GEOSTATIONARY SATELLITES LAUNCHED BY NASDA
II. MISSION ANALYSIS FOR MANEUVER

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ABSTRACT

This paper provides analyses, operational criteria and emergency operations related to the attitude and orbit control (maneuver) for Japanese geostationary satellite during from injection into the transfer orbit to the final station based on some actual operation data and our experience. The maneuver mission analysis defines base lines for preparation of maneuver task flow, judging criteria, emergency counter plan, etc.. Some sequential task flows and judging criteria are necessary for actual maneuver planning, preparation of commanding, monitoring and evaluation in order to prevent some confusions and wrong operations on actual mission. These are prepared considering not only nominal case but also off nominal missions including emergency. The topical maneuver data of actual operation on Japanese geostationary satellites are shown.

Keywords: Mission Analysis, Maneuver Task Flow, Operational Criterion, Emergency Operation, Geostationary Satellite

1. INTRODUCTION

The main objective of the mission analysis for maneuver of geostationary satellites is to obtain the optimized sequence of events for orbit and attitude controls (maneuvers) before launch of the satellite against a wide injection error range of the transfer orbit. As a basic tracking and control circumstance, the station coverage in Japan is limited because of localized tracking and control network in comparison with the world wide networks like those of NASA, ESA, etc.. In order to have a better coverage, satellite data are received at NASA STDN when the satellites are out of view from Japanese stations and the data are transmitted to Japan. However, maneuver operations for the satellites have been performed through the ground facilities under Japanese territory. Tsukuba Space Center, the core of the ground facilities, gathers all data and processes them and provides the information required for the maneuver operations.

It is important role of Tsukuba Space Center to make the detailed maneuver plan and set the operational criteria based upon those all data corresponding to the transfer orbit injection errors in the real time operation base. This paper describes several items related to the mission analysis for maneuver.

2. PRE-LAUNCH ANALYSIS

The mission analysis related to the attitude and orbit control for a satellite is generally classified based on the analysis phase as shown below;

- . Mission analysis for the satellite hardware design,
- . Mission analysis for the tracking and control operation.

2.1 Mission analysis for satellite design

The mission analysis for the satellite hardware design is necessary for the spacecraft design, development and manufacture phase. The major tasks are choice of transfer orbit for maximum mission payload, the apogee motor sizing, thrust level choice for auxiliary propulsion subsystem (APS) and APS fuel budget. The variable elements for the transfer orbit shaping are apogee radius, perigee radius, inclination and argument of perigee. Some apogee radii and inclination values are chosen as parametric factor, and searched so as to maximize the spacecraft weight on station under condition of the apogee motor size and useful fuel weight. The APS fuel budget is calculated considering factors of the injection transfer orbit, apogee motor velocity increment, and these errors. An example of the mission analysis items is shown in Table 1.

Table 1. Mission analysis items for the design

1. Launch Window Considerations
2. Transfer Orbit Phase Analysis . Choice of transfer orbit for maximum mission payload . AKM sizing . APS thruster, tank sizing and fuel budget . Satellite visibility and earth trace . TT&C Link budget
3. Drift Orbit Phase Analysis . AMF strategy and error analysis . Station acquisition analysis . Fuel budget

4. On-station Phase Analysis
- . Longitude stationkeeping
- . Latitude stationkeeping
- . Attitude keeping
- . Fuel budget
- . Antenna pointing

2.2 Mission analysis for satellite operation

The mission analysis for the tracking and control of the satellite is a task to be able to implement the satellite operation in order to exhibit its maximum mission performance assuming that the satellite hardware has been fixed. The analysis items and their relations and flow diagram are shown in Fig. 1 and 2.
These details are shown below.

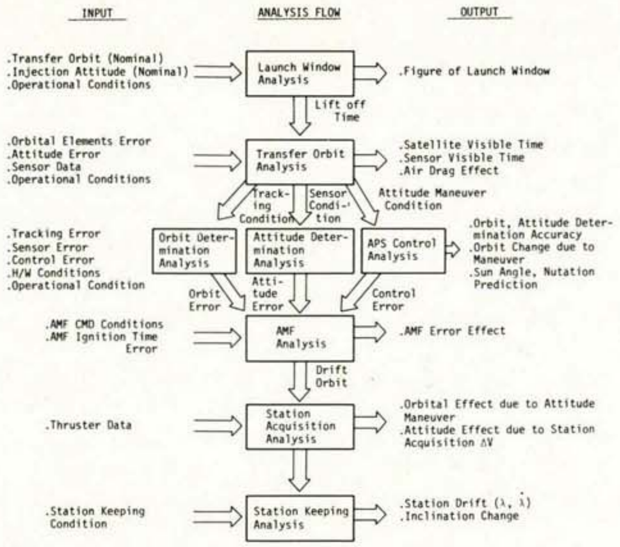

Figure 1. Mission Analysis Flow Diagram

2.2.1 Launch window analysis. Launch window is restricted by the items as follows;
- . transfer orbit errors, especially those of the apogee height (Ha) and the argument of perigee (ω),
- . attitude error at injection,
- . sun angle constraint in both injection and AMF attitude,
- . nodal shift limitation in the AMF planning,
- . duration of the eclipse, and
- . operational conditions of the launch-site.

An example of the launch window analysis is shown in Fig. 3.

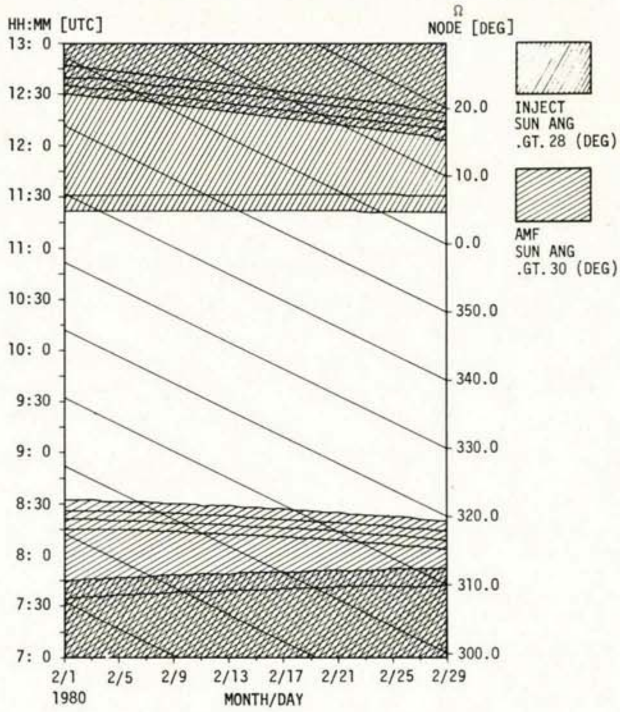

Figure 3. Launch Window (ECS-b)

