NASDA'S OPERATIONAL ORBIT COMPUTATION SYSTEM FOR LATE 80's

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1. INTRODUCTION

One of main activities of NASDA (National Space Development Agency of Japan) is to perform orbit determinations for artificial earth orbiting satellites launched by NASDA itself and ISAS (The Institute of Space and Astronautical Science). NASDA has developed a new operational orbit computation system in order to apply to satellites operated during the latter half of 80's. The development especially took as its target relatively low earth orbiting satellites used for earth observation like the Marine Observation Satellite (MOS-1) expected to be launched early in 1987. This is the difference from the old system developed mainly for the geosynchronous missions, that had been operated for almost 10 years since 1975 till March 1986. The objective of the development was to improve processing capability by introducing semi-automatic processing function as well as the system accuracy. We report here a general survey of its functions and the system's development procedures.

2. TRACKING NETWORK OF NASDA

The tracking network of NASDA consists of TACC (Tracking And Control Center) and TDSs (Tracking and Data acquisition Station). TACC performs the tracking data collection from TDSs, orbit determination, orbital events generation, orbit prediction data generation, and their transmission to TDSs. TACC is located at Tsukuba in Ibaragi prefecture. TDSs perform the tracking of the objective satellite by using the orbit prediction data obtained from TACC and send acquired tracking and telemetry data to TACC. TDSs are located at Katsuura in Chiba pref., Masuda in Tanegashima Island, and Okinawa respectively. In addition, KSC (Kagoshima Space Center) of ISAS, located at Uchinoura in Kagoshima pref., joins as a component of the network for the satellites of ISAS itself. NASDA receives support from NASA DSN (Deep Space Network) during the transfer orbit phase of geosynchronous satellite.
Figure 1 shows the tracking network of NASDA.

3. NASDA ORBIT COMPUTATION SYSTEM (NOCS)

The system consists of two large groups of subsystems, orbital data processing programs and environment and operations control subsystems. Orbital data processing programs perform
- Tracking data gathering and distribution,
- Tracking data pre-processing,
- Precise orbit determination,
- Prediction data generation for antenna acquisition, and
- Orbital ephemeris and events generation for users.

Environment and operation control subsystems consist of the following.
- System environment management.
- Operation control and supervising.

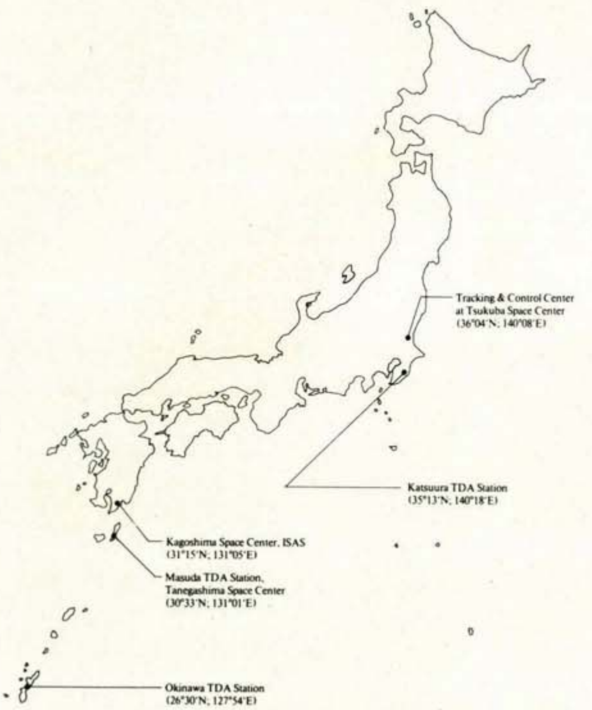

Figure 1. Tracking Network of NASDA

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The objectives of the whole system are as follows.
-Unified management of the system database and files.
-Semi-automatic routine operation.
System data flow is depicted in figure 2.

