

Fuel Minimization for Constellation Phasing Maintenance of Multi Classes of Low-Cost Satellites

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This paper studies the constellation phasing maintenance for satellites of different designs and launched separately from different launchers. Because of the difference of designs, the satellites have different ballistic drag characteristics. Due to the different launches, the satellites will not be likely on the same orbit plane. These factors cause the orbit phasing control to be demanding. With consideration of cost reduction and hardware availability, satellites may use the low efficient gas nitrogen propulsion subsystem. The capacity of fuel is limited for the satellite mass constraint, thus, leading to the minimization of fuel consumption to be critical. This paper presents the orbit control algorithms, named as Wait-and-Hit, for minimizing fuel use in the constellation rephrasing and phasing maintenance. The Argo satellite system is presented to demonstrate this concept. The study shows the significant reduction of the fuel consumption can be achieved. Furthermore, the orbit phasing operations can be much simplified without the needs of high accurate orbit determination and control. The algorithms, with the merits, can be applied to the general cases of low-cost satellite constellation.

I. Introduction

THE National Space Organization (NSPO) of Taiwan initiated a space program to develop and strengthen its satellite system and subsystems design and development capabilities as well as to establish a state-of-the-art heritage bus platform with open, modular and expandable architecture for future high performance remote-sensing missions. *Argo* marks the first mission to be developed in this program environment. The Argo is named after the Greek legend. In Greek mythology, Argo was the ship on which Jason

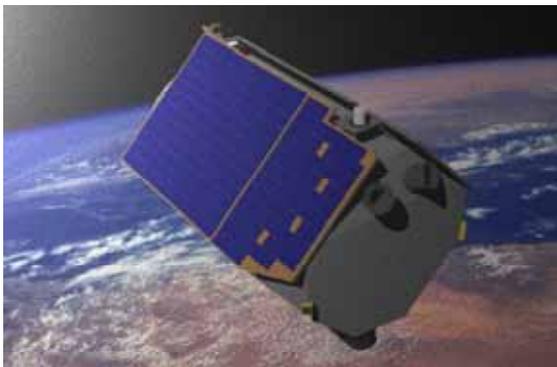


Figure 1. Simulation of Argo Satellite in-flight

and the Argonauts sailed from Iolcus to retrieve the Golden Fleece.

The ARGO spacecraft is intended to join the RapidEye mission¹ as an additional member of the constellation for international collaboration and commercial rewards. The original RapidEye constellation has five satellites. The available resources on the Argo spacecraft will be used to conduct leading-edge scientific researches with the additional payload packages.

The main payload of the ARGO spacecraft is a RapidEye multi-spectral imager (MSI)² operating in 5 bands and a 6.5 m ground resolution and 77.25 km swath width. The spacecraft will operate over 7 years life time on a sun-synchronous orbit at about 620 km altitude. The equatorial descending time is between 10:30 am to 11:30 am local time.

The design of the spacecraft will be driven by the aim to optimize the operational efficiency of the data acquisition and delivery to ground.

With considering to reduce cost and the hardware availability, satellites often use the low efficient gas nitrogen propulsion subsystem. The capacity of fuel is limited because of the satellite mass constraint, thus, leading to the minimization of fuel consumption to be

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critical. The present works would like to achieve the following objectives:

- 1) Defining parking orbit of launch vehicle insertion and initial constellation phasing operation
- 2) Orbit re-phasing analysis for joining the RapidEye constellation with minimizing fuel consumption

II. Parking Orbit Selection and Initial Phasing

One of the Argo mission requirements is to achieve as one additional member of the RapidEye constellation. Since there are five RapidEye satellites, Argo is considered as 5+1 mission. The RapidEye Mission Orbit is:

Altitude of 625km, Sun-synchronous orbit (for altitude of 625 km the sun-synchronous orbit is with inclination angle of 97.9 degree). The local time of descending node is between 10:30 am and 11:30 am.

