Orbital operation of Communications and Broadcasting Engineering Test Satellite (COMETS)

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Abstract

The Communications and Broadcasting Engineering Test Satellite (COMETS) was launched by the H-Launch Vehicle Flight No.5 on February 21, 1998. However, due to troubles in the second stage rocket, the COMETS could not be placed in its planned geostationary orbit. Therefore, we designed AEF(Apogee Engine Firing) maneuver plans to put the COMETS into an operation orbit which is lower than the geostationary orbit, so that we can conduct as many experiments on communications as possible. Finally, we put the COMETS into the operation orbit by performing the AEF seven times and the small maneuver five times.

This paper presents about the orbital maneuver plans and the result of the COMETS.

Key words: COMETS, Orbital operation, maneuver plan

Introduction

The COMETS which is a two-ton geostationary three-axis stabilized satellite of National Space Development Agency of Japan (NASDA) has purposes of acquiring new techniques of Inter-orbit Communications, advanced satellite broadcastingand advanced mobile satellite communications. It was launched by the H-Launch Vehicle Flight No.5 on February 21, 1998.

However, due to trouble in second stage rocket, the COMETS was put into an orbit which is lower than geostationary transfer orbit.(See Table.1) Therefore, we had to make an orbital altitude heightened to conduct as many experiments on communications as possible.

Table.1 : COMETS injected orbital parameters

	Nominal	Result
Perigee Height(km)	250	246
Apogee Height(km)	36,000	1,902
Orbit period(min)	636	107
Orbital Inclination(deg)	28.5	30.1

So, we designed AEF maneuver plans to put into the target orbit.

Orbit conditions

First, We investigated the optimal orbit, for experiment on communications and maneuver strategy the COMETS.

We had to control attitude of the COMETS for the experiments with a pair of earth-sensors. But, the earth-sensors are disabled when altitude is lower than 12,270km. So we had to increase an apogee altitude higher then 12,270km.

And, because the facility of the communications experiments station of Tsukuba had been constructed for geostationary satellites, we had to improve it for the satellite whose orbit was lower than geostationary one. The improvement was scheduled to be completed at the end of July, 1998, in order to conduct experiments from August, 1998.

And, we had to keep absolute value of beta angle() which is the angle between the sun line and the orbital plane, less than 45 deg. to charge a battery with electricity satisfactorily. We had to avoid radio wave interference with N-STAR(the communications satellite of Telecommunications Advancement Organization of Japan(TAO))

The summarized orbit conditions for carrying out the communications experiments are as follows.

[The orbit conditions]

(1) The apogee height is higher than 12,270km.
(2) The experiments will start from August, 1998.
(3) absolute value of is less than 45 deg.
(4) No radio wave interference with N-STAR.

Table.2 : Plans of the target orbit (#1)

	Apogee Height(km)	Perigee Height(km)	Orbit period(min)
Plan1	25,000	250	435
Plan2	15,000	1,900	299
Plan3	19,000	1,000	348

AEF conditions

There were some conditions to perform AEF. It is effective that firing duration of one AEF is short. Therefore, the maximum firing duration of an AEF was determined to be 10 minutes.

To confirm AEF maneuver, the first and the 2nd AEF should be performed while the COMETS was seen from any tracking control stations.

In the orbit which COMETS was put by the rocket, because the perturbation due to the atmospheric drag was large about the perigee, its attitude is disturbed and it was consumed much fuel for attitude control. So, we would perform the 1st AEF and the 2nd AEF in early time, the 1st AEF on March 14 and the 2nd AEF on March 19

In an original orbit change plan, the COMETS would obtain total delta-V about 1.79km/sec by AEFs. In fact, the COMETS could obtain delta-V about 1.67km/sec, because much fuel is consumed for attitude control until the orbit change completes.

The summarized AEF conditions to put into the target are as follows.