3.1 Orbital Data Processing Programs

The functional structure tree of orbital data processing programs is shown in figure 3. Their general functional descriptions are as follows.

3.1.1 Tracking data gathering program supervises the tracking data communication network, receives tracking data from TDSs, checks their format, and stores them in the tracking data file for pre-processing. It sends to TDSs prediction data consisting of antenna acquisition data and other orbital events information, and supplies the outside organizations with information such as mean orbital elements, satellite ephemeris data, etc. .

3.1.2 Tracking data pre-processing program performs data quality and status check, statistical inspection, and compression. The tracking data are transformed to the mathematical units according to their data types. The statistical data inspection is performed by using the Chebyshev polynomials and each datum with deviation greater than an assigned value depending on its type is considered anomalous are rejected. Moreover, data are compressed according to an assigned blocking parameter. The inspected and compressed data together with their standard deviation value are stored into the observation data file used by precise orbit determination program.

3.1.3 Precise orbit determination program chronologically merges and sorts the pre-processed tracking data. It generates the satellite trajectory by using special perturbations method that takes into consideration non-spherical effect of earth gravitation, tidal effect, luni-solar gravitation, air drag, and solar radiation pressure. Gravitational model such as GEM10B is selective according to its control parameter of the database. Air density model (Jaccia-Nicolet, Harris-Priester, or Jaccia-Roberts), air drag model (board, spin stabilized, or three-axis stabilized), and solar radiation pressure model (ibid.) can be chosen man-machine interactively through the display unit. The Baysean weighted least mean squares method is applied for the statistical estimation. Corrected orbital elements with corresponding covariance matrices are stored into the element file to be used by other programs or for other trajectory determinations that follow. Batch sequential