The original five RapidEye satellites will be on the same orbit plane. The constellation divides the orbit circle into 5 equal parts, as show in Figure 2. With the Argo satellite joining in the constellation, each of the six satellitess shares 1/6 circle apart. The five RapidEye satellitess will be launched in one time by Dnper roughly one year before Argo. In order for the Argo satellite to join the constellation, the five RapidEye satellitess will make phase adjustment as Figure 2 shows:

- 1) Satellite 1 phase unchanged
- 2) Satellite 2 flies ahead 12 degree of phase
- 3) Satellite 3 flies ahead 24 degree of phase
- 4) Satellite 4 flies behind 24 degree of phase
- 5) Satellite 5 flies behind 12 degree of phase
- 6) The Argo satellite inserted into the clear-out slot.

RapidEye mission can accept a range of altitude (from 600 km to 650 km), however, the orbit must be sun-synchronous. Therefore after separation from the launch vehicle, RapidEye will adjust the altitude according to the real inclination angle to reach the sun-synchronous orbit. Although RapidEye has no stringent requirement for the orbit altitude, it is not the case for Argo. It is because Argo need to be with the same as (very close to) the RapidEye orbit altitude, otherwise Argo will fly different speed from other RapidEye satellitess and the constellation phase (each of 1/6 orbit apart) can not be maintained. Since Argo need to adjust its orbit to be the same as the real RapidEye orbit, and Argo orbit needs to be sun-synchronous, thus *Argo also needs to adjust the inclination to be the same as (very close to) the RapidEye's*. Therefore *Argo has the much*

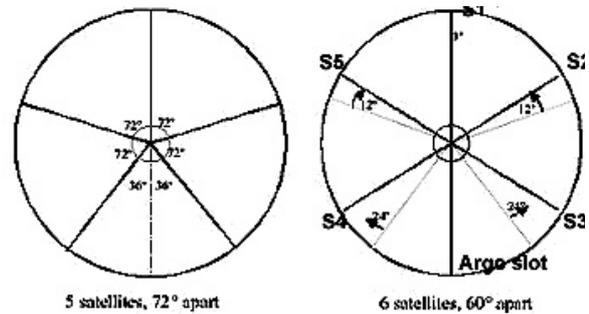


Figure 2. Rephasing for Argo satellite to join the constellation.

more demanding orbit correction requirement than RapidEye's.

As the Argo orbit needs to be the same as (very close to) the real RapidEye orbit (the orbit in real operation), the target of the launch parking orbit shall be the real RapidEye orbit. That is, after the RapidEye deployed in flight, the exact orbit information sets Argo Launcher (expected to be Falcon-1). The possible orbit insertion error of Falcon-1³ is 25km in altitude and 0.1 degree in inclination. Since the nominal mission orbit of RapidEye is with altitude of 625km, we conclude the Parking Orbit Requirement below.

The spacecraft bus will be carried by the launch vehicle into the parking orbit of circle orbit of altitude $625\text{km} \pm 25\text{km}$, inclination angle of 97.9 ± 0.1 degree.

Therefore, the maximum orbit correction capability for the Argo satellite should be **25km in altitude and 0.1 degree in inclination**. Any insertion orbit after separation which meets this range is acceptable.

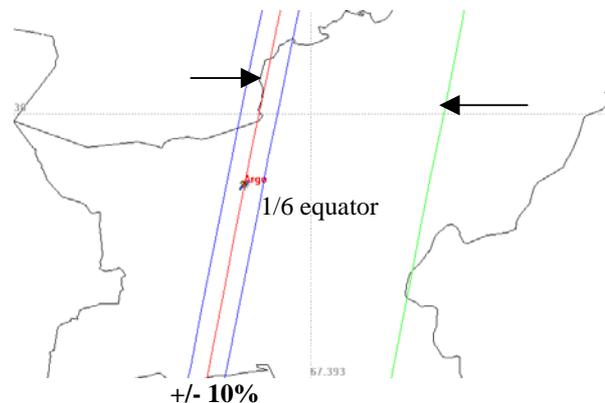


Figure 3. Rephasing Requirement for RapidEye Constellation.