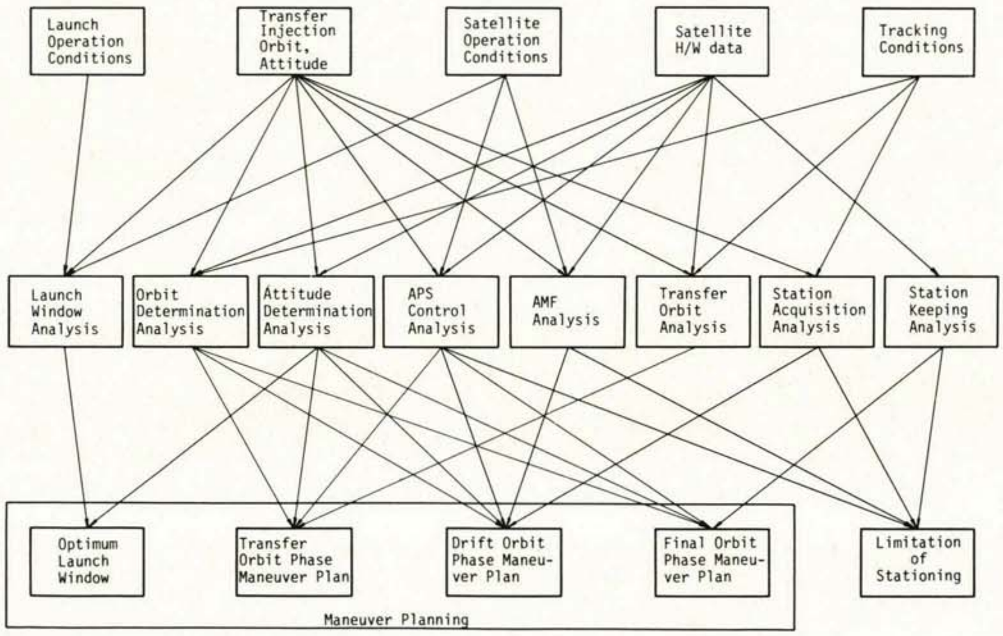

Figure 2. Mission Analysis Correlation Diagram

2.2.2 Orbit determination (OD) analysis. The precision of OD is limited by the noises and biases of the tracking data. For the given satellite and ground-station configurations, OD analysis presents the relation between the OD precision and the acquirable tracking data. For this purpose, not only covariance analysis but also OD simulation is available.

2.2.3 Attitude determination (AD) analysis. For the spin stabilized satellites, AD is performed using the sun angle, earth chord width, and/or dihedral angle data. AD analysis presents the relation between the AD precision and the acquirable sensor data. Geometrical and covariance analyses are performed for this purpose. If necessary, simulation is available using the operational program and sensor data generator.

2.2.4 Auxiliary Propulsion Subsystem (APS) Analysis. For the given APS configuration, proper simulations reveal the following items;

- . minimum controllable velocity increment and precession angle by APS,
- . variation of the orbital elements caused by the reorientation maneuver,
- . variation of the sun angle caused by the reorientation maneuver, and
- . nutation caused by maneuvers.

All results of these analyses are utilized for the reference of monitoring and evaluation of maneuvers.

2.2.5 Apogee Kick Motor (AKM) analysis. The realized drift orbit after AMF is deviated from the planned one because of the error sources as follows:

- . AKM sizing error and booster misalignment,
- . attitude determination error, and
- . AMF timing error.

AMF simulation is performed taking the errors as described above into consideration.

2.2.6 Transfer orbit analysis. The visible time from the ground-station is deviated by the injected transfer orbit error, especially, of the apogee height. Fig. 4 depicts the visible time in the time vs apogee height chart, which is useful to construct the maneuver sequence in the transfer orbit phase. For the spin stabilized satellite, earth sensor coverage must be analyzed taking attitude error into consideration. This result is utilized in the sensor data acquisition planning.

In the transfer phase, attitude change and apogee height descent are caused by the air drag near the perigee. These effects are taken into consideration for the attitude maneuver planning.
Link margin analysis is performed for the telemetry and command communication and ranging data acquisition.

2.2.7 Station acquisition analysis. The station acquisition sequence is seriously affected by the apogee height error of the injected transfer orbit because the station coverage of Japan is localized for the command and control operations.

In order to obtain the operationable AMF apogee, a convenient chart has been developed as shown in Fig. 5, where two coordinate systems are conjuncted to describe the drift orbit realized by the AKM ignition. Notice that drift rate after AMF corresponds almost linearly to the apogee height error. If necessary, Monte Carlo simulation is available to obtain the deviation of the stationing fuel.

2.2.8 Station keeping analysis. East-west, north-south, and attitude keeping analyses are performed to estimate the amount of the fuel necessary for the keeping maneuvers during the required mission duration. East-west station keeping analysis appears in the chart with the coordinate system determined by drift-rate and mean subsatellite longitude as shown in Fig. 6.

For the north-south station keeping analysis, inclination vector is utilized for the prediction of the orbital plane precession caused by the luni-solar perturtation.
Attitude drift is analyzed by the numerical integration of the torque caused by the solar radiation pressure.