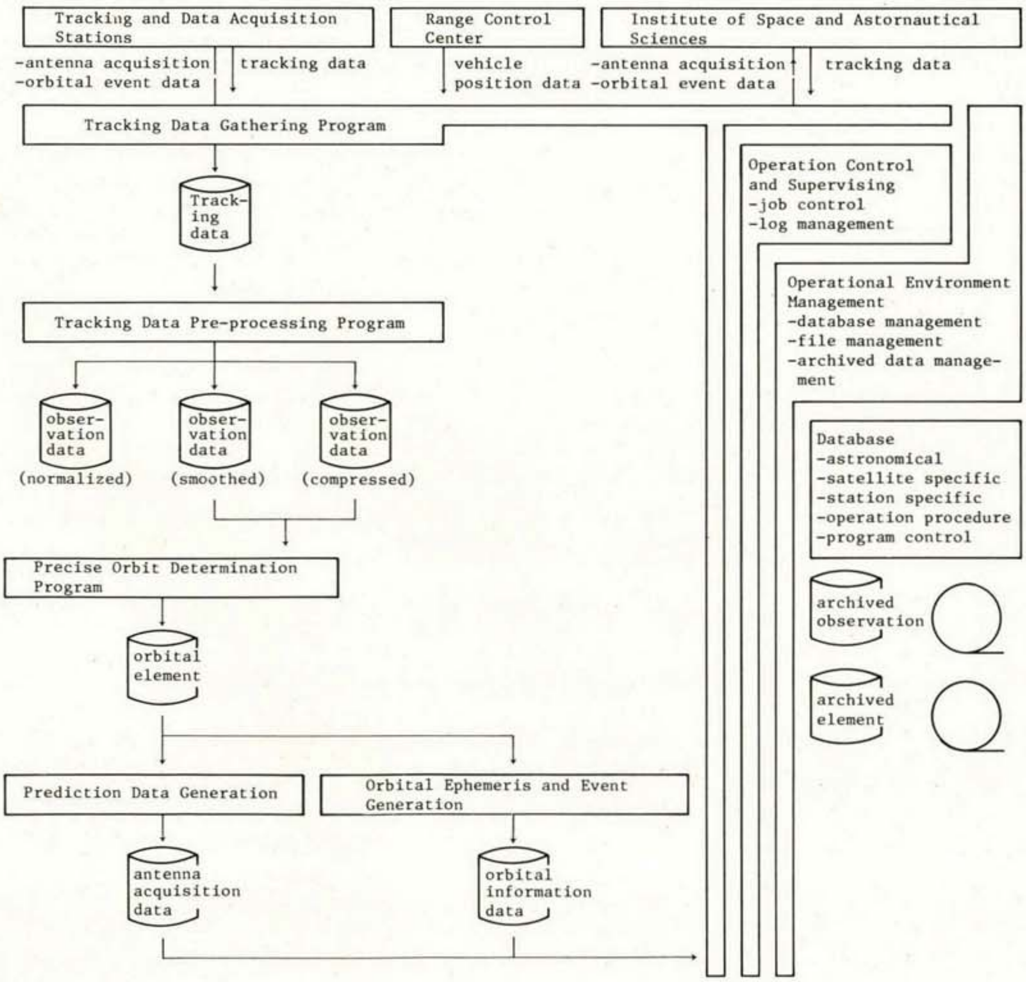

Figure 2. Data Flow of NOCS

estimation is possible taking appropriate process noise parameters into consideration.
Observation model takes the light time equation, tropo- and iono-spheric refraction, data biases, and station position deviations into consideration. Estimation parameters are orbital elements including dynamic parameters such as air density correction coefficient, solar radiation correction coefficient, data biases, and station positions. Moreover, early orbit determination using improved Harget method for angle and/or range data is available for dealing with an unknown trajectory. Evaluation as well as analysis of obtained orbital elements can be performed through comparison of any trajectory pair that are generated by general and/or special perturbations methods respectively.

3.1.4 Orbital prediction data generation program generates satellite trajectory, station events like AOS (Acquisition of Signal), LOS (Loss Of Signal), and antenna acquisition data for TDSs. Trajectory generation is performed by the special perturbations method and obtained back points and ordinate sums of Cowell integrator are stored directly into the satellite ephemeris file, which are retrieved and interpolated when orbital elements of an epoch are necessary. The station events are searched stepwisely and their precise times are searched by Newton-Raphson's method. Obtained events are then stored into the station event file which can be retrieved by specifying the date and the station name when necessary. The antenna acquisition data include station events and chronological sequence of azimuths/elevations, gimbal angles (X-Y), slant ranges and their rates. The generated data are stored into file for transmission to TDSs by the tracking data gathering program.

