ORBIT DETERMINATION OF SAKIGAKE AND SUISEI ENCOUNTERING HALLEY'S COMET

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ABSTRACT

Japanese first deep space probes "Sakigake" and "Suisei" were successfully launched on January and August 1985, respectively, and encountered Halley's comet without any trouble in March 1986.
In order to track these probes, we have used a tracking and control system newly constructed for deep space missions. With the ISAS orbit determinion program(ISSOP) that was developd as the nucleus of this system, we have performed orbit determination of these probes as well as generated prediction angle data used to drive Usuda's antenna.
In this paper, outline of ISSOP and results of orbit determination of these probes throughout their missions are described.

Keywards: Deep Space, Trajectory Genaration,
Orbit Determination, Software.

1. INTRODUCTION

Japanese first deep space probes Sakigake(MS-T5) and Suisei(PLANET-A) were successfully launched towards Halley's comet from Uchinoura launching site located at 1500km south-west of Tokyo, on January and August 1985, respectively.

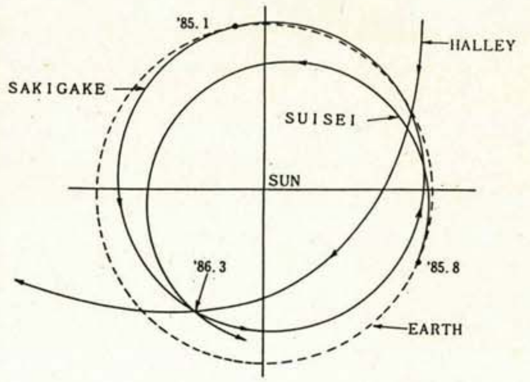

Fig. 1 Trajectories of Sakigake and Suisei

These probes encountered Halley's comet almost perfectly in March 1986 as scheduled.

In order to track these probes, we have constructed a new tracking and control system for deep space missions with the ISAS orbit determination program (ISSOP) developed as its nucleus. Prior to ISSOP, we had a trajectry generation program called TRIP developed to analyze the trajectory of deep space probes. This program is used as the trajectory generation part of ISSOP.

In this paper, outline of these programs and the results of orbit determination of these probes throughout these missions will be described.

2. OUTLINE OF SAKIGAKE AND SUISEI MISSIONS

Sakigake and Suisei are tiny probes weighing around 140 kg. The former is an engineering test probe, and was launched by a newly-developed solid propellant, four-stage booster called M-3S-II on January 7, 1985 (UTC). Hence launching experiment as well as tracking exercise were carried out as parts of this mission.

After cruising arround the sun for one and one third revolutions this probe approached at the distance of about 7 million km from Halley's comet on March 11, 1986.

Suisei, the main probe for observing the comet, was launched by the same booster on August 18, 1985. After cruising arround the sun for two thirds of a revolution this probe approached at the distance about 150,000 km from Halley's comet on March 8, 1986 (see Fig.1).

Table 1. Purpose of Sakigake and Suisei Missions

Name	Purpose
Sakigake	valuation of ability of instruments measuring of interplanetary magnetic fields interplanetary plasma waves solar wind
Suisei	photographing Halley's comet by ultra violet imagery

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3. TRACKING AND CONTROL SYSTEM FOR DEEP SPACE

In order to maintain communication links with these deep space probes, a new gigantic antenna with diameter of 64 meters was constructed at Uauda, which is located at 170km north-west of Tokyo.

S-band communication links are maintained between this tracking station and probes during their voyages, and telemetry, command as well as range and range-rate data are acquired throughtout the mission.

In order to overcome difficulty at the initial phase of tracking, two more antennas are used as support. One is located at Uchinoura launch site, having a diameter of 10 meters. The other is part of the Katsuura station possessed by NASDA, another space organization of Japan in charge of application satelites.

The telemetry and tracking data received at these stations were sent to Komaba Deep Space Operation Center located at ISAS in Tokyo, to be processed by the large-scale computers for orbit determination, attitude determination and maneuver plannings etc. Commands and Prediction angle data for antenna control calculated at this center were then sent to the stations. Tracking and control system with the orbit determination program ISSOP is shown in Fig.2.