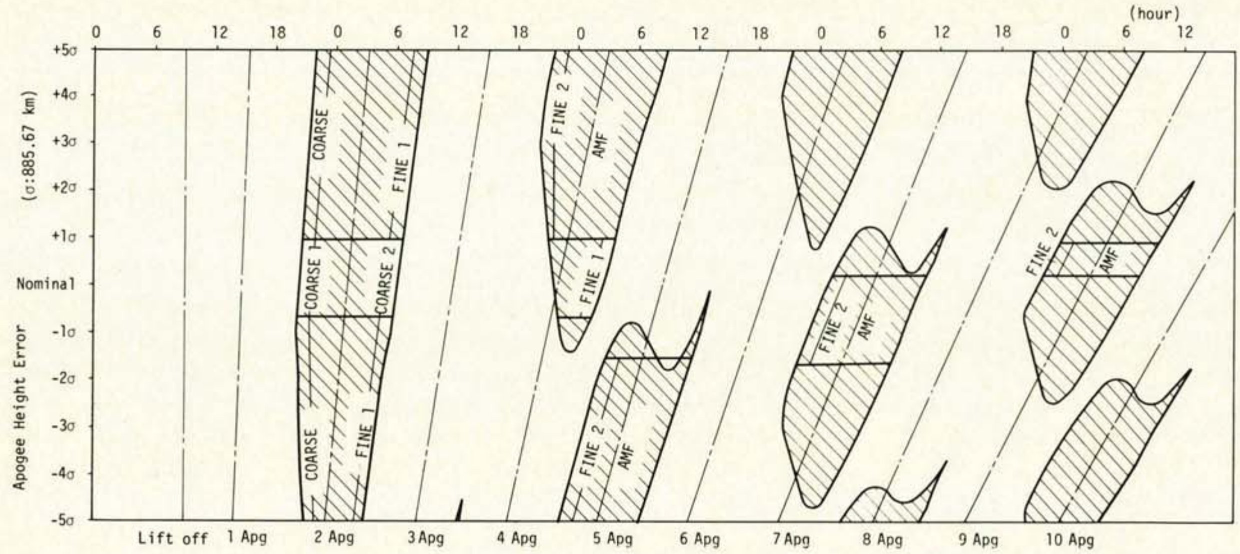

Figure 4. Satellite Visible Time from Japanese Stations (KTDS and MTDS) and Maneuver Plan

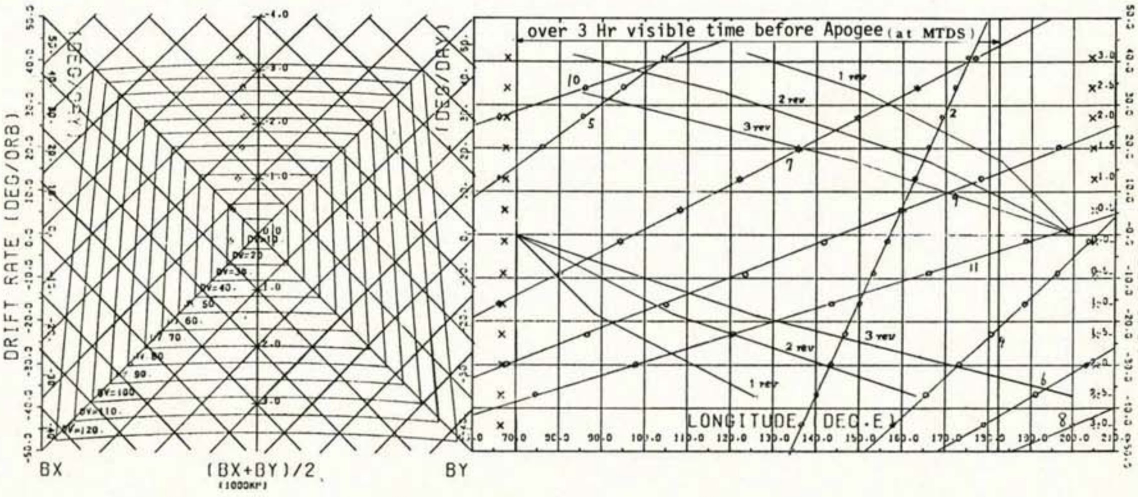

Figure 5. AMF Apogee and Drift Rate (ECS-b)

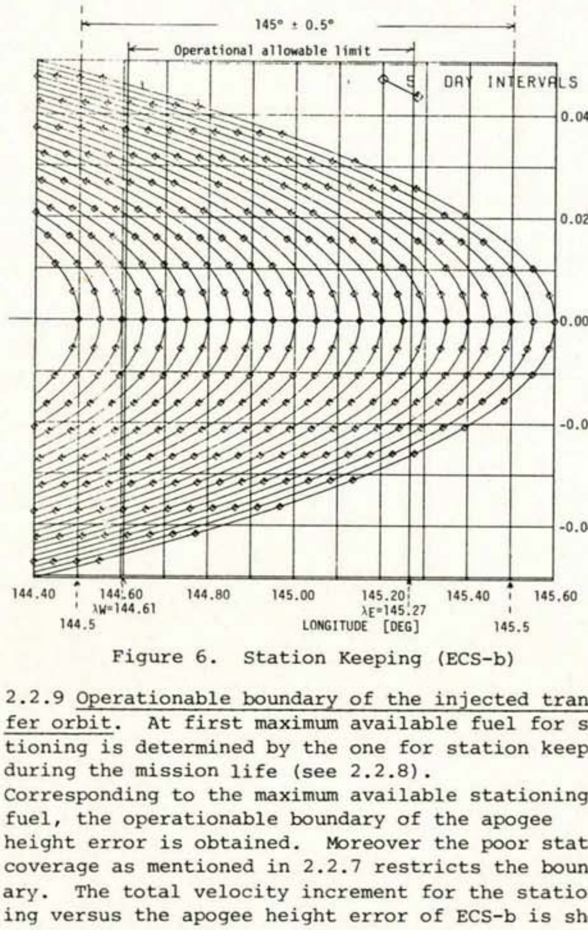

Figure 6. Station Keeping (ECS-b)

2.2.9 Operationable boundary of the injected transfer orbit. At first maximum available fuel for stationing is determined by the one for station keeping during the mission life (see 2.2.8).
Corresponding to the maximum available stationing fuel, the operationable boundary of the apogee height error is obtained. Moreover the poor station coverage as mentioned in 2.2.7 restricts the boundary. The total velocity increment for the stationing versus the apogee height error of ECS-b is shown in Fig. 7 as an example. For the anomalous apogee height error, post-burn sequence is prepared as the emergency counter plan.

2.2.10 Optimum maneuver sequence. All results of the analyses described in the preceeding subsections must be taken into consideration in order to construct the optimum maneuver sequence.
An optimum launch time is determined by the launch window analysis and attitude determination analysis. The optimum maneuver sequence is obtained corresponding to the apogee height error. Then, the following conditions must be noticed;

- sufficient ranging data for the required precision of OD (see 2.2.2),
- sufficient sensor data for the required precision of AD (see 2.2.3), and
- appropriate AMF apogee selection in order to enable the tracking and control operation through the stationing maneuver sequence (see 2.2.7 and 2.2.9).

The detailed description of the maneuver sequence corresponding the apogee height error appears in Fig. 4.