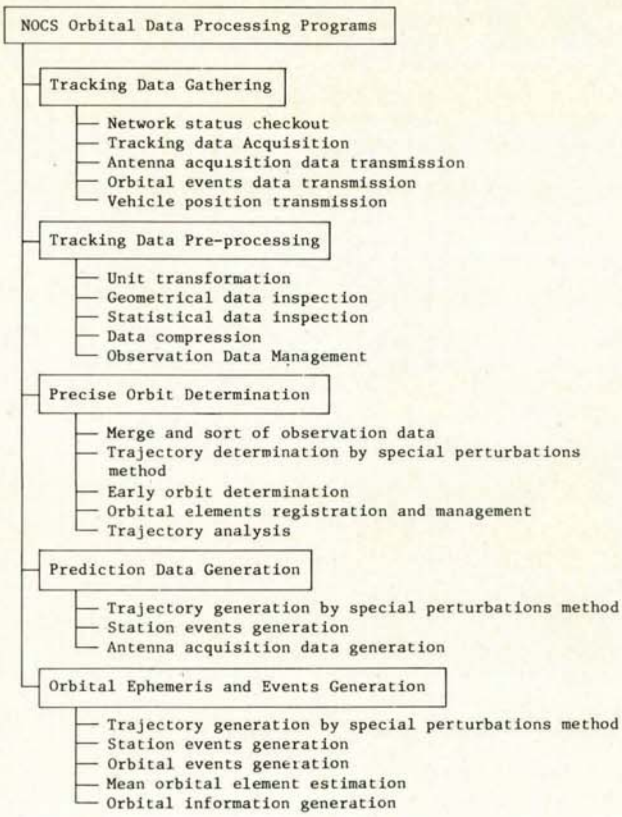

Figure 3. Functional Structure of Orbital Data Processing Programs

3.1.5 Orbital ephemeris and events generation program generates orbital events such as ascending/descending points, northern/southern most points, eclipses of earth/moon, ground track data, station events such as AOS/LOS, maximal elevations and uplink inhibited zone events. Orbital events are at first calculated roughly from appropriate mean elements, and thereafter precise times are searched by Newton-Raphson's method. Obtained orbital events are stored into the orbital events file to be retrieved when necessary.
This program also calculates the mean orbital elements with the numerical averaging method by which mean orbital elements and their time derivatives are estimated so as to minimize the mean square of Cartesian distances between the trajectories generated by the special and the general perturbations methods. The obtained mean elements and their time derivatives are served for outside users such as ISAS.

3.2 System Environment Management and Operation Control

The functional structure tree of system environment management and operation control subsystems are shown in figure 4 and their general functional descriptions are as follows.

3.2.1 System environment management subsystem generates and maintains the database necessary for orbit computation. This database is of a relational type and consists of astronomical constants, satellite and tracking station specific constants, program execution control parameters, and operation logs. It is read and utilized by subsystems and programs that perform initial setup and control execution.
The operational environment management subsystem also generates, initiates and maintains all NOCS files. If necessary, any file is referenced through display unit. The subsystem provides an important tool for the effective maintenance of the total system. This subsystem can also retrieve and recover observation data and element data in case of file breakdown.

3.2.2 Operations control and supervising subsystem provides key operational functions of the system and enables multi-satellite orbit computation operations. It controls semi-automatically cycles of routine work such as tracking data gathering, pre-processing of data, precise orbit determination, orbit prediction data generation and their

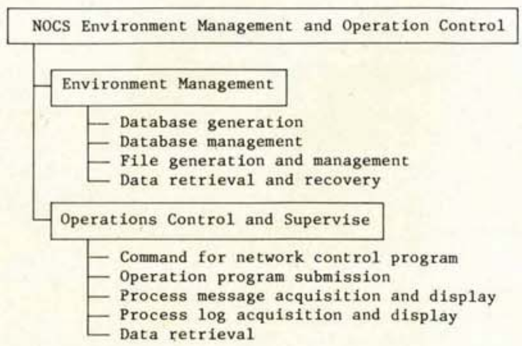

Figure 4. Functional Structure of Environment Management and Operation Control

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NOCS  <<処理経過画面>>  *** NOPCON ***     (V01/L20)          86-09-22
                                                                17:19
入力欄==>
メッセージ: 操作指令を入力してください。
.............................................................................

86-09-03
09:39:40 NTRAD3 37 TENMA         GENERATION END                        2100
09:39:40 NTRAD3 37 TENMA         PREDICTION START
09:41:50 NUSSUP 39 TENMA         PROGRAM START (EDIT MODE)
09:42:18 NUSSUP 39 TENMA         PRE-CHECK END                         1100
09:42:19 NUSSUP 39 TENMA         ELEMENT EDIT START
09:45:21 NTRAD3 38 OHZORA        GENERATION END                        2100
09:45:22 NTRAD3 38 OHZORA        PREDICTION START
09:47:37 NTRAD3 37 TENMA         PREDICTION END                        3200
09:47:46 NTRAD3 37 TENMA         PROGRAM END                           3200
09:52:28 NTRAD3 38 OHZORA        PREDICTION END                        3200
09:52:34 NTRAD3 38 OHZORA        PROGRAM END                           3200
10:07:06 NUSSUP 39 TENMA         ELEMENT EDIT END                      2200
10:07:13 NUSSUP 39 TENMA         PROGRAM END    (EDIT MODE)            2200
10:58:06 NTRNET 35 OHZORA        TRK DELAY       (KSC ) 860902-11(36)  0000
10:58:10 NTRAD1 36 OHZORA        860902-11(36) (KSC ) R                0000
10:58:12 NTRAD1 36 OHZORA        860902-11(36) (KSC ) AZEL             0000
14:49:08 NTRNET 35               (END ) COMMAND ACCEPTED
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Figure 5. Display Image of the Operation Control Program