III. Constellation Phasing Maintenance

The constellation phasing maintenance is simply designated as the satellite rephasing. The phasing is the relative position between satellites in the orbit circle. For the RapidEye mission, there is a stringent phasing requirement:

The satellite constellation shall be controlled so that the satellite ground tracks are nominally equally spaced at the equator. The ground track spacing shall be maintained to within $\pm 10\%$ of the distance between ground tracks (3 sigma) relative to the nominal position.

The satellite ground track for this requirement is depicted as shown in Figure 3. Since the ground track relation between satellites can be transformed into the relation of satellites along the orbit. That is, the Argo satellite shall not either catch up the former RapidEye satellite or move behind closer to the latter RapidEye satellite by 10% of the 60 degree of the orbit circle, which is equal to 6 degree. However, the Argo satellites in the orbit will have high tendency to be out of phasing because of two major reasons^{4,5}:

- 1) It is very difficult to perfectly adjust the Argo satellite in the same plane with other satellites (due to the orbit determination and control accuracy limitation), therefore the Argo satellite likely has different speed from other satellites
- 2) The Argo is of different size and mass, therefore it has different drag from others

The initial orbit adjustment error of the altitude between the Argo satellite from other RapidEye satellites is defined as the initial orbit bias.

Simulations to analyze the time for Argo to cross the 10% ground track limitation border vs. the initial orbit bias have been conducted with software Satellite Tool Kit (STK)⁶. For the simulations, it is assumed that the former and later RapidEye satellites are in the same plane (it could be reasonable assumption because all RapidEye satellites are injected in one launch). As shown in Figure 4, we put two Virtual RapidEye (Virtual RE) satellites into the orbit circle. One Virtual RE is 6 degree ahead Argo, designated VRE-1, in the orbit circle, and the other is 6 degree behind Argo, designated VRE-2. Then we are going to find out how much time the ground track of the Argo satellite coincides with it of any one of the Virtual RE satellites. It will be the same as how much time the Argo satellite coincides with any one of the Virtual RE satellites in the orbit circle. Herein, we should note that RapidEye is of different size and weight from the Argo satellite.

The parameters for the simulation computation are assumed as follows:

- 1) $C_d=3.5$, $F_{10.7}=145$

- 2) The Argo satellite with Area/Mass = $0.00763675 \text{ m}^2/\text{kg}$
- 3) RapidEye Area/Mass = $0.00630000 \text{ m}^2/\text{kg}$

The simulation result is summarized in Table 1

Table 1 Simulation Result Summary

If Argo fly lower than the other satellites by the distance of :	The time for ground track drift out $\pm 10\%$ of the nominal distance
2km	1 day
500m	10 day
200m	24 day
100m	37 day

The simulation shows that a small bias the can cause the drifting diverge quickly. Even with a small such as 100 meters, it takes 37 only days for the ground track drift out 10% limit from the nominal distance. However, the tolerance of 100 meters is already very difficult to achieve because of the current orbit determination and control techniques for the low-cost satellites. The normal GPS receivers with sophisticated filter processing can only provide accuracy of 100 meters.

We don't want to stop the normal mission

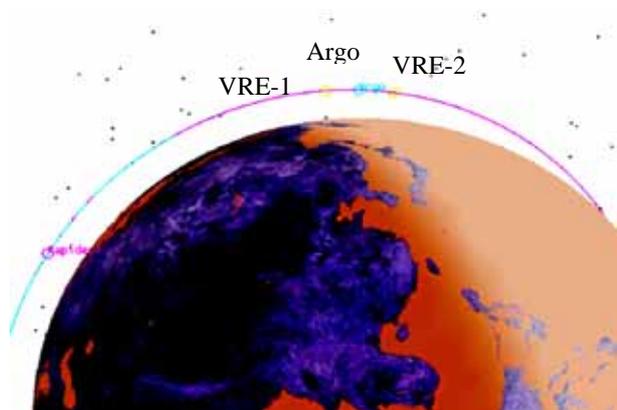


Figure 4. Simulation of Orbit Phasing

operations often for conducting orbit re-phasing, It is reasonably expected for conducting orbit rephrasing no more than twice a year. It implies that the initial orbit bias must be very small, and it is unfeasible and challenging. Furthermore, the fuel consumption for conducting orbit re-phasing is also critical if the operation is needed to conduct often.