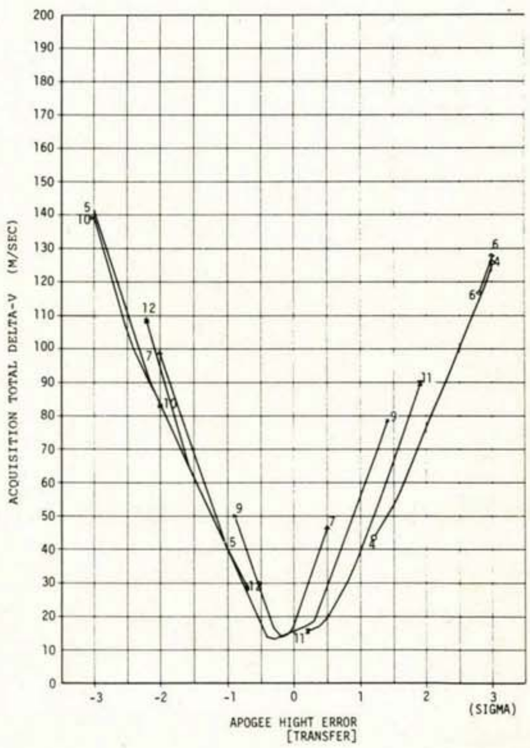

Figure 7. Total Velocity Increment for Stationing (ECS-b)

3. MANEUVER TASK FLOW AND OPERATIONAL CRITERIA

Based on the analysis results for the tracking and control shown in the 2nd chapter, the maneuver task flow and operational criteria to be used in the actual operations are prepared beforehand as a maneuver procedure document. The maneuver task schedule, flow and judging criteria for the maneuver planning, execution, monitoring and evaluation are prepared in order to perform the attitude and orbit control during from the transfer orbit injection to the station acquisition via the apogee motor firing (AMF).
These procedures and criteria are prepared considering not only nominal injection orbit but also off nominal one.

3.1 Total task block

First of all, the satellite visibility times from stations during the transfer orbit are calculated based on the transfer orbit injection errors. The maneuver task blocks which are time zone including the major maneuver tasks during the transfer orbit phase are defined considering the optimum apogee point for the AMF and a series of the attitude controls for the AMF maneuver. Major assumptions to define the task blocks are as follows;

- The command for the attitude control and the AMF should be transmitted during the visible time of Japanese ground stations,
- At least, attitude controls of three times are carried out by the AMF and then the AMF attitude is established, (One coarse maneuver and two fine maneuvers)
- The AMF, including the back up AMF, in the following revolutions should be carried out by the 11th apogee in ECS case, (requirement of the satellite thermal and power design specification)
- The data acquisition, the computation and planning prior to the execution of the related maneuvers for orbit and attitude control are sequentially allocated in the time chart.

As a performed example, a total task block of the transfer orbit for the ECS-b is shown in Fig. 8.
The total task block is divided into five blocks, such as block A to E which are correspondent to the apogee pass number based on the injection error of the launch vehicle.
Each block content is shown below.

Block A: When a satellite is launched from Tanegashima Space Center, the first apogee pass is not visible from the Japanese tracking station.
Then, the satellite check-out and evaluation in injected transfer orbit are carried out with telemetry data and orbital elements acquired by STDN.

Block B: A coarse attitude maneuver is carried out to rotate the spin axis from the injection attitude to the AMF attitude in the first half of the 2nd apogee pass.
A fine attitude maneuver for error correction of the coarse maneuver is executed in the latter half of the pass after the evaluation of the maneuver based on the results of the satellite and orbit determination.

Block C: A coarse attitude maneuver (No. 1) of the injection attitude to anti-orbit normal attitude is performed in the first half of the 2nd apogee pass. In the latter half of the pass, a coarse maneuver (No. 2) to AMF attitude is carried out.

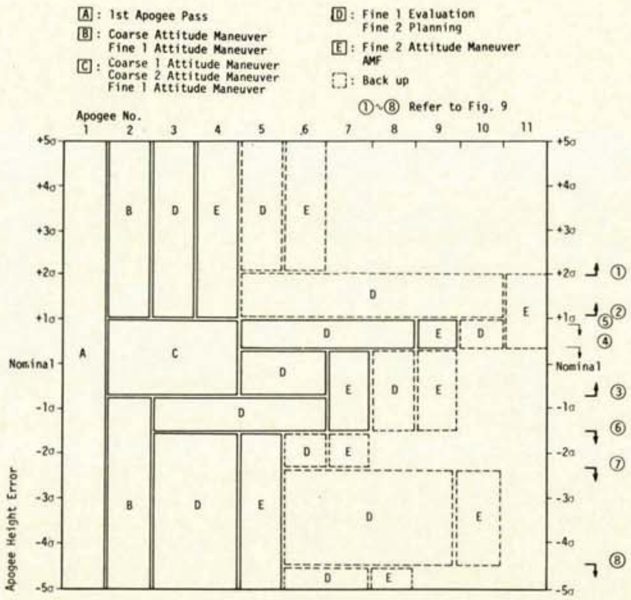

Figure 8. Total Task Block for Transfer Orbit (ECS-b)

The 3rd apogee pass has no maneuver. The fine attitude maneuver (No. 1) is carried out in the latter half of the 4th apogee pass. When the apogee height is nearly nominal, the visible area till the 11th apogee pass has comparatively enough time for the maneuver. Thus, the coarse maneuver is divided into two parts. The maneuver of anti-orbit normal attitude which is intermediate attitude of the injection attitude to the AMF attitude is planned in the case of C block.
In case of the anti-orbit normal attitude, as both earth sensors view always earth, more data for the earth sensor bias estimation will be acquired. Thus, it is expected that the accuracy in attitude determination will be improved.

Block D: The evaluation for the fine attitude maneuver 1 in the latter half of the previous block is carried out based on the orbit and attitude determination results.
The touch up maneuver (fine attitude maneuver No. 2) performed just before AMF is planned based on the final evaluation results.

Block E: This is the task block of the apogee pass selected for the AMF. The touch up maneuver will be carried out in the first half of the pass.
After the AMF attitude is established, the AMF command will be transmitted at the scheduled time near apogee. The blocks shown with broken line in the Fig. 8 are for back up blocks. When the normal AMF is not executed in the E block as a nominal case, the AMF command will be transmitted again in the E block shown with broken line.
As shown in Fig. 8, the back up blocks for AMF are prepared within apogee height error of $\pm 5\sigma$.
Both side lines of each block shown in Fig. 7 are separated with the each apogee pass of task contents.
The lines shown in Fig. 8, ①~⑧ are defined based on the visible time by the apogee height error, longitude of subsatellite point at apogee and visible time after AMF.