transmission to TDSs. The operation procedures and program control parameters are automatically read from database and programs operate as if the control parameters are set man-machine interactively. The operation messages and logs are obtained and can be seen at the operator's display console. An example of the display image and operation concept is shown in figure 5.

3.3.3 Man-machine interactive operation is necessary in the satellite launch phase and in emergency cases. Operational programs can be run independently through graphic display units or console displays according to decision criteria prepared beforehand. Graphic support includes the visualization of orbit information such as trajectory O-C values, ground track data display superposed on the world map, azimuth-elevation display etc..

4. SYSTEM DEVELOPMENT AND TESTING

NASDA started its preliminary design late in 1982 which defined the concepts and the basic structure of the system. Subsequently, the precise specifications of the system such as mathematical models, method of operation, external interface conditions and structure of each module of the system were defined in 1983. Based upon these specifications, the development and testing were performed from 1984 through 1985. The final step of the testing was system integration, and through integration testing, the operational system was built up and not only its functions but system data such as constructed database and files were also verified. Finally, the system was released for operation from April 1986. Throughout the software cycle, the configuration management has been conducted for the specifications of the system including mathematical models, the documents which define the testing and the program product itself. As the basic methodology, top-down and bottom-up policies were adopted for system development and testing respectively. The development phases and schedule are shown in figure 6.

4.1 Preliminary Design

At first analysis was done to clarify the operational requirements for the system.
Compatibility with the old system named SCOP (Spacecraft Orbit Operation Program) was partially taken into consideration. But major part of 'operation image' was renewed because the old system could not process in the multi-satellite orbit determination mode. To lighten the load on operators, concept of operation control and supervising was introduced. New concepts on database and file management were also introduced such as relational database and virtual storage access method.
To satisfy the functional requirements, a prototype orbit simulator was developed. This simulator was used to analyse the precision of some candidates

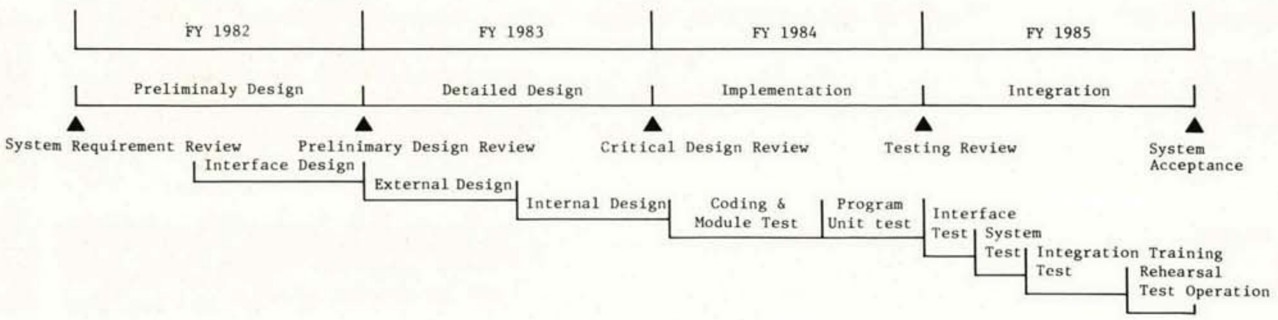

Figure 6. Phase and Schedule of the System Development

for integration methods and force models. According to these results, the algorithm breakdown structure which categorized all mathematical algorithms into relatively independent subgroups, was defined for designing the package library. Tracking and orbit data interface conditions were also described at the same time. Tracking data format was re-defined in taking hardware specifications such as precision of the tracking equipments, time tagging, data unit, etc. into consideration. Orbital ephemeris format was also determind for outside users.
Based on these results, the system design was carried out, and the system development specifications were described prior to the detailed design phase.

