CONSTELLATION DESIGN AND DEPLOYMENT STRATEGY OF TAIWAN REMOTE SENSING SATELLITES

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ABSTRACT: Constructing a satellite constellation is one of key development trends for remote sensing satellites, since a remote sensing satellite constellation can solve global coverage or temporal resolution issues raised by a single satellite.

FORMOSAT-5 and its Follow-on mission, the remote sensing satellite projects proposed by National Space Organization (NSPO), are the first and the second self-reliant space programs in Taiwan. The mission orbit for FORMOSAT-5 is a sun-synchronous orbit with 720 km altitude. Flying in this orbit, FORMOSAT-5 can repeat its ground-track every other day, and can reach the goal of two-day global coverage with 45 degree field of regard (FOR). The FORMOSAT-5 Follow-on mission, which is planned to consist of one or two identical satellites, is scheduled to launch after FORMOSAT-5 to form a Taiwan remote sensing satellite constellation with FORMOSAT-5.

The aim of this paper is to design the suitable orbit(s) for FORMOSAT-5 follow-on mission to increase the temporal resolution of overall constellation system and to propose a deployment strategy to avoiding collision, between satellites. Some different scenarios for Taiwan remote sensing satellite constellation are proposed in this paper. For each scenario, the orbit of Follow-on mission is designed and verified through STK (Systems Tool Kit) simulations. Finally, comparisons of the advantages and disadvantages for each constellation design are described in detailed.

1. INTRODUCTION

FORMOSAT-5 is the first Taiwan's space program that NSPO takes full responsibility for the complete satellite system design, manufacturing and integration & test, and it will operate in a sun synchronous orbit at 720-km altitude with 98.28-degree inclination angle. Operating in this orbit, FORMOSAT-5 can have two-day revisit property, and can reach the goal of two-day global coverage with 45 degree FOR (NSPO, 2008).

According to the second phase of Taiwan's space program plan, NSPO is planning to design and build FORMOSAT-5 follow-on mission. In order to reach the goal of global coverage and daily revisit, or in order to increase the temporal resolution for some specific regions at specific times. The follow-on mission, which may include either one or two satellites, is scheduled to launch after FORMOSAT-5 to group a Taiwan remote sensing satellite constellation with FORMOSAT-5. The FORMOSAT-5 is currently scheduled to be launched by Falcon 9 of SpaceX in the end of 2015.

Three orbit designs for Taiwan remote sensing satellite constellation, which includes FORMOSAT-5 and it follow-on mission, are proposed in this paper, and its advantage and disadvantages for each design are discussed.

In section 2 some related theories for orbit design are presented. In section 3 three constellation design scenarios are described, and comparisons of the advantages and disadvantages for each scenario, are described. Finally, some conclusions are offered in section 4.

2. RELATED THEORY FOR ORBIT DESIGN

2.1 Sun-synchronous orbit (SSO)

The rate of change of right ascension of the ascending node (RAAN) Ω due to J_2 is

$$\dot{\Omega} = -\frac{3}{2(1-e^2)^2} J_2 n \left(\frac{R_\oplus}{a}\right)^2 \cos i \quad , \tag{1}$$

where n is mean motion , $R_\oplus$ is Earth's equatorial radius, a is semimajor axis, e is eccentricity, i is inclination angle, J_2 is the second-order zonal harmonic of the earth's gravitational field.

The mean motion is determined from the semimajor axis of the orbit:

$$n = \sqrt{\frac{\mu}{a^3}} \quad , \tag{2}$$

where μ is the gravitational parameter of the Earth.

For a circular Sun –synchronous orbit($e \approx 0$), the nodal precession rate of the satellite orbit is

$$\dot{\Omega} = -\frac{3}{2} J_2 n \left(\frac{R_\oplus}{a}\right)^2 \cos i \approx 0.9856 \ , \tag{3}$$

The rate of nodal regression for SSO is a function of inclination and altitude, and a satellite on SSO pass over any given earth latitude at the same time (local mean time).