The bases of the definition are shown in Fig. 9 as criteria for the AMF apogee choice.
Japanese stations (Katsura and Masuda) visible area which is a basis for classification of each block are shown in Fig. 4.

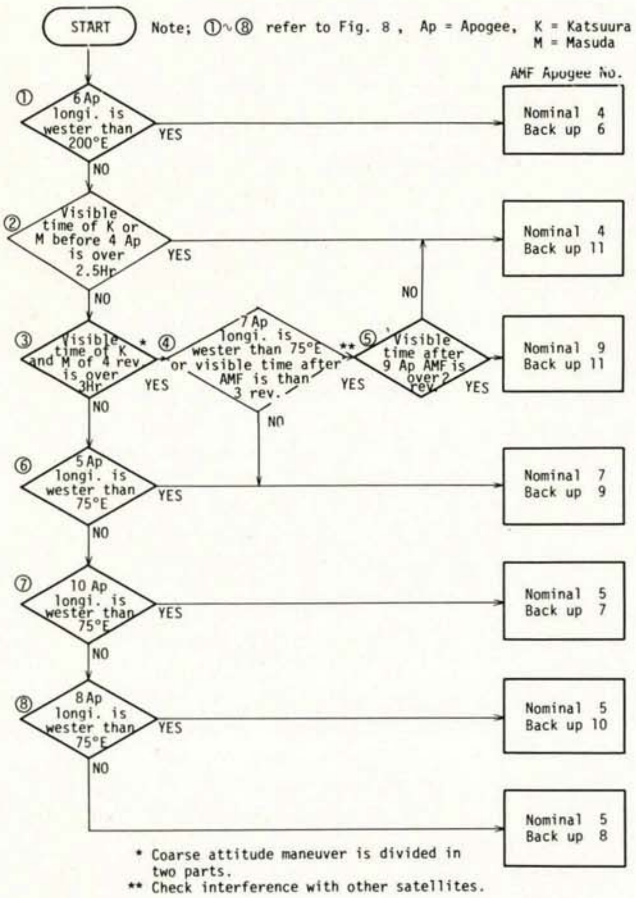

Figure 9. Criteria for AMF Apogee Choice (ECS-b)

3.2 Task flow

Task flow and judgement criteria flow for each block are prepared based on the classification of the total task block. In the summary chart of the each block, major events, maneuver judgement criteria flow name related to each time, based on apogee point are arranged sequentially so as to easily to understand the total task of the block. By using the total task flow for each block, maneuver operator can understand each maneuver task procedure and time relationship for each event .

3.3 Detail task flow

Following the block total task flow, detail task flow and judgement criteria flow for each maneuver plan, evaluation and monitor, necessary flow diagram, table, log paper and reports, are prepared as one package in each mission.
These detail task flow and judgement flow are prepared for not only nominal cases but also off nominal cases of the satellite, orbit and attitude according to the past actual operation and mission analysis experiences and also considering a lot of emergency cases.
Total task flow and detail task flow which was used in the ECS-b actual operation are shown in Fig. 10 and 11.

4. MANEUVER PLANS FOR EMERGENCIES

In order to get a higher mission success, the emergencies must be resolved as much as possible. We prepared some counterplans for the maneuver emergency including the satellite hardware trouble based on the mission analysis results and our experience of the past actual tracking and control mission. The maneuver plans for emergencies are prepared in order to prevent some confusions and wrong operations on actual mission. These counterplans for emergencies are shown below.

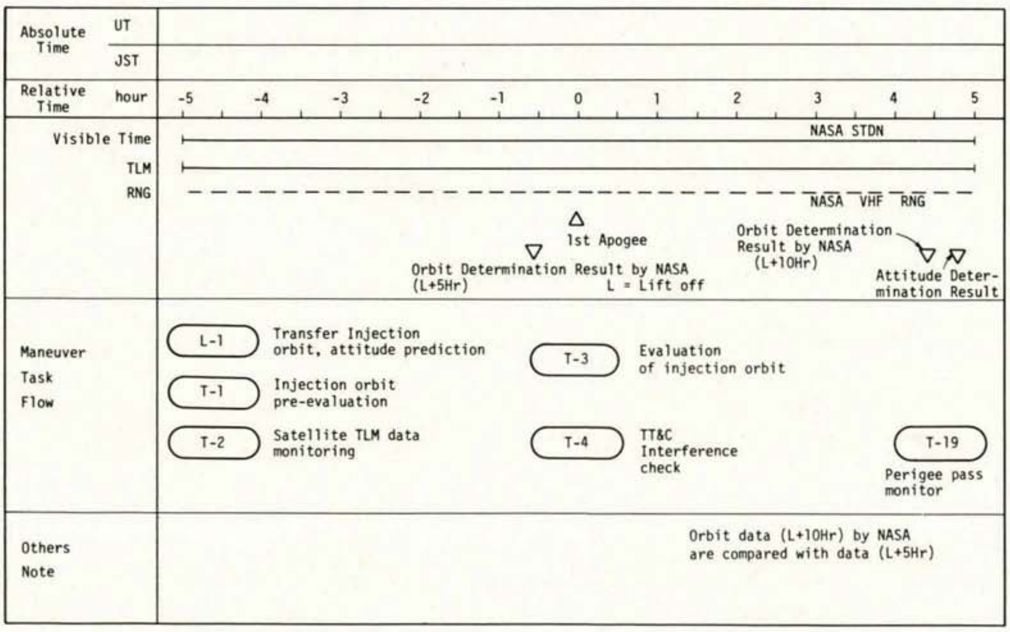

Figure 10. Task Flow for Block A (ECS-b)