4.2 Detailed Design

Top-down approach was introduced in the program design phase. The designing objectives were divided into two types, operational and functional. System development specification was then broken down into operational functions of man-machine interactive utilities and appropriate output items of the process data flow, thus defining the program external specifications. All interactive utilities were standardized and realized by the operational library modules. The system was designed to have two operation modes, semi-automatic and man-machine interactive. To realize these modes by only one set of modules, 'virtual man-machine interactive' concept was introduced. When semi-automatic operation mode is selected, the man-machine interactive library modules read operation procedure control database and operate as if indications are given from graphic display unit. This method was expected to save the development cost because only the man-machine interactive mode was designed and tested.
The functional specification was broken down and standardized to the algorithm library models. The algorithm breakdown structure mentioned above was utilized for designing the algorithm library to contain coordinate and time system transformations, force models, integration by Cowell method, trajectory generation by special and general perturbations methods, orbit events generation, station events generation, and so on. In order to verify some important algorithm parameters, trade-off study and results of the analyses using the prototype programs were taken into consideration. Both operational and algorithm libraries were tested thoroughly and independently using module test control specifications prepared beforehand to ensure the necessary reliability and performance. All NOCS programs were designed to use these libraries in order to ensure the required reliability and cost efficiency.

4.3 Implementation

Bottom-up testing policy was adopted. At first, library modules were tested using drivers and interactive debug aid tools, and were built-up gradually to large module packages. Each operational program could use the tested library module and needed to code and test the program specific, especially man-machine interactive, part because of virtual man-machine interactive concept. The module test was performed by the development team according to the method and criteria defined in the module test control document. The test results of each module were logged to assure the completion of the module testing phase.