IV. Minimum Fuel Algorithms for Orbit Re-Phasing: Wait-and-Hit

From previous section, we know that in order to minimize the times for orbit re-phasing, the high accuracy of orbit control is needed. However, the cost for such performance is not affordable. The innovative algorithms for orbit re-phasing have been developed for minimizing the operation efforts and fuel consumption. It is to relax the demanding needs of high accurate control and determination for adjusting the Argo satellite into the same plane of RapidEye. In addition, it relaxes the needs to conduct the re-phasing often. The algorithm is named as "Wait-and-Hit".

Here is the concept of Wait-and-Hit. After separation in the early orbit phase, we can fine tune the Argo orbit to roughly 200 meter above RapidEye satellites (as shown in Figure 5). The range of 200 meters is chosen because it is practically easy to achieve this level of orbit control. Argo is intended to be at the left ground track allowable limit (the same position as former Virtual RE-1).

Since the Argo satellite has larger drag than RapidEye, it will fly slower and slower comparing to RapidEye. Gradually the Argo satellite will drift from the position of Virtual RE-1 to Virtual RE-2. The Argo satellite will be caught up by the later Virtual RE-2.

At the same time, due to the larger drag, the orbit of Argo satellite will decay with the higher rate than RapidEye's. In the way flying going downward, the Argo satellite will pass the *EXACT* RapidEye orbit plane. The rate of phasing drift will be very slow at that moment when the Argo satellite will pass the *EXACT* RapidEye orbit plane.

Although it flies slower at the beginning at the higher altitude, however, as it going downward, it will speed up. Since the orbit decay rate of it is higher, the Argo satellite is accreting comparing with RapidEye. Consequently after coinciding with Virtual RE-2, Argo will catch up and toward the former Virtual RE-1 again.

At the time, Argo catches up the Virtual RE-1, it implies Argo's speed is much higher than RapidEye and the ground track limit is hit. This is the time to adjust phasing for Argo. We will move Argo till roughly 200 meter higher than RapidEye again. Then it is a complete cycle of operation, Wait-and-Hit.

The simulation studies shows that it can take as many as 230 days for one cycle of Wait-and-Hit. That is, we only need to adjust the phasing for 230 days a time. The initial orbit correction requires only 200 meter accuracy,

which is much applicable. The orbit raising operation roughly needs 0.15 kg of gas nitrogen. Because we don't need to adjust the orbit for phasing often, the Argo satellite does is not needed much Delta-V (propellant).

V. Propellant and Delta-V Budget

The Delta-V budget of the Argo satellite should include the following items:

- 1) The orbit transfer from the parking orbit to the mission orbit with the consideration of maximum insertion error from the launcher
- 2) The orbit maintenance and phasing maintenance for the mission lifetime plus 1 year
- 3) margin

As the application of the algorithms, herein, the Orbit Maintenance Requirement can be relaxed:

It shall be possible to maintain the spacecraft orbital radius to within a 20km orbital radius band during the operational lifetime of the spacecraft.

With considering the satellite assumed to be 420 kg and the cross section area is $1.2 \times 1.6 = 1.92$ square meters. For the required Delta-V and the cold gas propulsion system, considering the lifetime of 7 years, the Argo satellite requires for 28.56 kg propellant (GN2). The orbit re-phasing operation is needed once half a year.