2.2 Repeating Ground Track Orbit

For a repeating ground track orbit, the period of repetition T_r is

$$T_r = NT_\Omega = DT_G \quad , \tag{4}$$

where N is the number of revolutions along the orbit in one period of repetition, D is the number of sidereal days the earth completes during the period of repetition, and T_Ω is the nodal period of a satellite which is the time that elapses between successive passages of a satellite through consecutive ascending nodes (Michel Capderou, 2006; Sharon D. Vtipil1 and Brett Newman, 2010). It means a ground track will be repeated after the satellite completes N revolutions over D days.

The nodal period of Greenwich T_G is

$$T_G = \frac{2\pi}{\omega_\oplus - \dot{\Omega}} \quad , \tag{5}$$

where $\omega_\oplus$ is the earth's rotation rate.

Substituting equation (3) into equation (5), if there exit two integers, N and D, which are co-prime, to satisfy

$$\frac{N}{D} = \frac{1440}{T_\Omega} \quad , \tag{6}$$

then the orbit will have the properties of both Sun-synchronous and repeating ground track.

The ground shift λ_S is

$$\lambda_S = T_\Omega \left(\omega_\oplus - \dot{\Omega}\right) R_\oplus = \frac{2\pi R_\oplus}{(\frac{N}{D})} \quad , \tag{7}$$

It is the difference between successive passages of a satellite through consecutive ascending nodes. The difference between the consecutive ascending nodes in the period of repetition is

$$\Delta \lambda = \frac{\lambda_S}{D} \quad , \tag{8}$$

Let d be the FOR width at equatorial for a satellite. If $d > \Delta \lambda$, then the satellite can reach the goal of global coverage in the period of repetition.

Based on the orbital equations discussed above, FORMOSAT-5 can be global coverage, and some orbit related parameters for FORMOSAT-5 with a FOR of ±45° (cross-track or along-track) are listed in Table 1. (Chuang-Wei

Hsueh and Feng-Tai Hwang, 2013)

Table 1: The related orbital parameters of FORMOSAT-5

D	N	a (km)	i (deg)	d (km)	λ_S (km)	$\Delta\lambda$(km)	Global Coverage
2	29	7098.097	98.27	1536	2764	1382	Yes

3. CASE STUDIES AND SIMULATED RESULTS

Although there are no absolute rules to design a perfect constellation, and a constellation of satellites in randomly spaced low Earth orbit (LEO) may reduce the overall performance for a remote sensing mission. The goal to design a suitable orbit for FORMOSAT-5 follow-on mission is to increase the temporal resolution of constellation system. In order to assess advantages and disadvantages for different constellation designs of Taiwan remote sensing satellites, three different orbit design scenarios are proposed and results are discussed. First, some constraints (or conditions) for orbit designs are described below,

(1) FORMOSAT-5 will be operated in a SSO with an altitude of 720 km, circling the earth 14.5 times every day. It passes between Taiwan and Penghu Island every other day.
(2) FORMOSAT-5 is a satellite of octagonal shape (3 m in height and 1.2 m in diameter) with a wet mass of about 525 kg.
(3) All satellites specifications for Follow-on mission are assumed to be same as FORMOSAT-5 except the image resolutions.
(4) The Long-term orbit predictor (LOP) provided by STK is used for orbit decay prediction for the inclination and the semimajor axis in this study. The orbit epoch starts at 1 Jan 2016 00:00:00.000 UTCG, and the simulation duration is one year.
(5) The Chung-li station (25°N, 121.3°E) is used to count the number of revisit, if the Chung-li station during daylight hours within a satellite FOR of ±45°.

Scenario 1: The two satellites of both FORMOSAT-5 and Follow-on satellite (FO-1, the first satellite) will be on the same orbit plane with the phase of 180 degree, as show in Figure 1. The initial orbital elements of the two satellites are listed in Table 2. The ground track and coverage area of FORMOSAT-5 for Day 1 is shown in Figure 2. The ground track and coverage area of FORMOSAT-5 with FO-1 for Day 1 is shown in Figure 3. They will change their ground track and coverage area next day. The number of revisit in four days is shown in Figure 4, and the secular changes in altitude and inclination for one year are shown in Figures 5 and 6, respectively.