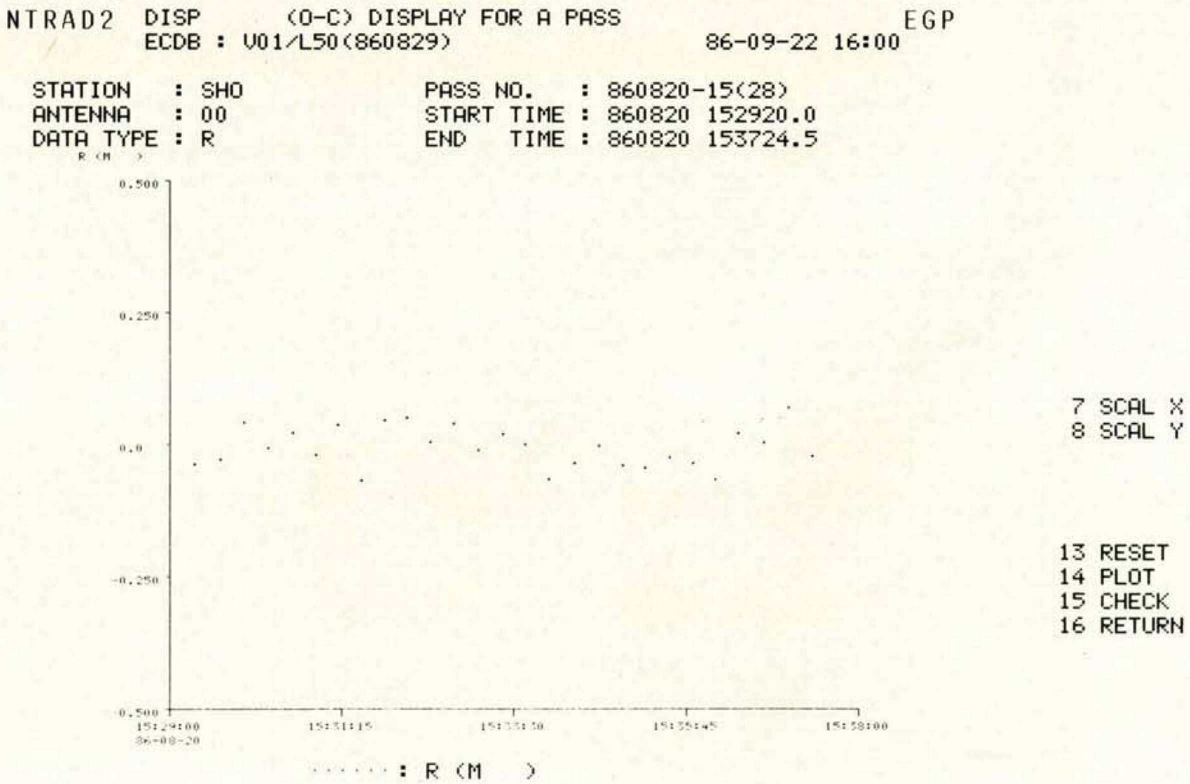

Figure 7. An example of O-C in Orbit determination of EGS

After that, the system was arranged for the testing team that contained some key-men who had played the central roles in the design phase. Testing was performed based on the 'partially' independent verification and validation (IV&V) method and each program unit was tested step-by-step according to the written test procedures carefully prepared beforehand. By using the man-machine interactive mode, testing evaluation and verification were able to be performed directly through the display unit. The new system composed of 440k line codes and written mostly in FORTRAN77 and a small part in COBOL was installed as base line for integration phase in the large scale computer M-380R at TACC.

4.4 System Integration

This phase included program interface test, system test, and integration test. Consistency between programs was verified through the interface test, and the total performance, easiness to operate and precision of orbit determination were verified through system test. Through the integration test the real operation environment was constructed, the total system was tested and certified, and the interface with TDSs and outside organizations was verified. In addition to normal cases, erroneous and contingency cases were also tested.
A handbook describing operation procedures was prepared for the coming real operations. Training for operators was performed using this handbook, and several operation rehearsals were hold. After several months of test run, the system was finally accepted for real operation.

4.5 Configuration Management

Configuration control is one of the most important work items because system is incessantly modified to get rid of 'bugs' and meet with new requirements.
Configuration management has been performed throughout the whole development and testing phases, for the system specifications documents, algorithm specifications documents, testing documents, and program codes. The logged results of the testing were analyzed and used for the measurement of the system reliability.
Configuration control played the central role especially in the integration phase, because one of the main objectives in this phase was to find system bugs. Actually, bugs of about 0.4 per kilostep were found and corrected, and several urgent changes were made. Bugs including those of specifications and codes themselves were found concentrated on the following software features;
-man-machine interactive operation,
-program interface, and
-large multi-functions library.
These features were considered very 'popular' in any software development. Therefore simplicity of interface and simplified function were predominant features that represent the system reliability.
All results of management were collected and reported for system acceptance.

5. CCNCLUSION

The new system satisfies operational requirements as expected, and the precision is considered sufficient for the satellite missions in the latter half of the 80's. NASDA launched TF-1 (the first Test Flight of H-I launch vehicle) in August 13, 1986. Orbit determinations have been performed using the laser ranging data of EGS (Experimental Geodetic Satellite) which is a payload of TF-1. Although the data of only one laser ranging site are available and evaluation of precision is very difficult, the O-C level (Observation minus Calculation) was of order of decimeters, (see an example shown in figure 7) and obtained orbital elements are in good agreement with those of NASA. The detailed evaluations of the adopted models will be performed for EGS and other satellites to be launched in the future.
Semi-automatic operation performs excellently well and will play the basic role in tracking and control especially for earth observation satellites like MOS-1 that will be launched early in 1987. The system is operative during latter part of 80's and possibly in the early years of 90's by adapting new functions based upon requirements of future missions using proper sustaining engineering methodology.