COMMUNICATIONS, TRACKING AND ORBIT DETERMINATION OF SAKIGAKE AND SUISEI ENCOUNTERING HALLEY'S COMET USING USUDA STATION

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Abstract

The first Japanese deepspace probes called SAKIGAKE and SUISEI were launched from the Uchinoura Launching Site, located at 1,500 km south-west of Tokyo, respectively on January 8 and August 19, 1985. The Institute of Space and Astronautical Science has constructed a gigantic antenna - 64 m in diameter - in Usuda, located at 150 km north-west of Tokyo. These probes successfully encountered Halley's comet in March, 1986.

In this paper, the outlines of communication systems, tracking systems and the way of orbit determination of the probes throughout the mission, will be discussed together with operational results.

1. Introduction

Halley's Comet returned close to the Earth after an interval of 76 years. The European Space Agency, the U.S.S.R., the U.S.A. and Japan sent probes to gather complementary data on the comet. They all encountered the comet successfully in March, 1986(1).

The Usuda Deep Space Center (UDSC) was constructed in October, 1984 first to communicate with and to track two Japanese probes in S-band(2). The gathered data were used to determine the orbit of the probes. The operation of deep space communication and tracking system was the first experience for ISAS. The operation scheme was determined carefully considering such factors as slant ranges, visible times for two probes and communication capabilities of both probes and the UDSC.

2. Outline of Missions to be Tracked

One of Japanese probes SUISEI which was launched on August 19, 1985 is shown in Fig.1. The spacecraft is 1.4 m in diameter and 0.7m in height, is equipped with an ultra-violet camera and a solar wind detector. An offset parabolic antenna (HGA) is installed on the upper side together with a colinear array antenna (MGA) and a crossdipole antenna (LGA) both under the lower side(1).

SUISEI has a sister spacecraft named SAKIGAKE which was put into orbit on January 8, 1985. They are very similar except for the scientific instruments(1).

The trajectories of SAKIGAKE and SUISEI are shown in Fig.2. After cruising around the Sun for one and half revolution in the case of the former, and three quaters revolution in the case of the latter, both spacecrafts encountered Halley's comet in early March, 1986. The closest approach distance to the comet was about 7 million km on March 11 for SAKIGAKE and 150 thousand km on March 8 for SUISEI. The keplerian elements in the Sun-centered ecliptic coordinate for both spacecrafts are shown in Table 1.

The direct ascent scheme was employed for SAKIGAKE and SUISEI launching. Namely, skipping the usual parking orbital flight, the spacecraft was launched directly into the deepspace, igniting the third and the fourth stage motors in sequence, thus attaining the exit velocity of 11.2 km/s. This scheme was used in order to increase the payload, but placed some burden on the initial tracking of the spacecraft, as will be discussed later. The same scheme was adopted for the launching of SUISEI(6).

3. Outline of UDSC and its related facilities

UDSC is composed of equipments shown in Fig.3. Low noise amplifiers (LNA), high power amplifiers (HPA) and first and second IF stages of a heterodyne receiver are installed in the building below the antenna. Other equipments are installed in another building about 100 meters apart from the antenna.

The antenna is cassegrain type with a 64 m diameter main dish. It is fed through a beam waveguide system which enables LNA and HPA to be placed on the floor and makes the maintenance and operation very convenient. Its characteristics are summarized in Table 2. The generated noise by HPA in reception bandwidth is strictly limited to prevent the interference to LNA as well as direct leakage power to LNA in transmission bandwidth. The details of the design principle and performances of other equipments are described in another paper(5).

From the viewpoint of operation, each equipment has following characteristics. The equivalent noise bandwidth 2 BL can be changed between 3 Hz and 1 KHz The transmit frequency is swept in order to establish synchronization of a phase lock loop in the spacecraft for coherent communications.

		SUISEI	SAKIGAKE
Launch Date		Aug. 19, 1985	Jan. 8, 1985
Arrival Date		March 8, 1986	March 11, 1986
a	(km)	126,859,131	136,611,357
e		0.195	0.106
i	(deg)	0.714	1.427
Ω	(deg)	143.60	287.22
ω	(deg)	4.13	319.51

Table 1 Keplerian elements of SUISEI and SAKIGAKE in ecliptic coordinate

Frequency	S-band (2.1~2.3 GHz) X-band (7.1~8.5 GHz)
Antenna gain	62.6dB (2293MHz)
Aperture efficiency	77% (S-band)
Noise temperature (at the zenith)	12K (antenna alone) 22K (with diplexer)
Polariation	RHC or LHC
Half power beamwidth	0.13deg. (S-band)
Pointing accuracy	0.003deg.RMS

Table 2 Characteristics of Usuda 64m antenna

Range and range-rate (RARR) subsytems enable two way coherent range-rate (doppler) and range measurement. The systems are precisely controlled by cesium and rubidium atomic clocks, yielding 1 mm/s in range-rate (60 s count-time) and 10 m in range respectively.