In the two following sections, the important features of the trajectory generation program and the orbit determination program will be described.

4. TRAJECTORY GENERATION PROGRAM

A trajectory generation program called TRIP has been developed for deep space missions. TRIP takes an important part in orbit determinations as one of components of ISSOP. The features of the program is described in the following.

TRIP is basically a software package that numerically integrates the equation of motion in the interplanetary space. It is quite different from the one mainly used for the satellites circling around the earth in the following points. In the first place, planetary gravitational accelerations must be taken into account, which are usually ignored in the case of missions around the earth.
Hence appropriate ephemerides of planets must be prepared and adjustment of proper time system such as Ephemeris Time(ET), etc. is required.
In the second place, attention must be paid to the integration method and control of stepsizes, since such interplanetary missions cover a time-span from a half year to several years and excessive computer time will be expected, unless efficient algorithms are employed for numerical integrations.

4.1 Equation of Motion of a Spacecraft

The accelerations adopted in TRIP are as follows:
(a) Acceleration due to sun, moon and nine planets including the earth, regarding them as Newtonian point masses.
(b) Acceleration due to oblateness of each planet when a spacecraft is placed within its sphere of influence. Zonal harmonics J_n, tesseral and sectorial harmonics $C_{n,m}$, $S_{n,m}$ are specified up to n=10, m=10 for the earth.
(c) Acceleration due to solar radiation pressure. The simplified spacecraft model and fine spacecraft model are alternative.
(d) Acceleration due to maneuvers correcting spacecraft's trajectory. Maneuvers are modeled by poly nomials with time as the independent variable. Instantaneous motor burns are also modeled.
(e) Acceleration resulting from the general relativity effect.
(f) Atmospheric deceleration around the Earth. Jacchia-Nicolet model is adopted as the upper atmospheric density model.

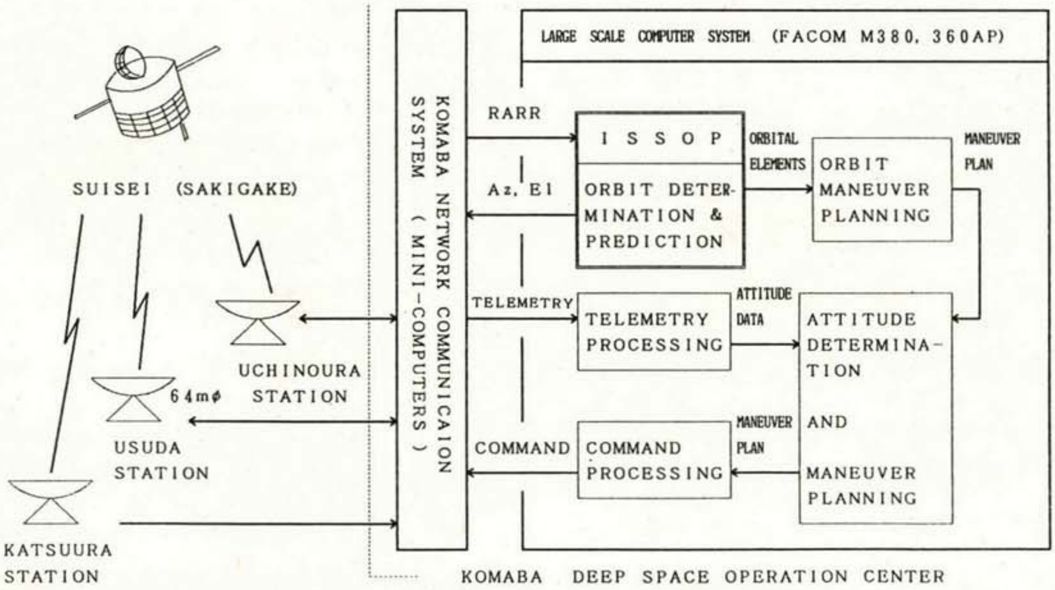


FIG. 2 OUTLINE OF ISAS TRACKING AND CONTROL SYSTEM

(g) Acceleration due to low-thrust forces such as gas leaks from the attitude control system and noncoupled attitude control jets.

