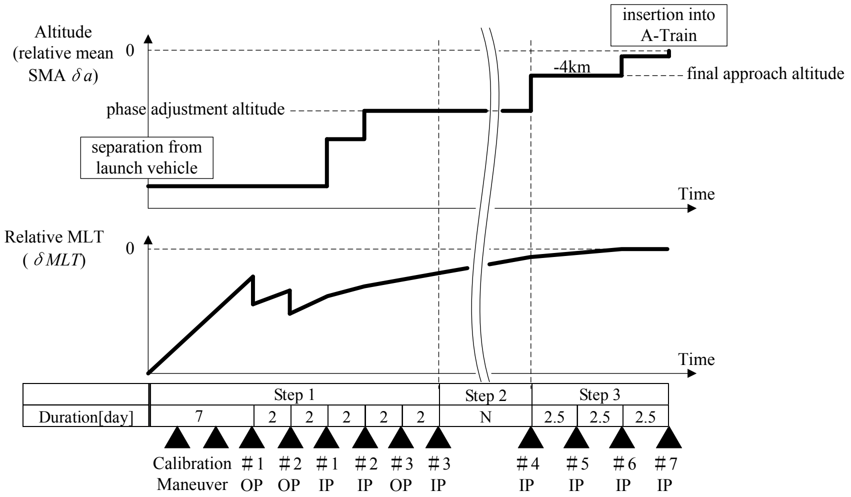


Figure 7. Schematic of the GCOM-W1 ascent plan to A-Train
(OP: Out-of-plane maneuver, IP: In-plane maneuver)

Table 3. List of maneuvers

	Maneuver	Days elapsed since launch	Note
STEP1	Test maneuver	Y+3	Fixed procedure regardless of launch date. Only the amount of delta-V changes
	Test maneuver	Y+5	
	#1 Out-of-plane maneuver	Y+7	
	#2 Out-of-plane maneuver	Y+9	
	#1 In-plane maneuver	Y+11	
	#2 In-plane maneuver	Y+13	
	#3 Out-of-plane maneuver	Y+15	
	#3 In-plane maneuver	Y+17	
STEP2	Phasing	N days	N days (depending on launch date)
STEP3	#4 In-plane maneuver	Y+17+N	Insertion into final approach altitude (4km below A-Train)
	#5 In-plane maneuver	Y+19+N	Error correction
	#6 In-plane maneuver	Y+22+N	Insertion into altitude of 200m below A-Train
	#7 In-plane maneuver	Y+24+N	Trimming maneuver

Subsequently, during Step 1, six maneuvers are allocated in the nominal time schedule. An interval between maneuver events is 48 hours (2 days). When the rocket injection errors are so small that a maneuver is unnecessary, the event is simply skipped. On 7th, 9th and 15th days, out-of-plane maneuvers are performed, which correct the inclination to the target value, and adjust the RAAN so that the MLTAN reaches the target value at the time of injection of GCOM-W1 to the A-Train. On 11th, 13th and 17th days, in-plane maneuvers to raise the orbit are performed, which adjust the altitude so that any relative phase angle errors induced by the rocket injection errors at altitude is absorbed in Step 2.

During Step 2, no maneuver is planned. The duration of Step 2 depends on the launch date. The altitude of Step 2 is properly set so that relative phase angle errors induced by rocket injection errors at altitude is absorbed during this step. The descent rate of altitude caused by atmospheric drag is considered to dictate the initial altitude of Step 2.

During Step 3, four time slots for in-plane maneuvers are allocated in the time schedule and the interval between maneuvers is to be 60 hours (2.5 days). In Step 3, maneuvers should be executed carefully since relative semi-major axis and relative eccentricity vector must be adjusted properly to prevent GCOM-W1 from invading the A-Train ZOE. Therefore maneuvers are performed as a pair of burns to maintain the relative eccentricity vector. By the #4 in-plane maneuver, GCOM-W1 reaches the final approach orbit. The altitude 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 #4 in-plane maneuver should not be so large that it causes invasion of the ZOE due to overburn. Therefore the size of the maneuver is designed to be less than 5 m/s by taking 5% burn errors into account. Conversely, the change in altitude caused by the maneuver should not be too small, because a certain amount of altitude change is necessary to adjust the relative eccentricity vector by a pair of acceleration maneuvers. The altitude change in the maneuver is then designed to exceed 5.32 km. These upper and lower maneuver constraints help avoid invasion of the ZOE. The #5 in-plane maneuver is the spare slot for fine tuning of altitude or eccentricity vector.