Scenario 2: The three satellites of both FORMOSAT-5 and FO-1/FO-2 (FO-2, the second satellite) will be on the same orbit plane with the phase of 120 degree, as show in Figure 7. The orbital elements of the three satellites are shown in Table 3. The ground track and coverage area of FORMOSAT-5 with Follow-on mission (FO-1+FO-2) in Day 1 is shown in Figure 8. The number of revisit in four days is shown in Figure 9.

Scenario 3: The three satellites of both FORMOSAT-5 and FO-1/FO-2 will be on the three different orbit planes, as show in Figure 10. The orbital elements of the three satellites are listed in Table 4. The ground track and coverage area of FORMOSAT-5 with Follow-on mission (FO-1+FO-2) in Day 1 is shown in Figure 11. The number of revisit in four days is shown in Figure 12, and the secular changes in altitude and inclination for one year are shown in Figures 13 and 14, respectively.

For scenarios 1 and 2, the behavior of secular changes in altitude and inclination are the same for each satellite. That means the constellation geometry can be preserved without additional orbit maintenance, so that can reduce the fuel usage and then increase the lifetime of the satellites. For scenario 3, the trends of secular changes for each satellite in altitude are the same, but the trends of secular changes in inclination are different. Although the rate of inclination change is small, the accumulated deviation in RAAN will be significant after a few years, and the local mean time will no longer satisfy the mission requirement (Chia-Chun Chao, 2005).

For scenarios 1 and 2, the two constellation designs can satisfy the goal of global coverage and daily revisit. All remote sensing images are acquired in the same local time for scenario 1 and 2. However, the temporal resolution for scenario 2 is better than the temporal resolution for scenario 1, since there are three satellites for scenario 2 but two satellites for scenario 1. For scenario 3, the images of each satellite are acquired in different local time due to the different RAAN. There are two imaging opportunities per day for the Chung-li station for this scenario, but it cannot attain the goal of global coverage unless these satellites are placed on different orbits with proper phase.

The Comparisons of the advantages and disadvantages of the three scenarios are listed in Table 5.

Table 2: The orbital elements of scenario 1

Parameter	FORMOSAT-5	Follow-on mission (FO-1)
Semimajor Axis (km)	7098.09	7098.09
Eccentricity	0	0
Inclination (deg)	98.2744	98.2744
RAAN (deg)	70.5015	70.5015
True Anomaly(deg)	42	222

Table 3: The orbital elements of scenario 2

Parameter	FORMOSAT-5	Follow-on mission (FO-1)	Follow-on mission (FO-2)
Semimajor Axis (km)	7098.09	7098.09	7098.09
Eccentricity	0	0	0
Inclination (deg)	98.2744	98.2744	98.2744
RAAN (deg)	70.5015	70.5015	70.5015
True Anomaly(deg)	42	162	282

Table 4: The orbital elements of scenario 3

Parameter	FORMOSAT-5	Follow-on mission (FO-1)	Follow-on mission (FO-2)
Semimajor Axis (km)	7098.09	7098.09	7098.09
Eccentricity	0	0	0
Inclination (deg)	98.2744	98.2744	98.2744
RAAN (deg)	70.5015	110.502	150.502
True Anomaly(deg)	42	42	42

Table 5: Comparisons of the advantages and disadvantages

Scenarios	Advantages	Disadvantages
1	1. It can reach the goal of global coverage and daily revisit. 2. It can get all remote sensing images in the same local time. And the consistent lighting conditions of the Earth's surface enable scientists to easily compare images. 3. The behavior of secular changes in altitude and inclination are the same for each satellite.	1. It cannot get the remote sensing images in different local time because of all satellites on the same orbital plane. 2. It is easy to lose the imaging opportunity, once a day, due to cloud cover.
2	1. It can reach the goal of global coverage and daily revisit, and the temporal resolution for scenario 2 is better the temporal resolution for scenario 1. 2. It can get all remote sensing images in the same local time. And the consistent lighting conditions of the Earth's surface enable scientists to easily compare images. 3. If a satellite fails, it has the capability of rephrasing the rest two satellites to form the constellation of scenario 1. 4. The behavior of secular changes in altitude and inclination are the same for each satellite.	1. It cannot get the remote sensing images in different local time because of all satellites on the same orbital plane.
3	1. It can get the remote satellite images in different local time because of the different RAAN. 2. It has two imaging opportunities per day for the Chung-li station in this scenario, but it cannot attain the goal of global coverage unless these satellites are placed on different orbits with proper phase.	1. The behavior of secular changes in altitude is the same for each satellite, but the behavior of secular changes in inclination is different. The cost to keep geometry is the most expensive of the three scenarios. 2. The satellites will very close to each other, especially when crossing other orbit planes near the polar circles, if the orbital elements are the same except RAAN.