VI. Conclusion

The present works show the significant reduction of the fuel consumption can be achieved. Furthermore, the orbit control for orbit phasing operations can be much simplified without the needs of high accurate orbit determination and control. The algorithms proposed, with the merits, can be applied to the general cases of low-cost satellite constellation, of which satellites have no sophisticated propulsion and control hardware.

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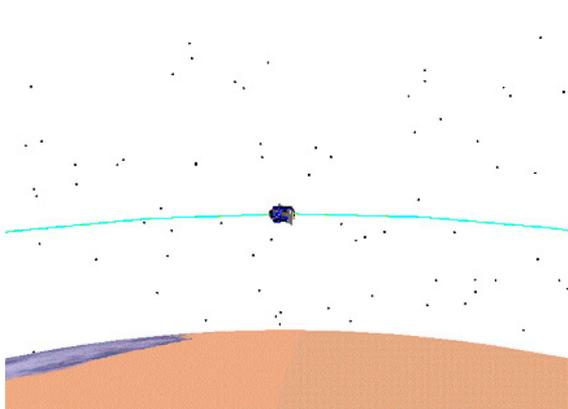


Figure 5. Argo satellite 200m above RapidEye and at the front 10% limit

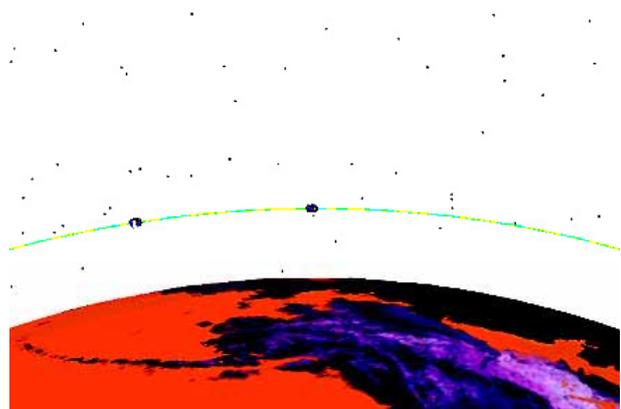


Figure 6. Argo satellite is going downward and caught by the later Virtual RE-2

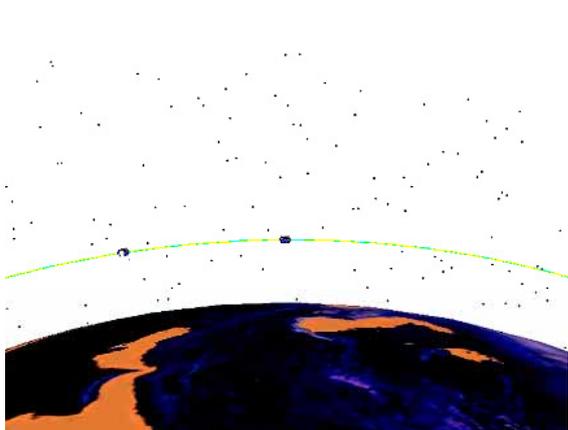


Figure 7. As Argo satellite speeding up, it catches the former RE-1

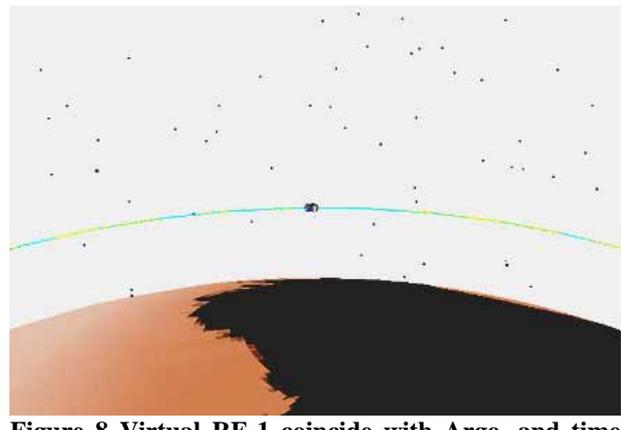


Figure 8 Virtual RE-1 coincide with Argo, and time for adjustment

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