A #6 in-plane maneuver is the injection maneuver. The GCOM-W1 goes up to the target position. Fig. 8 shows the graphical explanation of the #6 injection maneuver and the #7 trim maneuver. If the velocity of the #6 injection maneuver exceeds the planned level, then the subsequent #7 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 may induce unexpected velocity increments. Therefore, to improve the accuracy of the final insertion of GCOM-W1, the target altitude of the #6 injection maneuver is designed to be lower than that of the A-Train so that the altitude achieved does not exceed the latter. By taking a 5% error into account, the target altitude is designed to be 200 m below the A-Train orbit. The #7 maneuver is a trim maneuver. The remaining altitude difference is corrected by this maneuver. GCOM-W1 is expected to be inserted within ±9 seconds from the target position by this acceleration maneuver.

Tab.4 shows a summary of the computed 16 ascent plans for each launch date. The total time and launch time shift are proportional to the initial relative phase angle $\delta\phi_{a0}$. Total delta-V in the nominal case (meaning zero rocket injection errors) is 20.4 m/s, 49.9 m/s in the worst case (meaning 3-sigma rocket injection errors). It does not change according to launch date. The total time of the ascent is dependent on the launch date and independent of launch injection errors.

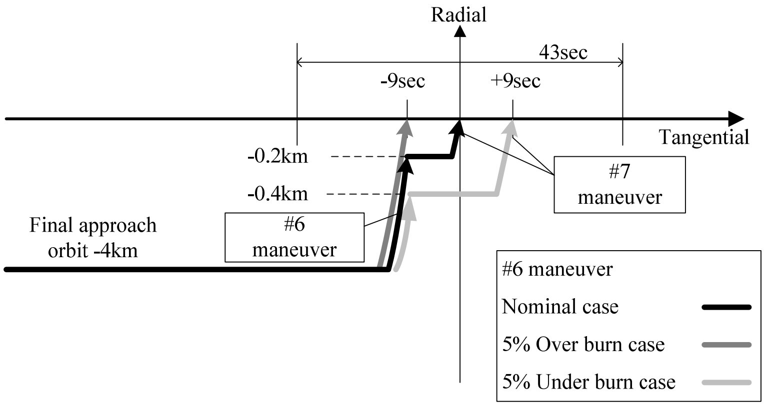


Figure 8. Insertion into target location from final approach altitude

Table 4. Summary of 16 ascent plans for each launch date

Launch date [day]	Initial relative phase $\delta\phi_{a0}$ [deg]	Total time [day]	Launch time shift [sec]	ΔV Nominal case [m/s]	ΔV Worst case [m/s]
Y	0	44	61	20.4	49.9
Y+1	202.5	30	39		
Y+2	45	41	56		
Y+3	247.5	51	73		
Y+4	90	38	51		
Y+5	292.5	48	68		
Y+6	135	35	47		
Y+7	337.5	45	63		
Y+8	180	32	42		
Y+9	22.5	42	58		
Y+10	225	53	75		
Y+11	67.5	39	54		
Y+12	270	50	70		
Y+13	112.5	36	49		
Y+14	315	47	66		
Y+15	157.5	33	44		

5. Flight Results

The GCOM-W1 was successfully launched on May 17, 2012 by an H-IIA rocket from the Tanegashima Space Center, with launch injection error far smaller than the 3-sigma worst case. The launch time was at the beginning of its 3-minute launch window. Consequently the target location of the GCOM-W1 in the A-Train is decided to be 259.5 seconds ahead of the Aqua. Following attitude acquisition and initial spacecraft functional checkouts, the ascent maneuver was initiated. Tab. 5 shows a summary of the GCOM-W1 ascent maneuvers.