4. CONCLUSIONS

The comparisons of the advantages and disadvantages for three different scenarios based on the STK simulations are presented in this paper. These constellations are designed so that all of Taiwan remote sensing satellites are in circular orbits at same altitude and inclination; this means that the period, mean motion, and node rotation rate will be almost identical for all of the satellites, and any orbit perturbations affect each satellite in approximately the same way to reduce the fuel usage and hence increase the life of the satellites.

There are two kinds of natural perturbations to change the local time. The sun's attraction will result in the secular change in inclination, and the drag from the atmosphere will result in a loss of altitude. In scenarios 1 and 2, the behavior of secular changes in altitude and inclination are the same for each satellite. However, in scenario 3, the rates of RAAN change for three satellites are slightly different since these satellites are placed on different orbit planes.

Three specific constellation designs for Taiwan remote sensing satellites are outlined, and they can solve the global coverage/ temporal resolution issue raised by a single satellite. Each design has its own advantages and disadvantages. Each scenario is a feasible design for FORMOSAT-5 and its follow-on mission constellation.

5. REFERENCES

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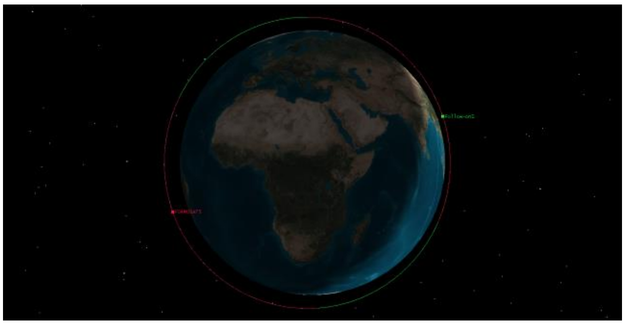

Figure 1: The constellation of FORMOSAT-5 and Follow-on mission (Scenario 1)

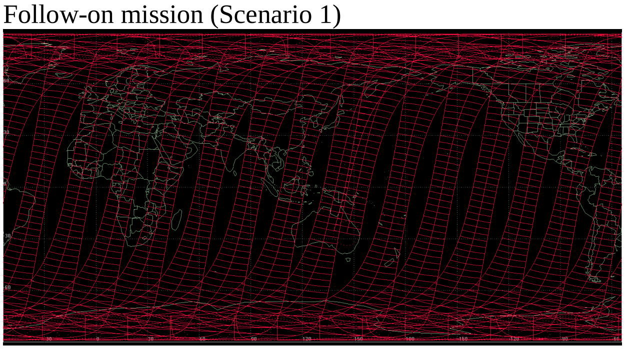

Figure 2: The ground track and coverage area of FORMOSAT-5 (Day 1)

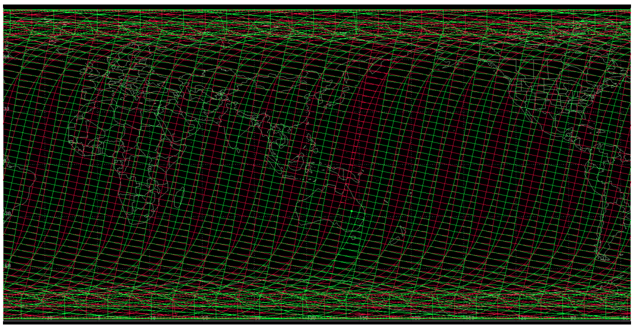

Figure 3: The ground track and coverage area of FORMOSAT-5 and FO-1. (Day 1)