[The AEF conditions]

(5) We must send the series of command for AEF while the COMETS is seen from any tracking control stations.
(6) Maximum firing duration of any AEF is 10 minutes.
(7) The first and second AEF is performed while the COMETS is seen from any tracking control stations.
(8) The 1st AEF is performed on March 14 and the 2nd AEF is performed on March 19.
(9) AEF is performed at intervals of more than 5 days in consideration of the recovery of an electrical battery.
(10) We can obtain total delta-V about 1.67km/s.
(11) the AEF to change the plane of the orbit is not performed.

Investigation of orbit altitude

First of all, we investigated altitude of the target orbit under the condition(1). We designed the target orbits(#1) , is shown in Table 2. Plan 1 orbit was made by raising the apogee of the COMETS's put orbit. Plan 2 orbit was made by rising the perigee. Plan 3 orbit was made by raising the apogee and the perigee.

Because the facility of the communications experiment station was made for a geostationary satellite, Doppler shift and antenna drive speed made been small. In the orbit which has higher apogee height, antenna drive speed is smaller and visible time is longer than in the orbit which has low apogee height. But, the significant difference of doppler shift was not seen in each orbit.

On the other hand, PAD(Solar Array Paddles) decays rapidly by proton lay in the orbit that passes the Van Allen belt. Prediction electrical power of decay rate of PAD 1 year after launch is shown in Table 3. It is shown that decay rate of PAD increase in proportion as apogee altitude become high.

Table.3 : Prediction of decay rate of electrical power by PAD

	decay rate of PAD after 1 year
plan1	42%
plan2	68%
plan3	51%

The comparative result of each orbit is shown in Table 4. Because plan 1 is most excellent for a target orbit, we decided that plan 1 is the basis of a target orbit.

Next, we optimized the perigee altitude and apogee altitude of the orbit of plan 1. In the orbit when it was separated from the rocket, the decrease of the apogee altitude is big, because the atmospheric perturbation is big. Therefore we elevated perigee altitude 500 km.

We can make communications experiments efficiency in recurrence orbits which the satellite's visibility pattern from station is cyclic. The recurrence orbits which has the recurrent period of less than three days and 500km height at perigee, is shown in Table 5.

Table.4 : Evaluation results of plans of the target (#1)

	Visible time	antenna drive speed	Doppler shift	electric power	result
plan1					
plan2					
plan3					

Table.5 : Plans of the target orbit (#2)

	arrival apogee height	recurrence (recurrence revolution)	the possible period of attitude control	the possible period of communications experiment	the possible time of experiment per 1 recurrence	total amounts of experiment possible time
plan1-1	18500km	3days(13Rev.)	5 month	5 month	100min	5000min
plan1-2	17700km	2days(9Rev.)	6 month	5 month	90min	6750min
plan1-3	16900km	3days(14Rev.)	9 month	5 month	80min	4000min
plan1-4	15600km	1day(5Rev.)	12 month	5 month	40min	6000min

In this table, the possible period of attitude control which is a period that we can control axis from after injection into a target orbit, is long time when the apogee is low. The possible period of communications experiments is the period when an apogee is in a northern hemisphere.

Because the COMETS orbital inclination was 30 deg., an apogee was made a round trip to a northern hemisphere and southern hemisphere in 10 months by the perturbation from the flatness of the earth in the target orbit. Therefore, this period when the COMETS is visible from the communications experiment station of Japan, is limited in about 5 months.

The total amounts of experiment possible time is total amounts of the time that we can experiment in 5 months when are the possible period of communications experiments.

It is calculated by the following formula(1).

$$\text{total amounts in experiment possibility time} = \frac{\text{possible time of experiment per 1 recurrence} \times \text{5 months(150 days)}}{\text{days of recurrence}} \cdots(1)$$

As that result, we defined the plan 1-2 (altitude is 500km at perigee and 17,700 km at apogee) that the total amounts of communications experiment possible time is biggest, at a target orbit.

Adjustment in a communications experiment period

When the latitude of an apogee is in the north, we can make a communications experiment in the station of Japan. When we adjust an argument of perigee(ω), the latitude of an apogee is changed. It is the same as that shifts a communications experiment period.