Table 5. GCOM-W1 Ascent maneuver summary

	Maneuver	Date	Nominal plan (Planned before launch)	Results (Re-planned after launch considering injection errors)	
			Delta-V[m/s]	Delta-V[m/s] plan / result	Accuracy[%]
STEP1	Test maneuver	May 20	0.210	0.210 / 0.190	9.7
	Test maneuver	May 22	-0.430	-0.430 / -0.452	-5.1
	#1 Out-of-plane maneuver	May 24	-4.180	-1.504 / -1.353	10.1
	#2 Out-of-plane maneuver	May 26	Skip	Skip	-
	#1 In-plane maneuver (a pair maneuver)	May 28	2.116 3.073	2.788 / 2.357 3.823 / 3.232	15.5
	#2 In-plane maneuver	May 30	Skip	Skip	-
	#3 Out-of-plane maneuver	June 1	0.281	-0.811 / -0.835	-2.9
	#3 In-plane maneuver (a pair maneuver)	June 3	2.332 2.300	2.225 / 2.216 2.400 / 2.390	0.4
STEP2	Test maneuver (deceleration maneuver)	June 8	-	-0.026 / -0.043	-66.5
STEP3	#4 In-plane maneuver (a pair maneuver)	June 24	1.700 1.700	1.606 / 1.604 1.776 / 1.774	0.1
	#5 In-plane maneuver	June 26	Skip	Skip	-
	#6 In-plane maneuver (a pair maneuver)	June 28	1.005 1.005	0.945 / 0.942 0.924 / 0.921	0.3
	#7 In-plane maneuver	July 1	0.110	Skip	-
Total Delta-V			20.442	19.442	18.266

Considering the result of the launch injection errors, the ascent maneuver plan was recomputed to adjust its trajectory to the target position. Thanks to the methodology described above, the date of each maneuver was not changed by launch injection errors. The injection error was so small that the #2 out-of-plane and #2 in-plane maneuvers were skipped following the pre-planned nominal case.

During Step 1, maneuver calibration was performed. Telemetry data of thruster impulses were collected to investigate the relationship between the commanded burn duration and resulting delta-V. An off-modulation duty-cycle of orbit control thrusters due to offset of spacecraft center of mass was analyzed and corrected so that maneuver accuracy was improved. Consequently, 0.4% accuracy of the #3 in-plane maneuver was achieved, which far exceeded the assumed 5% worst case maneuver error. It was decided to cancel the #7 trim maneuver because it was confirmed that the injection maneuver could be so accurate that the GCOM-W1 could stay inside of the control box without a drag make-up maneuver for a month, even correction by the trim maneuver was not performed.

Fig. 7 shows the history of orbital elements during the ascent maneuver. As seen in Fig. 7a, the dates of the maneuver were identical to those of the plan computed before the launch, even in the event of launch injection errors. The mean eccentricity vector of the GCOM-W1 was inserted into the frozen value which is close to that of the Aqua as seen in Fig. 7b. The initial inclination of the GCOM-W1 after its launch was closer than the planned nominal value to that of the Aqua, meaning the amount of out-of-plane maneuver declined as shown in Fig. 7c. The target nominal mean inclination was intentionally shifted to larger value than that of the Aqua to avoid invasion of secured MLTAN area for the OCO-2, even in the event of 5% maneuver error. As shown in Fig. 7d, the GCOM-W1 arrived at the target MLTAN (Aqua – 259.5 s) as planned. Also, as shown in Figs. 7e and 7f, the relative mean argument of latitude of the GCOM-W1 with respect to that of the Aqua was successfully adjusted into the inside of the control box. The target location of the GCOM-W1 in the control box was slightly shifted from center, and the target semi-major axis was set to a slightly lower altitude than the Aqua to keep the GCOM-W1 inside the control box without a drag make-up maneuver for a month. Consequently, the GCOM-W1 arrived at a position close to the Aqua rather than the center of the control box, and its slightly lower altitude induced along-track drift of the GCOM-W1, which caused a gradual increase in distance between the two spacecrafts.

Fig. 8 shows the location of the GCOM-W1 with respect to the Aqua just after the ascent maneuver operation. The GCOM-W1 arrived at the planned MLTAN and the target control box. The equator crossing time with respect to the Aqua was slightly shifted toward Aqua to keep the GCOM-W1 inside the control box without a drag make-up maneuver for long time. The GCOM-W1 will maintain its position within the control box by performing regular drag make-up maneuvers in a nominal operation. The insertion of the GCOM-W1 into the A-Train was successfully completed.