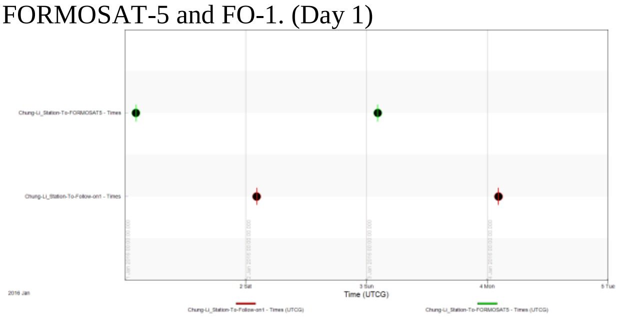

Figure 4: The number of revisit of scenario 1 in four days

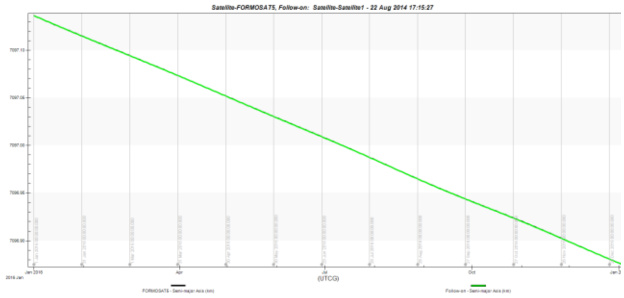

Figure 5: One-year semimajor axis histories of the two satellites of scenario1 without orbit maintenance.

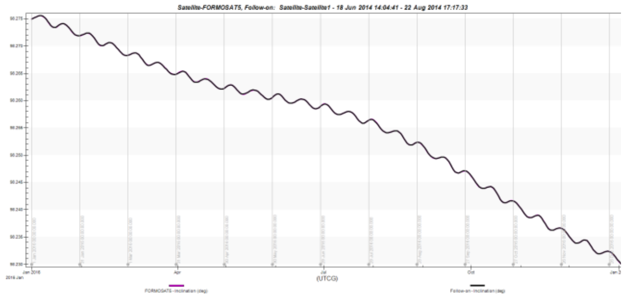

Figure 6: One-year inclination histories of the two satellites of scenario 1 without orbit maintenance.

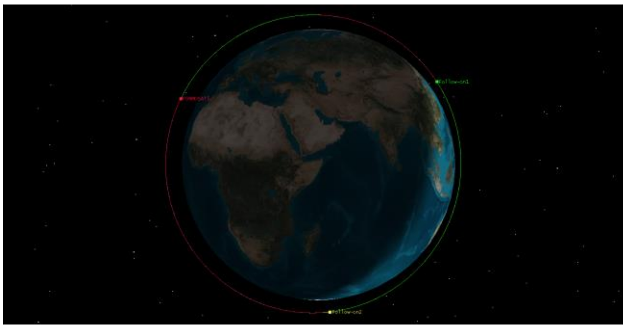

Figure 7: The constellation of FORMOSAT-5, FO-1 and FO-2. (Scenario 2)

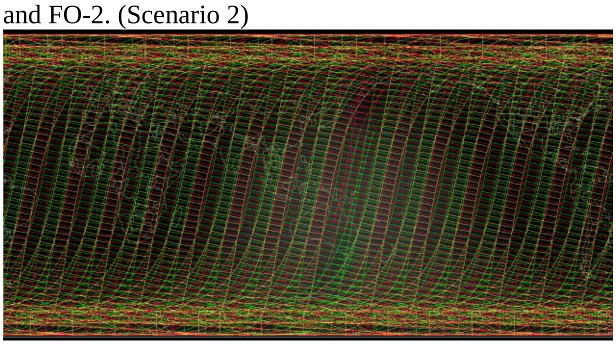

Figure 8: The ground track and coverage area of FORMOSAT-5, FO-1 and FO-2. (Day 1)

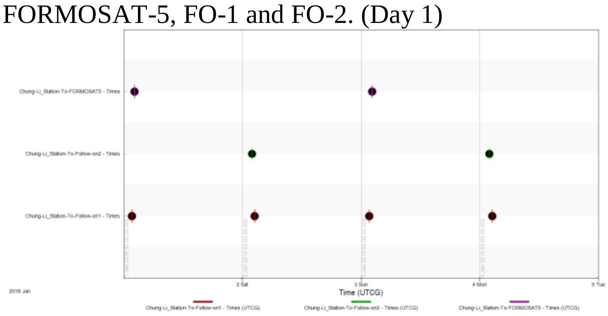

Figure 9: The number of revisit of scenario 2 in four days.