To adjust ω, we could perform the AEF on off apsis. But, because the fuel is necessary to perform the AEF and control attitude, we must avoid this method as much as possible. So we adopted the method that ω is adjusted by utilizing perturbation from the flatness of the earth. We can estimate ω-dot by perturbation, in a formula (2).

$$\dot{\omega} = \frac{3}{2} \frac{a_e^{\,2} J_2}{a^2 \left(1 - e^2\right)^2} n \left(2 - \frac{5}{2} \sin^2 i \right) \cdots(2)$$

The visibility of the satellite from the station in Japan is optimal when ω is 270 deg. However, ω in the orbit of plan1-2(the orbital inclination is 30 deg.) increases 1.29 deg. a day. Even if ω is set once to 270 deg., it gradually increases, and the apogee moves southward. When the apogee reaches to the southern hemisphere, we can’t perform experiment.

We can make communications experiments from 70 minutes after the earth sensors are enabled, to 30 minutes before the sensors are disabled.

We defined possibility of experiments as the passes when the COMETS is visible from the station and when condition mentioned above is satisfied during 1 recurrence. The relation between ω and possibility of experiments are shown in Table 6.

The possibility of experiments when ω is between 150 deg. and 380 deg. (20 deg.), is over 1 pass with 1 recurrence. The possibility of experiments when ω is between 180 deg. and 360 deg., is over 2 passes with 1 recurrence.

Table6 : Relation between ω and possibility of experiments

possibility of experiments	a range of ω (deg)	term(day)
over one pass	150380	179
over two passes	180360	140

Therefore, we define the suitable period of experiments that is a period when ω is between 150 deg. and 380 deg. To set the suitable period of experiments from August to the end of December, we had to adjust ω to about 150 deg. during the last ten days of July, and we designed ω of a target orbit on July 2 as 120 deg.

Adjustment to charge a battery with electricity

we had to adjust the ascending node(Ω) in order to adjust the orbit to meet the condition(3). We can adjust ω using perturbation. Similarly, we can adjust Ω using perturbation. Ω-dot by the perturbation is shown in a formula(3). Ω-dot of plan 1-2(the orbital inclination is 30 deg.) decrease 0.81 deg. a day.

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

Like ω, we investigated Ω on July 2. The relation of range of the from August to the end of December and Ω on July 2 is shown in Table 7.

Table.7 : Ranges of from August to December in 1998, with Ω on 2 July.

Ω on July 2 (deg)	maximum (deg)	minimum (deg)
0	50.1	-27.6
45	31.5	-17.9
90	17.8	-10.2
135	27.5	-6.6
180	37.2	-27.8
225	45.4	-45.6
270	51.0	-45.4
315	53.4	-37.2

When Ω is more 225 deg. or less 45 deg. on July 2, an absolute value of is over 45 deg. during experiment period. So, we would set Ω between about 30 deg. to 220 deg. on July 2.

Method of the control that optimizes the condition of Ω and ω

We performed the first and second AEF to meet the conditions (7) and (8). From the next AEF, the enforcement timing of the AEF ware shifted in order to adjust the Ω and ω. The change of Ω and ω is small when semi-major axis is large. Therefore, we adjusted the orbit by shifting the enforcement timing of the AEFs after the 3rd, while the semi-major axis is as small as possible.

Table.8 : Orbital parameters after second AEF (mean orbit)

Epoch	98/3/19 17:27:20(UTC)
semi-major axis	7821.2(km)
eccentricity	0.134
orbital inclination	30.0(deg)
Ω / $\dot{\Omega}$	170.6(deg) / -4.4(deg/day)
ω / $\dot{\omega}$	35.5(deg) / 6.9(deg/day)

An orbit after the 2nd AEF is shown in Table 8.

In the case that we perform the AEFs based on condition(6) and (9), Ω and ω on July 2 will be changed by the enforcement timing of the 3rd AEF.(see Figure 1.) Then, we will perform the AEFs from the 3rd to the 7th at intervals of 5 days. The firing duration of AEFs from the 3rd to the 6th will be 10 minutes. The 7th AEF firing duration will be about 3 minutes because the 7th AEF is a remaining control to put into a target orbit.