The equation of motion, in which all above-mentioned accelerations are included, is solved numerically in a rectangular coordinate system to give the spacecraft ephemeris with time as an independant variable. The injection epoch may be specified either in UTC or ET time scale and must be transformed to ephemeris seconds past the origin of Modified Julian Date. The transformation between ET and TAI is formulated to keep the accuracy 10^{-5} second considering general relativity effect.

The frame of reference is the mean earth equator and equinox of 1950.0, which is the inertial coordinate system. Body-fixed coordinates are introduced when the acceleration of spacecraft produced by a nonspherical central body is computed.
The center of integration is located at the center of the sun, the moon, or one of the nine planets. It may be specified as one of these bodies or allowed to change as the spacecraft passes through the sphere of influence of a planet or the moon. The ephemerides are given by JPL ephemeris tape (DE118).

4.2 Numerical Solution of Equation of Motion

The equation of motion, which is the second order ordinary differential equation, is solved to give the spacecraft ephemeris. The method adopted in TRIP is the multistep predictor-corrector method:

· velocity	predictor	Adams-Bashforth formula
	corrector	Adams-Molton formula
· position	predictor	Stormer formula
	corrector	Cowell formula.

Although there are some ingenious one-step methods with automatic step size control, their disadvantage is that no use is made of past information on the solution, and many derivative evaluations for each step are necessary if high accuracy is desired.
On the other hand, multistep methods have the advantage of using already computed values, thus reduce the computational effort. A disadvantage of multistep method is that, before it can be applied, the starting point must be computed by some other method.

In TRIP, as a starter, either Runge-Kutta method (8th order) or a two-body corrector method is selective. The latter
- assumes a two-body motion giving an initial value at starting points and,
- corrects them by corrector formula.

This method is much more efficient than Runge-Kutta starter, because the number of derivative evaluations is very small.

The step size is controlled automatically estimating the local truncation error. Attention must be paid to the step size control algorithm. If the trajectory of the spacecraft is not smooth enough to fix the step size, it may happen that the step size is changed quite frequently, which, as a result of roundoff error and truncation error, may increase the accumulated error enormously. In TRIP, step size is controlled ingeniously, so that frequent step size change may not happen keeping high accuracy and efficiency.

4.3 Performance of TRIP

TRIP is written in FORTRAN-77 and the size of the program is about 15,000 lines of FORTRAN code including graphic output utilities. For verification of the program three cases of trajectories are compared with the JPL program (DPTRAJ) (see table 1). The result shows that TRIP sufficiently satifies the high accuracy required. A difference of 30 meter in position from the distance of 1.5×10^{8} km means the relative accuracy of 2×10^{-10}. The local truncation error 10^{-13} (like relative accuracy) is assigned for numerical solution, and number of integration steps are nearly 10^{3}. That means the accumulated error is at least nearly 10^{-10} in order. So the difference of these two programs is of the same level as the accumulated error.

Tabel 2. The comparison between TRIP and DPTRAJ

	Generation Conditions	Difference
Case A	Sun cruising phase, Newtonian gravitation.	13 m
Case B	Injection to encounter, Newtonian gravitation.	33 m
Case C	Injection to encounter, Newtonian gravitation, plus oblateness.	38 m

5. ISAS ORBIT DETERMINATION PROGRAM (ISSOP)

ISSOP is an orbit determination program for deep space mission, which took about 5 years to develop. This program estimates the orbital elements of the spacecrafts, and calculates the predicted azimuth and elevation angles for driving the Usuda antenna. The 64-meter diameter antenna at Usuda has some limited auto-tracking capability, and because of its large and heavy dish, it normally operates in the programmed control mode. The beam-width of this dish is only 0.13 degrees and there is danger of losing the sight of the probe unless precise information on the azimuth and elevation angles are supplied to the control device of the antenna. Hence ISSOP is operationally required to calculate these predicted angle values within the accuracy of 0.13 degrees by using radio-metric tracking data.

5.1 Main Features of ISSOP

ISSOP is quite different from the program used for near-Earth missions because of the significant phenomena of the deep space. Such phenomena are
- the long distance from the spacecraft to the earth, which causes the poor observability,
- the effect of general relativity nearby the sun, and etc.