The conditions or the operational modes of UDSC, probes and radio links are checked out through the monitor and control consoles at both UDSC and Komaba Deep Space Center (KDSC) in Tokyo. The operation is supported by super-computers at KDSC, and data processing and communication systems are shown in Fig.4.

4. Operation planning

The visible time of a probe from UDSC is determined mainly by the probe's location in space and relative attitude to the Earth.The computed results are shown in Fig.5 for two Japanese probes as well as for U.S. cometary probe ICE whose signal was received from May to November in 1985 intermittently(3).The actual visible time is further reduced due to the skyline of mountains surrounding the big dish(8). UDCS tracks plural probes sequentially in a day to satisfy the demand from each mission and the spacecraft maneuvering. To accomplish this, the time overlaps of probes shown in Fig.5 must be adjusted.

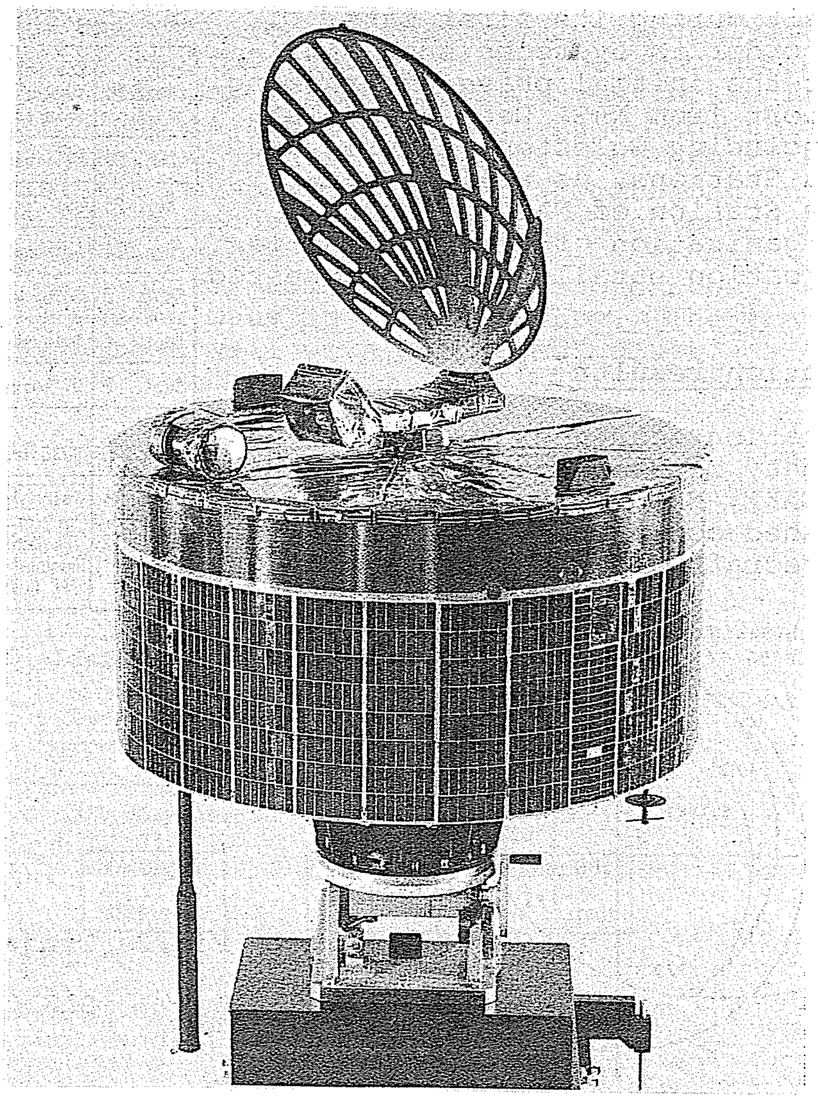

Fig.1

Spacecraft SUISEI

The conditions of radio links are dominated by the probe-earth slant range, the shape of space-borne antenna in use and the spacecraft's attitude. In the near range the higher speed telemetry mode of 2 kbps can be utilized using a well-pointed high gain antenna. Otherwise only the lower speed mode is feasible.