The optimal point of ω on July 2 for experiments is neighborhood 120 deg. Therefore, it is better to perform the 3rd AEF on May 6. On the other hand, the suitable Ω on July 2 is 220 or less deg. from the condition(3). Therefore, it is better to perform the 3rd AEF after May 15.

Namely, on May, we couldn't meet the conditions of both Ω and ω by perturbation. As also, the formula(2) and formula(3) show that the change of Ω and ω is in subordination relation. Therefore, even if the interval of the AEFs from the 3rd to the 7th is changed, we couldn't change the relation between Ω and ω of Figure 1.

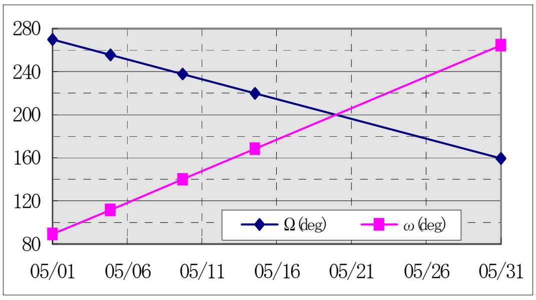

Figure 1 : The Ω and ω on 2 July correspond with enforcement timing of the 3rd AEF

If we perform the 3rd AEF on July 10, both conditions are filled. However, we couldn't adopt it because an experiment start will be delayed. Thereupon, we would adjust ω to shift the AEF performing point from perigee.

From Figure 1, when we delay the 3rd AEF enforcement timing to adjust Ω, ω increases. If we want to decrease ω, we should perform the AEF in the front point of the perigee.

Table9 shows the result of simulate of the AEF using above method.

By the above method, ω is decreased about 24 deg. When we perform the 3rd AEF on May 15, without using the above method, ω on July 2 is 170 deg. However, ω is 146 deg. when we use the above method. And the suitable period of experiments is advanced until the end of almost December.

To delay the 3rd AEF enforcement timing as mentioned above, we will be able to optimize both of Ω and ω.

However, we performed the 3rd AEF as early as possible, in consideration of the charging to electrical battery and fuel that uses for attitude control from a viewpoint of satellite planning.

Therefore, we abandoned the optimization of Ω. We fixed to perform the 3rd AEF on May 6.

Adjustment of radio wave interference avoidance

In the recurrence orbit which revolves 9 times in 2 days, there are 9 points of the longitude passing apogee(λ) at intervals of 40 deg. In this orbit, λ increase 1 deg. when ω increase 1 deg., and increase 1 deg. when mean anomaly(M) increase 4.5 deg. If we put into the recurrence orbit perfectly, λ increase 1.3 deg. in a day because ω increase 1.3 deg. in a day. If we put into the recurrence orbit(the semi-major axis is 15449km), λ increase 1.3degree in a day. To fix λ, we should put into the orbit whose the semi-major axis is larger then the recurrence orbit's one. So, we introduced a satellite position phase(ϕ) on an orbit is a parameter that show λ by the change of the ω and M . ϕ is added a M and 4.5 times of ω when a Greenwich meridian passes the ascending node.

$$\phi = M_{an} + 4.5\omega - 180n \cdots (4)$$

where M_{an} is mean anomaly when a Greenwich meridian passes the ascending node.

Figure 2 is shown the relation between ω and ϕ, and includes ranges of the possible period of experiments of Tsukuba and the radio wave interference with the N-STAR. When the λ is 100 deg.E, ϕ which increases 180 deg. when λ increases 40 deg., is 0 deg. The increase of ω corresponds to the progress in time. In target orbit, ω increase about 23 deg. in a month. Lines of (A) to (C) is shown ϕ-dot. line(B) which is a line when the semi-major axis is about 15486km, is regular. Line(A) which is a line when the semi-major axis is higher than 15486km, drops the right. Line(C) which is a line when the semi-major axis is lower, rise the right.

Table.9 : Simulation result of AEF which are performed at the fixed front point of the perigee.