As a result, in ISSOP, a square root filter form is adoped in addition to the normal-equation form as the estimation formula since filtering itself is expected to have some numerical difficulty because of poor observability due to the long distance between the probe and the tracking station. Also the effect of general relativity is taken into account in the equation of motion as well as in the observation model.
The main features of ISSOP are listed below.

5.1.1 Solve-for parameters and consider parameters. Each parameter shown in table 3 can be designated as either a solve-for parameter or a consider parameter. In most cases, only the state of the spacecraft (position and velocity) is specified as solve for parameters. However, such parameters as solar pressure, station location, time bias etc. are estimated or considered depending on the circumstances.

Table 3. Solve-for / Consider Parameters

No.	Solve-for / Consider Parameters
1*	position and velocity of spacecraft at epoch
2	parameters due to solar radiation pressure
3	parameters due to aerodynamic force
4	parameters for instantaneous burn motor
5	coefficients of small force model
6	relativity parameter
7	station parameters(height, latitude, longitude)
8	time bias of the tracking station
9	constant bias for range observables
10	constant bias for range rate observables

* : solve-for only

5.1.2 Filter Algorithm. The fundamental form of the filter for estimating solve-for parameters is the Bayesian Weighted Least Square method (i.e. the the normal equation form) with iteration capability. In order to overcome the problem of the poor observability, the square-root filter mode is also employed as an option, which is theoretically equivalent to the Bayesian's method but is numerically superior. After obtaining the spacecraft's coordinates at the epoch, they are propagated to the certain target time together with the associated error covariance. Futhermore, the actual covariance evaluating the consider parameters, sensitivity and perturbation with respect to these consider parameters can be computed in order to analyze the effects of unestimated parameters.

5.1.3 Data types and data accuracy. Range, range-rate, 1-way doppler observables and the azimuth and elevation angles of the antennas are available to the orbit determination program. But due to the long distance from spacecraft to the tracking station in the case of deepspace mission, angle data are effective only in the near earth phase, and hence range and range-rate data are mainly used in the ordinary operation. Range and range data observables have accuracies of 10m and 1mm/sec respectively.

5.1.4 Corrections and computations of observables. Before radio metric data is used in the orbit estimation, deviations due to tropospheric and ionospheric effects are corrected. Also transponder delay time and station time delays are removed from the data. Regarding troposphere correction, the semi-empirical formula obtained by D.L.Cain is used. In the computations of all observable quantities, the effect of general relativity due to the sun is taken into account. For example, the light time equation is solved in the accuracy of 0.1 μs in order to obtain the time at which the signal is received and retransmitted by the spacecraft.

5.1.5 Equation of motion and variational equation. The variational equation is a linear, first-order differential equation consisting of first-order derivatives of the equation of motion. The solution of this variational equation is required both for constructing the observation matrix and for mapping the error covariance matrix from an epoch to another.

In ISSOP, the orbit of the spacecraft is generated by TRIP. Hence, not only the accelerations adopted in the equation of motion as well as the variational equation but also the method of the numerical integration of the equation of motion is equivalent to those of TRIP. With respect to the numerical integration of the variational equation, Adams type predictor-corrector method is adopted, which is variable in order and step, and is sufficient enough to satisfy the required accuracy.

5.2 Structure of ISSOP

ISSOP consists of three components, namely ISSOP1, ISSOP2 and ISSOP3. Those are the pre-processing program, orbit determination program, and orbit projection program respectively. The characteristics and main functions of ISSOP are shown in Fig.3. The total program size of ISSOP is about 80,000 lines. ISSOP is now running under OSIV/F4 M380 (Fujitsu machine) and it is operated by intervening the graphic display.