For tracking of spacecrafts ISAS has two antennas that can be used, one at Uchinoura Launching Site in Kagoshima Pref., having a diameter of 10 meters, and the other at Usuda Station. The former can reach only 100 - 150 thousand km when the medium gain antenna on board the spacecraft is in use, as is expected in the early stage of missions, before the high gain antenna is directed towards the Earth.

The first major problem in establishing the tracking strategy in these Halley's comet missions was that the orbit of spacecrafts must be determined as early as possible using the range and range-rate information during the first pass (from 5 hrs to 14 hrs after launching) acquired by the Uchinoura Station, then appropriate information in the form of Az and El must be conveyed to the Usuda Station, so that a communication link will be established between the spacecraft and the Usuda antenna. This is not an easy task, however, because the spacecraft will become invisible from the Japanese stations in a few minutes after its separation from the last stage of the launching vehicle and one has to wait for five hours before it becomes visible again. Hence available tracking information are very much limited for determining the orbit of the spacecraft during its first pass.

In order to overcome such difficulty at the initial phase of tracking, the support from NASA Deep Space Network, including Goldstone, Madrid and Canberra Stations, as well as the Katsuura Station of NASDA, another space organization of Japan in charge of application satellites, was requested.

1985 Aug. 19	Launch, Spacecraft transmission level = 70mw→5w, UDSC transmission level =200w, Spin rate =29→6.5rpm, Attitude control
Aug. 20	Attitude control, Antenna =LGA → MGA
Aug. 23	UDSC transmission level =200w→2kw
Aug. 24	Antenna =MGA → HGA, Despin start
Sept. 2	Solar wind observation start
Sept. 4	Spin check of 0.2rpm
Sept. 7	UV imaging start
1986 Jan. 5	UDSC transmission level =2kw →20kw
Jan. 14	Telemetry mode=high speed→low speed
Mar. 12	JPL Madrid Station receiving, Eucounter with Halley's Comet, JPL Goldstone Station receiving

Table 3 Operational events of SUISEI

5. Operation results

(1) Operation sequence

Twenty minutes after the launching of SAKIGAKE, NASA Goldstone Station established communication linkage with the spacecraft. Then, after about four

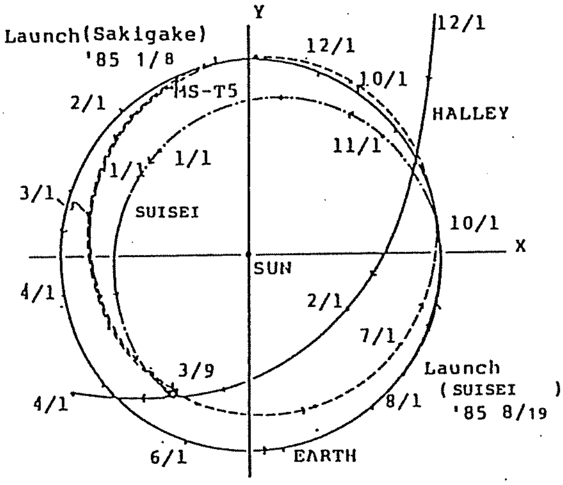

Fig.2 Trajectory of SAKIGAKE and SUISEI

hours, early report of spacecraft's coordinates was sent from NASA stations to ISAS. After four and half hours, the Uchinoura and the Katsuura Station captured the spacecraft and their antenna angle information were sent to ISAS in Tokyo and they were conveyed to the Usuda Station, after applying some coordinate transformations.

Based on the information thus conveyed, the Usuda antenna successfully acquired beam from the spacecraft and tracking was performed for about six hours.

Main events concerning communication after the launch are summarized for SUISEI in Table 3. Space-borne antennas were switched according to the probe's attitude. Transmission levels of the probe and UDSC were also changed depending on the slant range. After January 14, telemetry mode was kept in lower speed. The status parameters of the receiver at UDSC were changed in accordance with these operations, though they are not described in Table 3.

(2) Transmission and reception

Received carrier level for telemetry is plotted against slant range in Fig.6. It is seen that space-borne antennas were switched from LGA to MGA in the second pass and finally to HGA in the fifth pass. In the case of LGA the variation of the received level reached 7 dB, probably because the non-uniformity of the anenna pattern appeared significant due to an offset spin-axis from the Earth.