	Delta-V (m/s)	the altitude of apogee and perigee(km)	M before / after AEF(deg)	the decrease level of ω (deg)
(initial orbit)	-	2511.0 / 394.2	-	-
3rd AEF	286.87	4048.6 / 443.7	333.4 / 345.0	-11.5
4th AEF	317.87	6297.2 / 468.7	345.0 / 351.0	-5.9
5th AEF	356.93	9832.1 / 483.7	351.0 / 354.6	-3.6
6th AEF	408.27	16218.3 / 493.7	354.6 / 357.0	-2.4
7th AEF	68.14	17684.6 / 494.9	357.0 / 357.3	-0.3
(total)	1438.08	-	-	-23.7

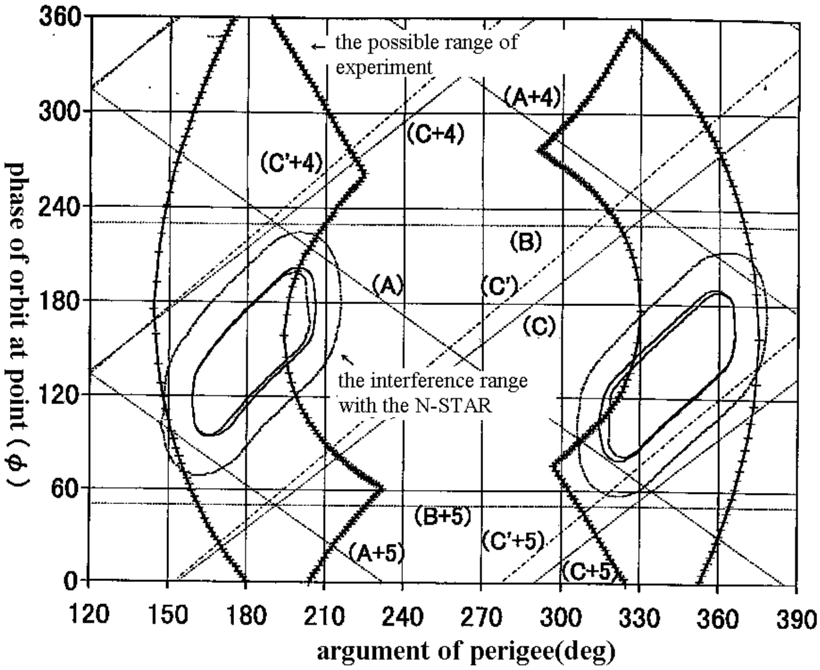

Figure 2 : The major experiment conditions

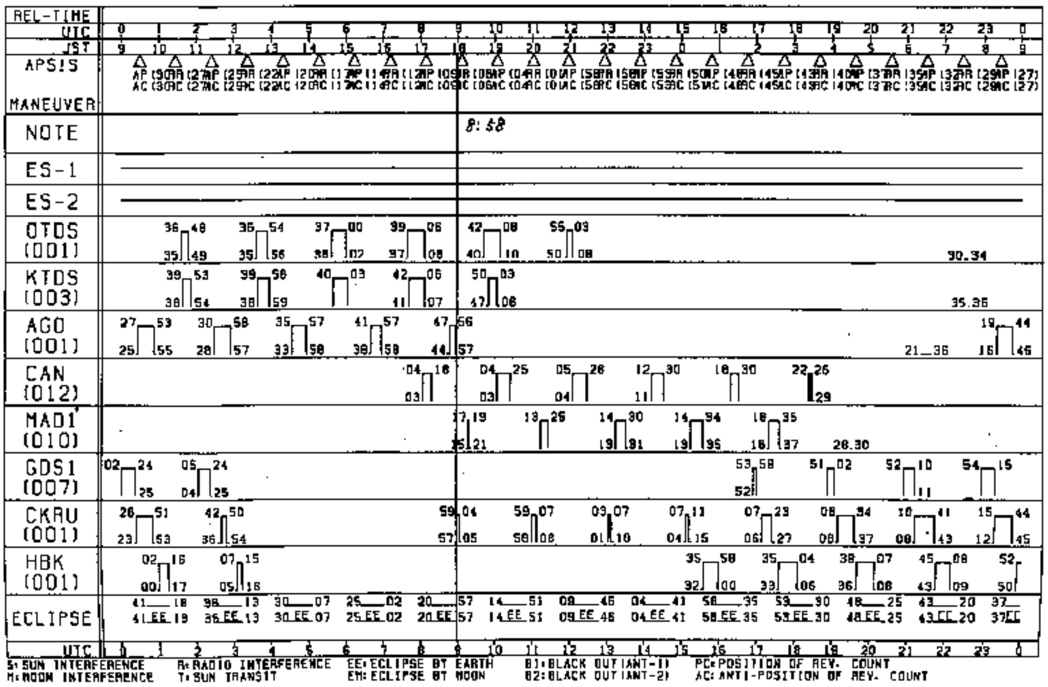

Figure 3 : the visibility at tracking control stations

Finally, in consideration of ranges of radio wave interference with the N-STAR and communications experiments possibility, we examined optimization ϕ-dot for communications experiments. As result, we selected line(C) in this Figure as the semi-major axis. we could adjusted ϕ and ϕ-dot to adjust the semi-major axis until COMETS is put into the target orbit.

We planed the 6th AEF and the 7th AEF to adjust ϕ which is 135 deg. when ω is 120 deg., and ϕ-dot which increase about 1.3 deg. when ω increase 1 deg.

the result of AEF

After we performed the 1st to 3rd AEF, due to trouble in the rate integration gyro for axis control, the 4th AEF was put off from May 11 to May 20.

as mentioned above, when the AEF is put off, the possible period of experiments is advanced. So, we coordinated to turn back ω to delay the possible period of experiments.

Because the AEF was put off, we added and amended conditions follows.

(12)The 4th AEF is performed on May 20.
(13) each AEFs is performed before perigee.
(14) AEF is performed after 4th at intervals of 3 days.