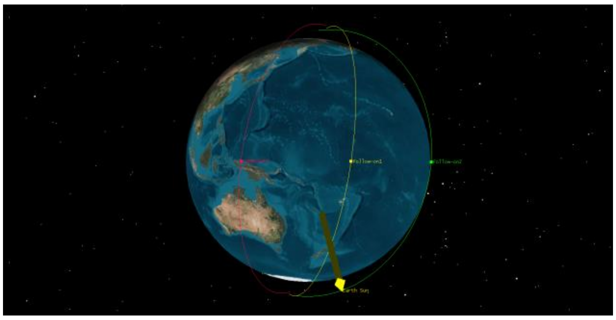

Figure 10: The constellation of FORMOSAT-5 and Follow-on mission (Scenario 3)

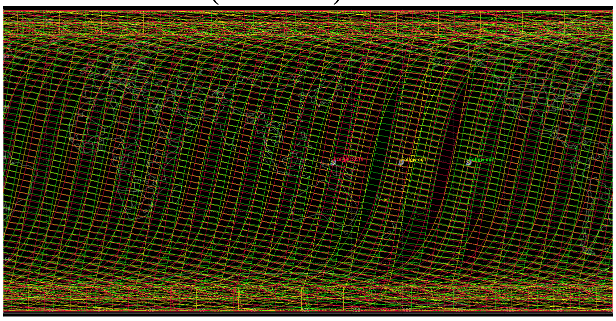

Figure 11: The ground track and coverage area of FORMOSAT-5, FO-1, and FO-2. (Day 1)

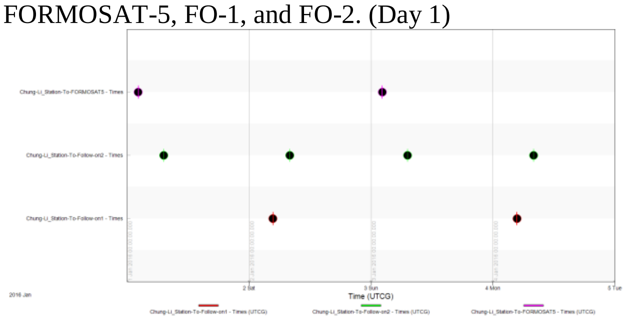

Figure 12: The number of revisit of scenario 3 in four days

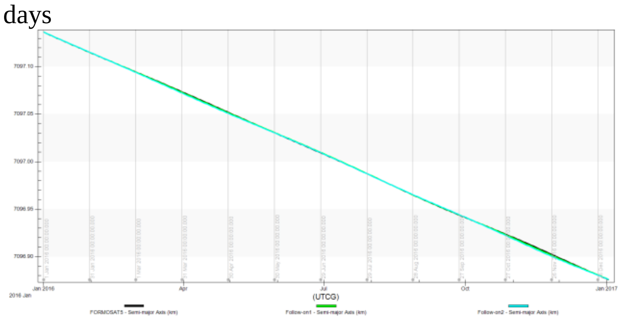

Figure 13: One-year semimajor axis histories of the three satellites of scenario 3 without orbit maintenance.

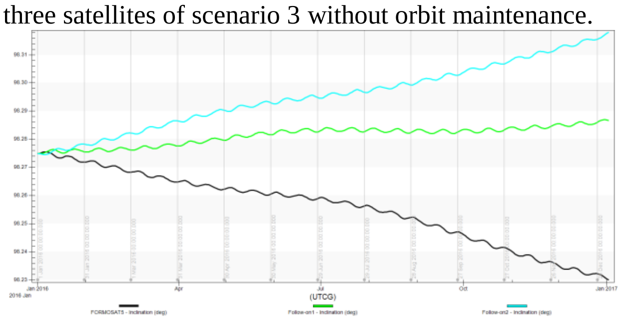

Figure 14: One-year inclination histories of the three satellites of scenario 3 without orbit maintenance.