In the fourth pass the received level increased abruptly as MGA pointed to the Earth after attitude control. At the encounter the carrier was received at -149 dBm. Theoretical curves in the figure include carrier reduction due to modulation (4.1 dB). The theoretical values and the measured values agree well each other, as is the verification of satisfactory performances of communication subsystems. The Eb/No at the encounter was 17 dB which corresponds to the estimated value based the value of S/N.

The uplink which is used for command or ranging can be monitored through housekeeping data in the telemetry. The transmitted data of the link agrees well with estimated values.

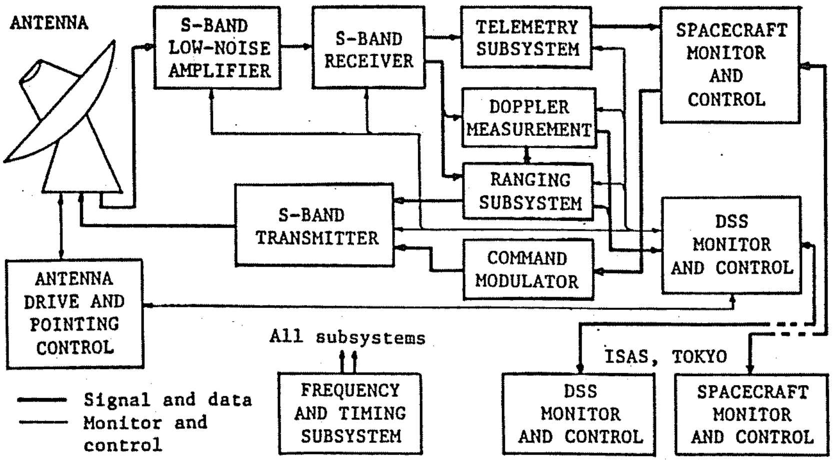

Fig.3 Functional block diagram of the Usuda Deep Space Center

6. Orbit Determination

A trajectory generation program called TRIP and an orbit determination program called ISSOP have been completed for deep space missions. Features of these programs are described in the sequel. (9), (10)

6.1. Trajectory Generation Program

This is basically a software package that numerically integrates the equation of motion in the interplanetary space and is quite different from the one mainly used for the satellites circling around the Earth.

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 systems such as Ephemeris Time (ET), Universal Time (UT), etc. is required.

In the second place, attention must be paid to the integration method and control of step-size, since such interplanetary missions cover a time-span from a half year to several years and excessive computer time will be required, unless efficient algorithms are employed for numerical integrations.

The accelerations considered are Sun, Moon and 9 planets, harmonics of gravitational potential, solar pressure, maneuvers, general relativity effect and air drag. The program thus developed is called TRIP.

6.2. Orbit Determination Program

Development of a software package called ISSOP for the purpose of orbit determination in deepspace missions has been completed befor the launch. In principle, it does not differ very much from the one for the near-Earth missions. However, care must be exercised on pre-processing of data such as range and range-rate, taking into account the solar plasma and ionospheric effect as well as the effect due to the general relativity. Also filtering itself is expected to have some difficulty because of poor observability due to a long distance between probes and the ground station.

Solve-for parameters:

They are six coodinates of probes in most cases. However, such parameters as solar pressure, station locations etc. will be estimated depending on the circumstances. An option is added to the program so that it is equipped with the evaluation capability. Hence such parameters as station locations, solar pressure, and fuel leakage from the control valve can be chosen as the possible candidates for consider parameter.

Filter:

The fundamental form of the filter for estimating solve-for parameters is the Bayesian Weighted Least Square method with iteration capability. In order to enhance the precision of numerical computation, the square root filter (information matrix type) is adopted as an option. (9) After obtaining the spacecraft's coordinates at the epoch, they are propagated to certain target time together with the associated error covariance. Also the actual covariance evaluating the consider parameters, sensitivity and perturbation with respect to these consider parameters are computed both at the epoch time and target time.

6.3. Results of Orbit Determination Analysis

During the first ten days after launching of SAKIGAKE and SUISEI, NASA provided ISAS with their estimates of the probe's coordinates. When they were compared with the computations of ISAS itself, the differences were within one hundred km in distance and one meter/s in speed. More precise post-flight analysis diminished these differences considerably.

After this period, only ISAS data have been available, and the tracking has been carried out smoothly since then. Predicted angle data for the Usuda antenna have agreed with the actual beam direction in the order of one hundredth of degree, which is within the tolerable range, since the beam-width of the 64-meter antenna is 0.13° in S-band.