AEF start time was decided based on the visibility from stations. Figure 3 is the visibility from stations that was used to decided start time of 3rd AEF. In this Figure, marks of triangle shows perigees and apogees of the COMETS. rectangle lines shows the AOS and LOS of stations. And we set a station that sent commands of AEF for the COMETS was AGO(Santiago) station. We show a result of the AEF.(See Table.10) In the case of original AEF plan, We would schedule to perform two AEF to put into geostationary orbit . In fact, we performed AEF of seven time. And these was succeeded all.

At that time, it was possible that the COMETS interfere the N-STAR by radio wave, because ϕ wasn't adjusted well. So, we performed some little maneuvers by 1N thruster in June 9 and June 10. Then, we increased the COMETS semi-major axis about 1.3 km. As a result, the COMETS avoided a radio wave interference with N-STAR.

Conclusion

Due to troubles in the second stage rocket, the COMETS was not put into the geostationary orbit. So we planed a target orbit that we can conduct as many experiments on communications as possible.

We completed all maneuvers and put a target orbit. Finally, communications experiment has been enforced from August, 1998.

Reference

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Table.10 : the result of AEF

No.	AEF Name	center time of AEF(UT)	delta-V (m/s)	the altitude of apogee and perigee(km)	mean anormaly (deg)	used fuel (kg)	note
0	initial orbit	-	-	1863.9 / 256.6	-	-	Epoch:1998/3/14
1	1st AEF	98.03.14 16:00:00	39.38	1863.1 / 401.4	170.3	48.2	firing time: 90sec
2	2nd AEF	98.03.19 17:27:20	134.39	2507.2 / 393.3	10.9	162.6	firing time: 300sec
3	3rd AEF	98.05.06 08:58:00	289.40	4028.3 / 435.7	335.9	325.2	firing time: 600sec
4	4th AEF	98.05.20 19:12:00	317.70	6227.2 / 447.2	348.3	323.3	firing time: 600sec
5	5th AEF	98.05.23 18:36:01	353.32	9552.5 / 457.1	352.8	320.9	firing time: 600sec
6	6th AEF	98.05.26 20:23:00	385.49	15188.6 / 463.9	354.5	317.1	firing time: 600sec
7	7th AEF	98.05.29 18:28:30	124.82	17739.2 / 472.4	353.9	93.9	firing time: 178sec
total	-	-	1644.50	-	-	1591.2	2968sec