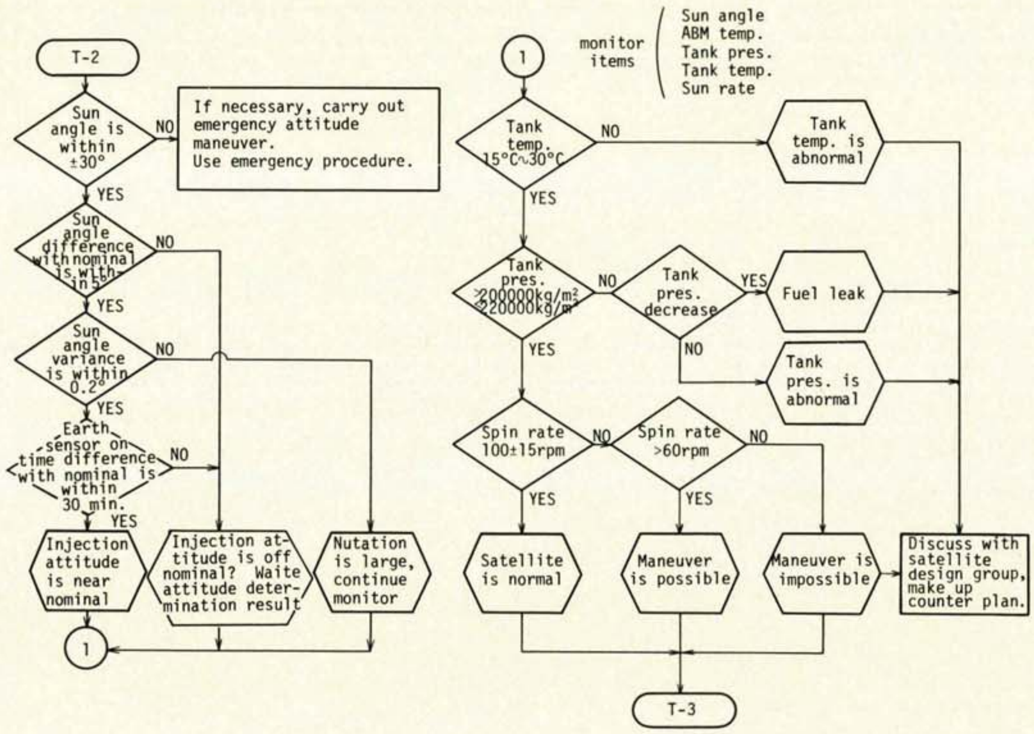

Figure 11. Monitoring of Satellite TLM data on Maneuver

4.1 Launch vehicle injection condition

(1) A case that the perigee height of the transfer orbit is less than 170 Km.

When the final perigee height will be decreased less than 150 Km by the effect of the coarse attitude maneuver from the injection attitude to the AMF attitude, judging from the attitude change and thermal condition by the air drag near perigee, perigee up maneuver will be necessary.

Counter plan: The coarse maneuver should be performed near apogee so as to get a perigee up.
In case of lack of perigee up magnitude, perigee up maneuver with orbit normal attitude will be performed or, AMF will be carried out at 2nd apogee.

There are some possibilities that we could not obtain final orbit, even though counter plan is performed.

(2) Emergency that Sun angle at injection attitude is without ±30 deg.

From condition of the power generated by solar cell and the thermal, Sun angle of the injection attitude shall be kept within ±30° deg.

Counter plan: Emergency attitude maneuver shall be performed to realize within ±30 degree of sun angle.

(3) Emergency on the satellite spin rate of injection.

Generally, the spin rate by the launch vehicle is within nominal ±10%.
There is some cases that the spin rate is deviated over 10% by the launch vehicle trouble.

Counter plan: When the space craft has no spin rate control system, we have to confirm whether the attitude maneuver could be performed with the abnormal spin rate.

4.2 Subsystem emergency on the maneuver

(1) No change of the chamber temp. after maneuver

Even though the maneuver command was transmitted, when the change of sun angle, tank pressure, and orbit were not recognized, clearly, we can predict that the thruster didn't work.
But, only when the change of chamber temperature are not recognized, some trouble in the thermister is predicted.

Counter plan: Naturally, another thruster will be used.

(2) Tank pressure decrease continuously after maneuver

When sun angle change and chamber temp. change are observed, we can predict the thruster leak, but note a trouble of pressure sensor only.

Counter plan: Each thruster shall be jetted a few pulses, because of considering trouble of thruster valve.
In case of tank pressure trouble, prediction values of tank pressure will be used.

(3) Sun angle change during maneuver is over the predicted zone.

Before the attitude maneuver execution, we calculate a prediction of the sun angle change by the maneuver and prepare the change prediction curve with some deviation width due to jet timing error and efficiency.

When monitoring the sun angle change during the maneuver, if the observed curve exceeds the predicted criterion, we should consider that the maneuver is abnormal and stop the maneuver, and examine the cause of the trouble.

Counter plan: When the change curve exceeds the prediction zone of 3 delay counts as a jet timing error, the maneuver should be stopped. We have to evaluate and examine the cause after getting the attitude determination results.
determination results.
If the causes are found in an area of the jet timing trouble or efficiency trouble (calibration data trouble, thruster hardware trouble), the another thruster will be used.
There is a case that the maneuver will be performed by only correction of efficiency factor of maneuver command generation program.
In case of the attachment misalignment, compensation of the misalignment on the program are necessary.

(4) Emergency on spin rate change by the maneuver

The spin rate change is over the predicted one and when the satellite spin rate will exceed its allowable limit during life time, the maneuver is stopped and the cause is examined.

Counter plan: In the case of the cause on the thruster misalignment, another thruster will be used so as not to exceed allowable spin rate limit at end of life.

(5) Sun sensor trouble

When a sun sensor necessary for the attitude control and monitor does not work, we have to take the following counter plan;

Counter plan: As a general rule, another sensor will be used.
In case of trouble of both sensors, reference pulse for the control is generated by earth sensor.

(6) Earth sensor trouble

In case of a trouble of the earth sensor which is necessary for the attitude determination, if both sensors are getting in trouble, we could not keep the mission, but in case of a trouble one sensor, attitude determination is possible by using the other sensor so that we can perform the maneuver.

(7) Apogee motor trouble

When the apogee motor is not ignited during the AMF window, apogee motor ignition will be tried again at the back up apogee.
In case that trouble happens just after apogee motor ignition, Doppler frequency change measurement around that time is important as a methods for examination of the cause. If doppler frequency shift around AMF is measured by three or more ground stations simultaneously, the acquired data could contribute something on the fault analysis.
In case that the apogee motor thrust level is insufficiency, APS could support its shortage.

4.3 Ground station trouble

(1) Ranging impossible

Changing redundancy transponder (for example, VHF, S and C band, we have to examine the available band.

(2) Japanese ground station trouble

Two stations data are necessary for the transfer orbit determination.
Then if one station is getting in a trouble, STDN data will be requested for orbit determination.