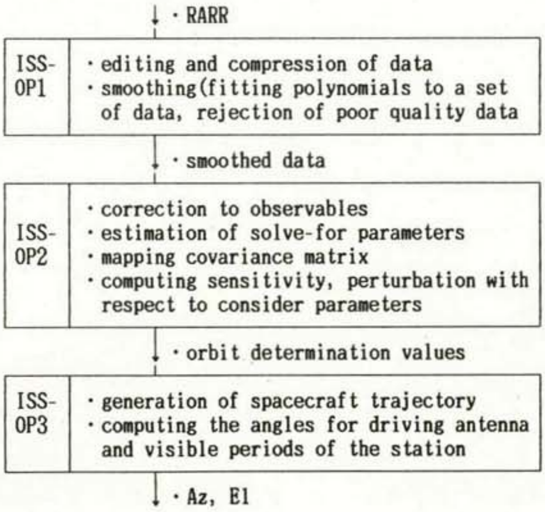


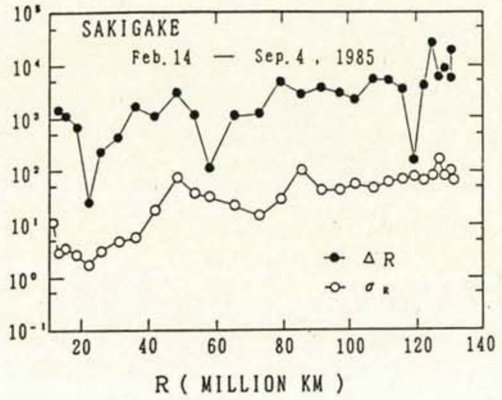
Fig.3 Components of ISSOP

6. TRACKING RESULTS OF SAKIGAKE AND SUISEI

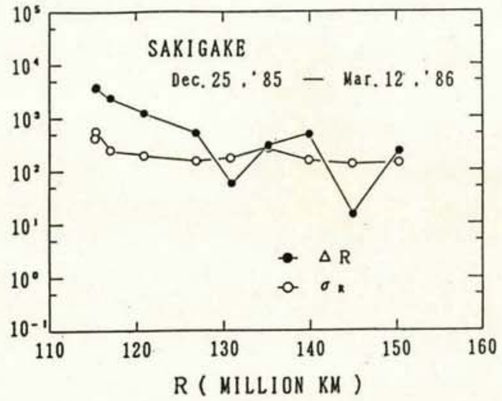
6.1 Tracking Results of Sakigake

Fig.4 shows the position error ΔR betweeen inputs and estimated values of orbital elements for Sakigake. The standard deviation of position σ_R is also depicted. The position error ΔR and the velocity error ΔV give the measure of projection error or validity of the orbit determination. These values are inclined to be less fitted with the radiometric data step by step from launch (τ) as shown in Fig.4 (a). Fig.5 shows the (O-C) values [RMS] of the first and the last iterations of the estimation with respect to range and range-rate observables, which also show the trend discussed above.

We estimated time bias other than state of Sakigake simultaneously after September 4 in 1985. After estimating it, orbit determination values are found to fit well with data (see Fig.4(b), Fig.5(b)). These figures indicate that orbit determinations are executed normally until Halley encounter, because both position error and velocity error are the same order as the standard deviation of position and that of velocity each other. Although removing a few sec., there has still been a little bit time bias. This is mainly due to the use of predicted values of time transformation data as a substitute for measured values from BIH because the latest data are not in time for orbit determination.