6. Conclusions

The methodology of maneuver planning for the GCOM-W1 insertion into the A-Train is presented, and the results of the actual ascent are shown and discussed. The key point of the methodology is the ability to determine dates of orbital maneuver operations before its launch date, regardless of launch injection errors. This means that maneuver operations can be scheduled before the launch and need not be changed, even in the event of a 3-sigma launch injection error. The GCOM-W1 was launched on May 17, 2012 and its ascent into the A-Train constellation was successfully completed on June 28, 2012. Thanks to the methodology developed for the GCOM-W1 insertion into the A-Train, the dates of maneuver were identical to that of the plan computed before the launch even launch injection error appears. This feature of the methodology could contribute to efficient ground operations in terms of their preparation and execution.

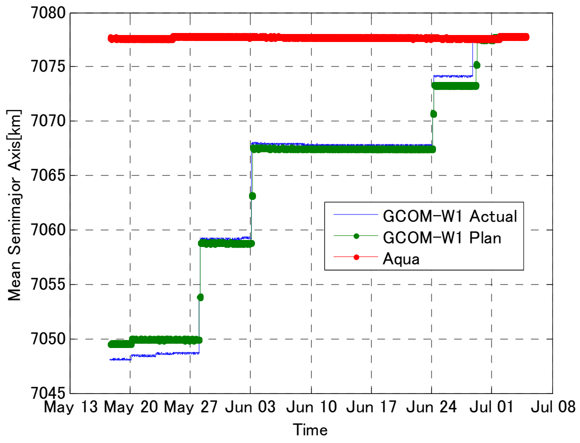


Figure 7a. Mean semi-major axis history

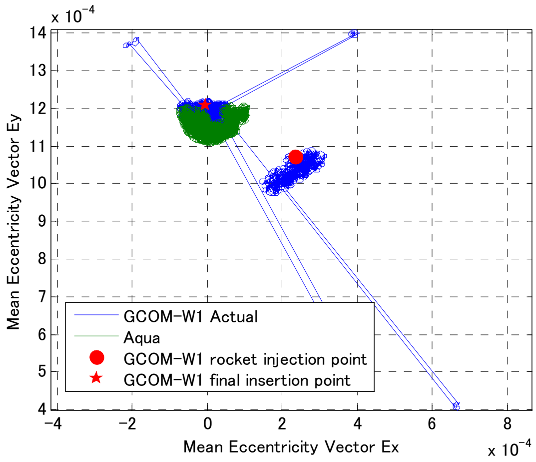


Figure 7b. Mean eccentricity vector

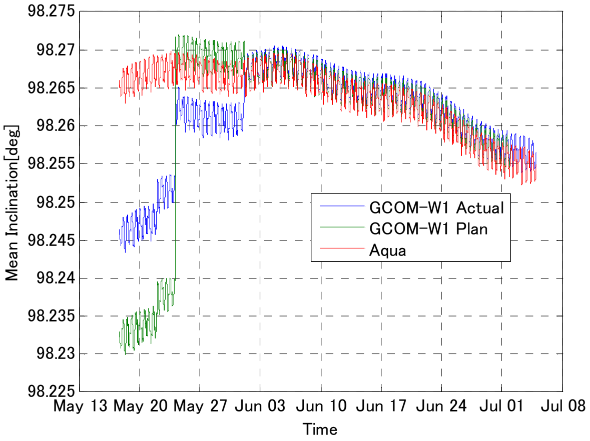


Figure 7c. Mean inclination history

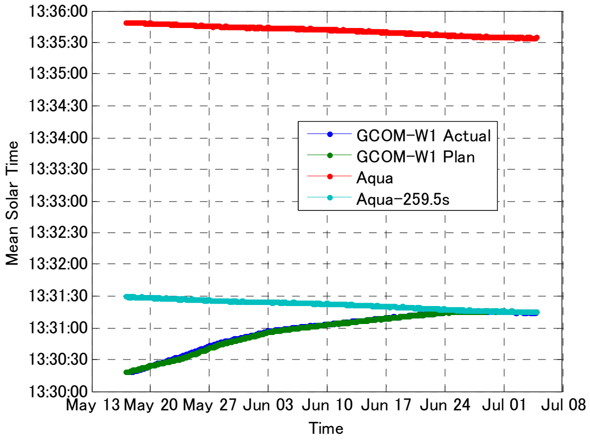


Figure 7d. MLTAN history

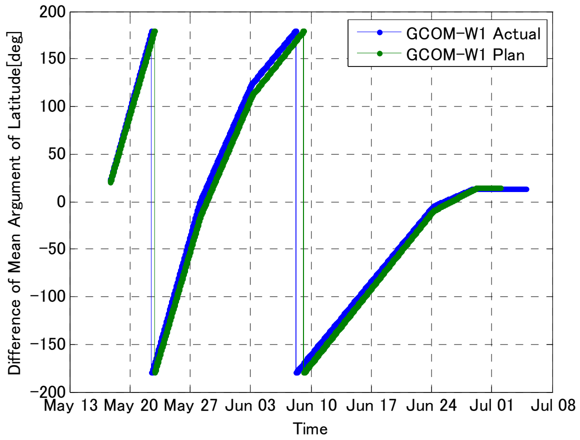


Figure 7e. Relative mean argument of latitude w.r.t. Aqua history

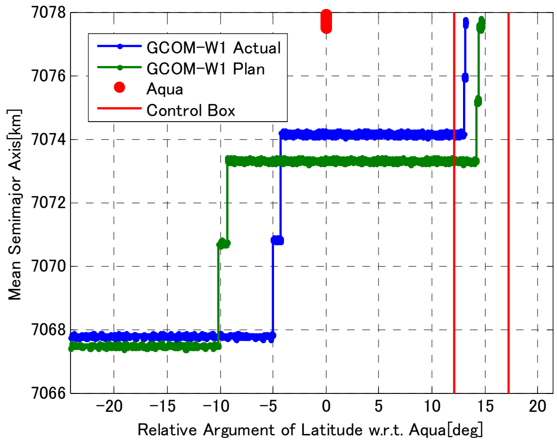


Figure 7f. Relative mean argument of latitude and mean semi-major axis when GCOM-W1 is inserted into the control box

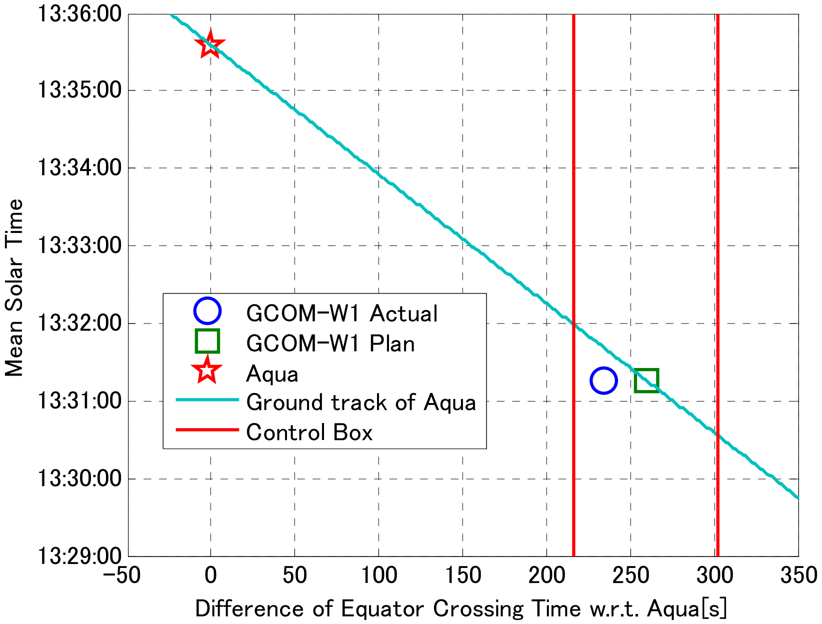


Figure 8. Location of GCOM-W1 w.r.t. Aqua just after ascent maneuver operation

7. References

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