(3) TACC (Tracking and Control Center, Tsukuba Space Center) trouble

In case of off line system trouble, we have to wait for recovery of TACC, but if quick response will be necessary to get the results, we could perform the maneuver calculation by using electronic calculator.

5. PERFORMED MANEUVER DATA

The performed maneuver data of the spin stabilized satellites (ETS-II, CS, ECS and ECS-b) of Japanese geostationary satellite are shown below.
Some topics including emergency counter plan related to some maneuver for the transfer orbit and stationing are described.

5.1 Transfer and drift orbit

First, the maneuver comparisons of four satellites from the transfer orbit to stationing are shown in Table 2.

The visibility condition and maneuver events on ECS-b in the transfer orbit phase are shown in Fig. 12, and the station acquisition sequences of ETS-II and CS which had obtained successfully stationing are shown in Fig. 13 and Fig. 14.
The transfer injection errors for the above satellites were within about $\pm 1\sigma$, which were good results.

5.2 ECS topics

Even though a sufficient preparation had been performed against wide range problems which might be happened, it would be difficult to find out a case that one of the assumed situation meets the actual one, especially in contingency case.
Therefore, the preparation shall include not only documents, but also all resources, such as, persons who know the satellite, spare hardwares in the ground, the satellite inherent data, etc..
An actual operation for the orbit injection should utilize those available resources as much as possible. The following example is our activities taken in ECS contingency case.

• Spin rate off nominal contingency

After the nominal separation between the third stage and the satellite, the former came into collision with the latter as the result, the spin rate had changed nominal 100 rpm to 60 rpm and a partial damage was given to the satellite.

Unexpected information was acquired in the ground, however, the satellite situation was judged correctly based upon interpretations of the acquired data and results of some trials, on which the partial damaged satellite was conducted to be transmitted the correct AMF command. The following are

Table 2. Maneuver Comparison from Transfer Orbit to Stationing

Items \ Satellites	ETS-II (KIKU-2)		CS (SAKURA)		ECS (AYAME)		ECS-b (AYAME-2)	
Lift off Time (UT)	1977-2-23 8:50:00.8		1977-12-15 00:47:03		1979-2-6 8:46:00.7		1980-2-22 8:35:00·7	
Launch Vehicle	N-I		DELTA 2914		N-I		N-I	
Transfer Injection Orbit	Actual	Nominal	Actual	Nominal	Actual	Nominal	Actual	Nominal
Epoch (UT)	1977-2-23 9:13:50	1977-2-23 9:13:40	1977-12-15 01:00:40	1977-12-15 01:00:40.5	1979-2-6 09:10:00	1979-2-6 09:09:54	1980-2-22 8:53:53.6	1980-2-22 08:58:53.6
a km	24355.417	24690.9	24377.129	24523.981	23768.884	24277.37	24304.365	24277.37
e	0.730088	0.733942	0.731480	0.733123	0.723608	0.729418	0.729179	0.729418
i deg.	23.912	24.065	28.816	28.780	24.088	24.4096	24.515	24.4096
Ω deg.	323.827	324.41	274.773	272.289	304.819	304.668	317.612	317.445
ω deg.	175.937	176.86	178.891	178.797	179.034	178.740	178.474	178.740
M deg.	359.721	359.61	357.479	0.238	359.578	359.588	356.660	359.588
Ha km	35758.9	36434.4	35830.369	36124.934	34590.096	35607.579	35648.456	35607.579
Hp km	195.7	191.1	167.605	166.744	191.387	190.877	203.990	190.877
Transfer Injection Error Apogee Height Error Km	-675.5 (-0.77σ)		-294.565 (-0.98σ)		-1009.697 (-1.14σ)		+91.98 (+0.10σ)	
Times of Attitude Maneuver for AMF	3		3		4		4	
AMF Apogee	7		3		7		7	
Stationing Days from Lift off	about 10 days		about 9 days		—		—	
Final Station	130°E		135°E		—		—	
Keeping Longi.	±0.5°		±0.1°		—		—	
Lati.	±1.0°		±0.1°		—		—	

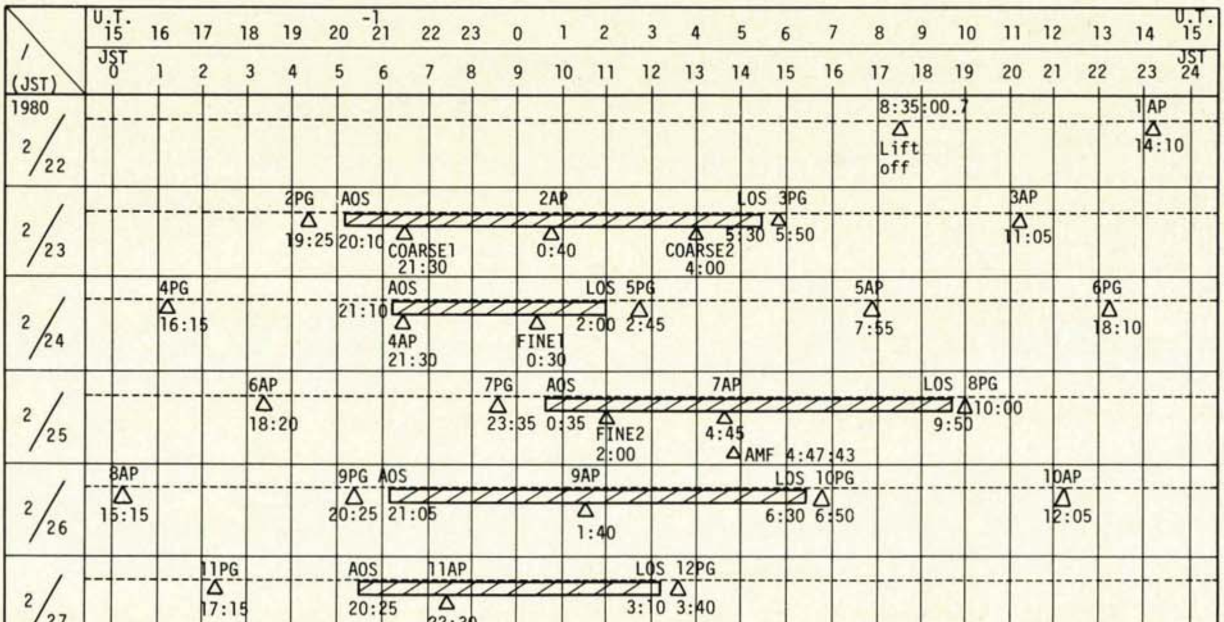

Figure 12. Transfer Orbit Maneuver Plan (ECS-b)

a summary of the disposed process of this contingency.