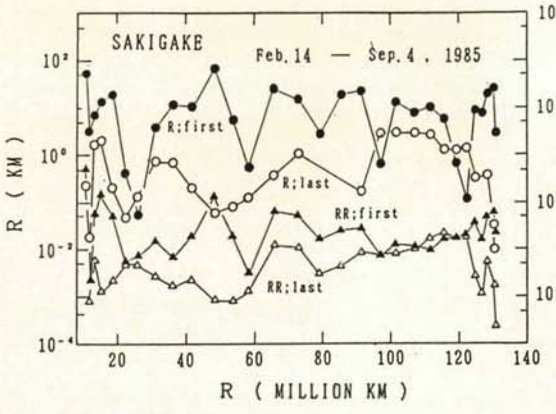


(a) before estimating time bias

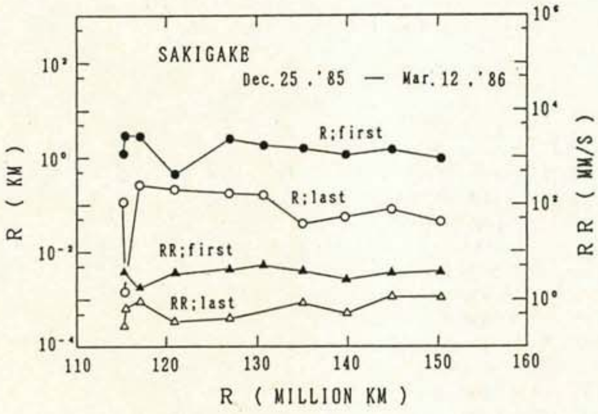


(b) after estimating time bias

Fig. 4 Position error ΔR and standard deviation of position σ_R



(a) before estimating time bias



(b) after estimating time bias

Fig. 5 (O-C) values [RMS] of range and range-rate observables

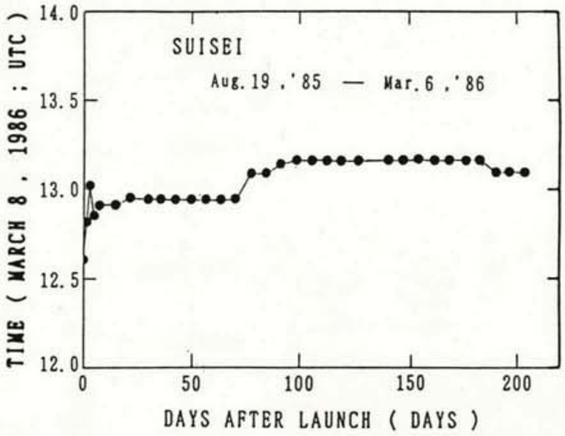
Sakigake modified its own trajectries twice by motor-burns ; one of them was occurred on January 11 in 1985 (τ +4 days), and another on February 14 in 1985 (τ +38 days). It was the former that strongly affected its trajectory. The latter can be neglected to the orbit of the effects. The closest approach time and distance to Halley's comet give the measure how much the trajectry of Sakigake improves. Each value before and after trajectory correction maneuver(TCM) are as follows;

Term	Pre-TCM	Post-TCM
closest approach time (UTC)	14 : 00~15 : 00 March 11 1986	3 : 30~ 4 : 30 March 11 1986
closest approach distance (km)	7.56 ~7.60 million km	~7.0 million km

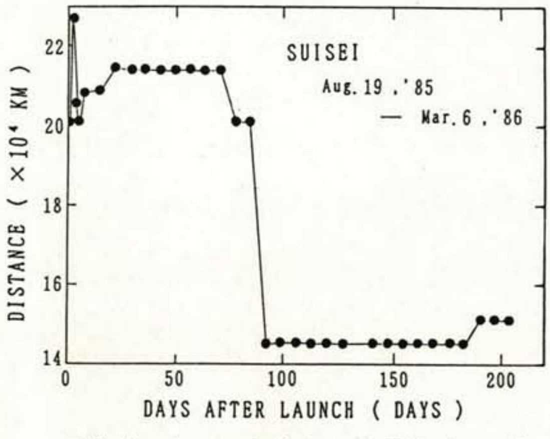
6.2 Tracking Results of Suisei

As we estimate time bias for Suisei from the beginning of the mission, position error ΔR and velocity error ΔV are always as same order as the standard deviation of the position σ_R and that of the velocity σ_V throughout the mission. The estimated values of time bias for Suisei are nearly similar to those for Sakigake. Fig.6 shows the closest approach time and distance to Halley's comet for Suisei. Suisei changed its trajectries on November 14 in 1985 (γ+ 88 days) by TCM. Value before and after TCM are as follows;

Term	Pre-TCM	Post-TCM
closest approach time (UTC)	12:55~13:05 8.March 1986	13:05~13:10 8.March 1986
closest approach distance (km)	201,000 ~ 204,000 km	145,000 ~ 151,000 km



(a) closest approach time to Halley's comet



(b) closest approach distance to Halley's comet

Fig.6 Closest approach time and distance to Halley's comet

7. CONCLUTION

Outline of the trajectory generation program and the orbit determination program for deep space missions, and the results of the first Japanese deep space mission are described in this paper. Both Sakigake and Suisei successfully encountered Halley's comet in early March, 1986.

The second deep space mission called MUSES-A are being planned. The deep space probe "MUSES-A" will be launched in 1990 for the experiment of lunar swing-by. We will improve ISSOP for this mission on the basis of the experience of Sakigake and Suisei missions.

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