The spacecraft telemetry could not inform such low spin rate because of less than the lower limit of the hardware specification, and no test data was acquired in this region.

Satellite hardware team suggested that the actual spin rate was 60.4 rpm considering overflow mechanism of the spin rate register, the ground receiver AGC data told 60.4 rpm or 120.8 rpm according to the spin ripple. Assuming 60.4 rpm of the spin

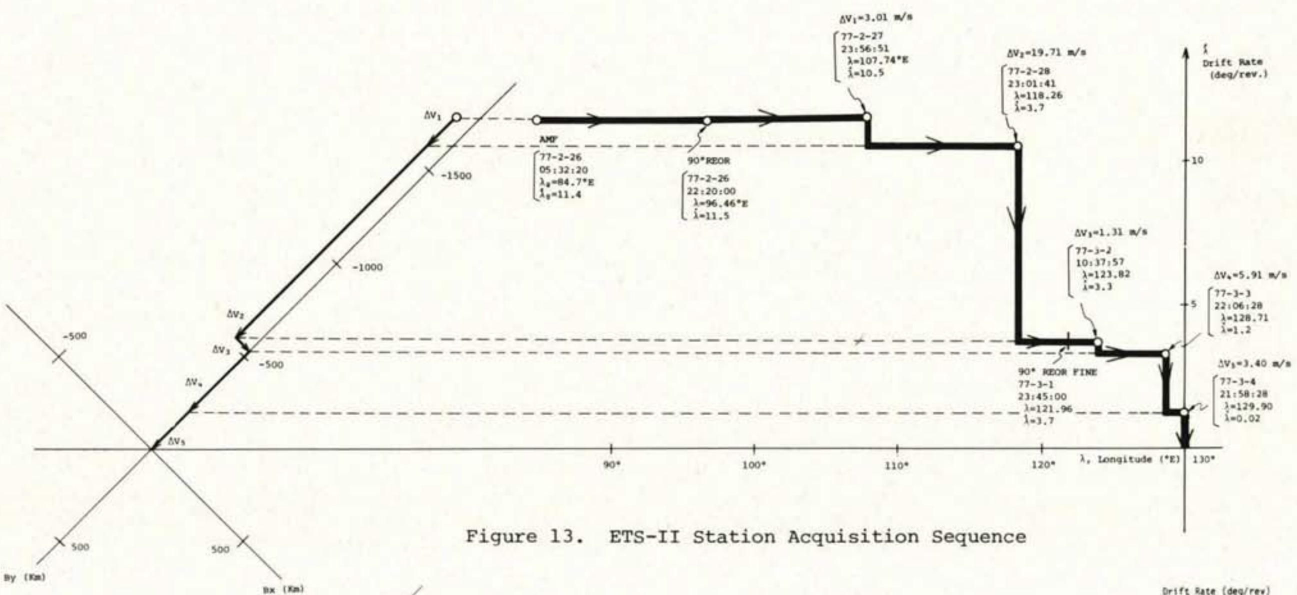

Figure 13. ETS-II Station Acquisition Sequence

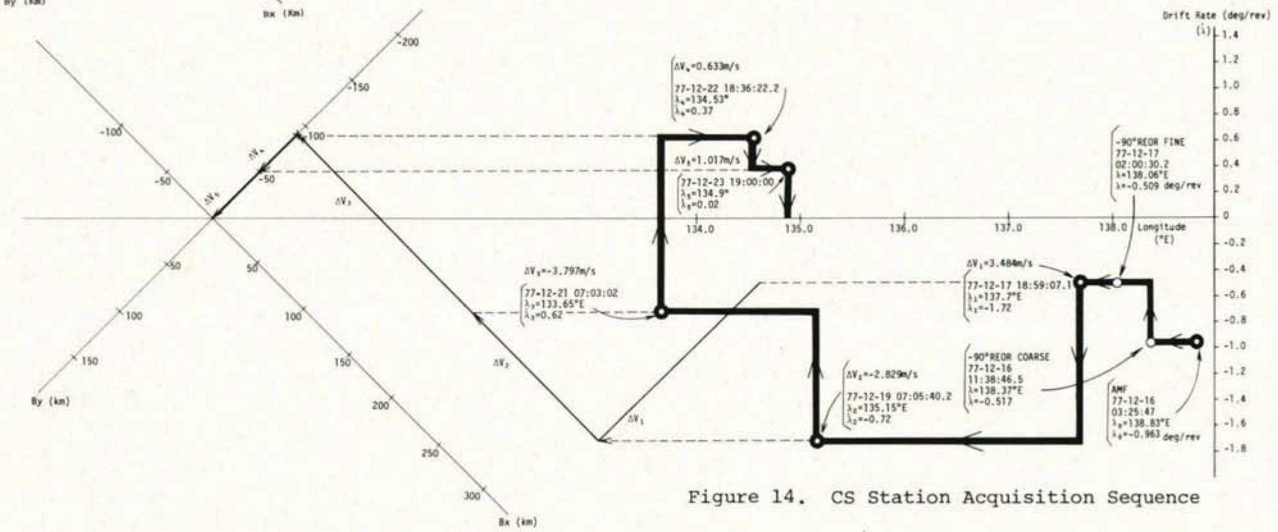

Figure 14. CS Station Acquisition Sequence

rate, an injected attitude was calculated, and predicted to deviate from the nominal one. The observed acquisition time of the earth sensor data was almost coincident with the predicted time. Those activities was performed during the 1st revolution of NASA visible zone. A test maneuver was planned to confirm whether the assumption of 60.4 rpm was correct or not by actual dynamic movement of the satellite in the 1st Japanese visible region.

The fact acquired by the test proved that the assumption above was correct. Based upon the confirmed spin rate, all attitude maneuver had been successfully performed and a correct AMF were attained.

6. CONCLUSION

NASDA had launched six geostationary satellites, four of which were successfully stationed, and normal operation on the final orbit has been carried out.
Methods of the mission analysis for the tracking and control have been established, and the maneuver procedure documents including contingency counterplan have been also prepared. Many ground facility and operational programs shown in the paper I (NASDA Tracking and Control System) are necessary for the maneuver. In order to operate effectively these facilities and satellites, it is indispensable to prepare documents like hand books including the operational procedure and judging criteria on the maneuver tasks.

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8. REFERENCES

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