Another verification for the orbit-determination results is the so-called O-C, which is the difference between the observed data and computed values for range and range-rate, respectively. They are less than 1 - 2 handred meters for range and 1 - 2 mm/s for range-rate data. Both results appear satisfactory.(Fig.7,SUISEI)

The precision of orbit determination appeared to be in the order of 2-300 km at the encounter time, which is close enough to the expected values from the covariance analyses.

The chained line is the rms values of differences of probe's coordinates between the actual estimates and the predicted values, and the dotted line is the standard deviation from the covariance analysis (Fig.8-a). Fig.8-b shows those for the velocity. (SUISEI)

The closest approach distances of SAKIGAKE and SUISEI to the comet were 7 million km and 150 thousand km respectively. (Fig.9)

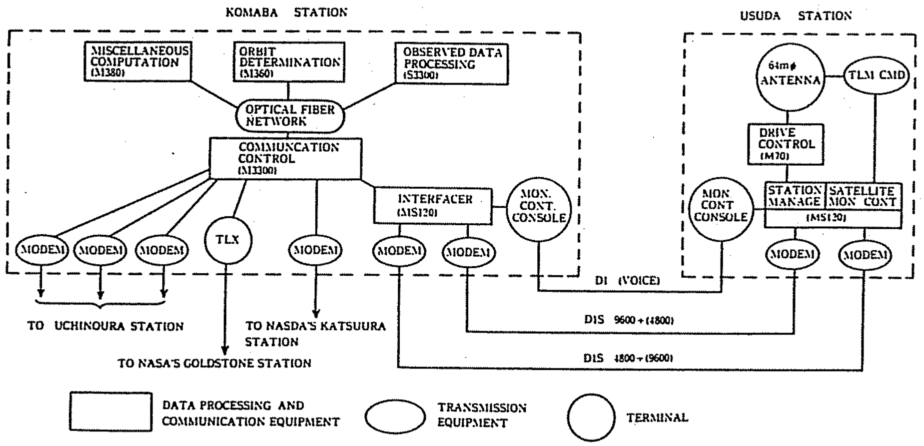

Fig.4 Functional diagram of the data communication and processing system

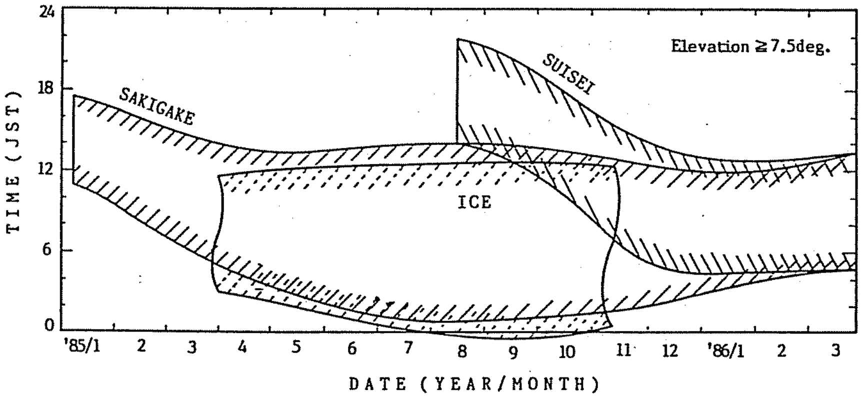

Fig.5 Visible time of the probes from UDSC

In the case of the latter, it was capable to approach much closer to the comet. However, in oder to protect the probe from damage due to impacts of dust particles, the above distance was maintained.

7. Conclusions

The operation results of communication facilities in UDSC which supported the Halley's comet exploration is described in the first part of this paper. The operation of UDSC was quite successful and the communication facilities showed satisfactory characteristics as well as those of two Japanese probes.

Then in the latter part the tracking and orbit determination problems associated with the Japanese first deepspace missions are described. Both SAKIGAKE and SUISEI successfully encountered Halley's comet in early March, 1986.

Various technical problems that arised before and during the mission are discussed, and the final results are reported. Generally speaking, the navigation and tracking systems functioned smoothly both hardware-wise and software-wise, and contributed very much to the accomplishment of the mission objectives.

Acknowledgement

The operation of Usuda Deep Space Center and Komaba Deep Space Center (Tokyo) has been carried out smoothly throughout the mission, not only by ISAS personnels, but also by many devoted engineers from the companies such as Mitsubishi Electric Corp., NEC Corp., Fujitsu Corp., etc. Also successful initial tracking owes very much to the cooperation by Katsuura Station of National Space Development Agency of Japan, as well as to NASA Deepspace Tracking Systems.

We extend our sincere gratitude to those people who helped us in the accomplishment of successful tarcking operations in the first Japanese deepspace missions.

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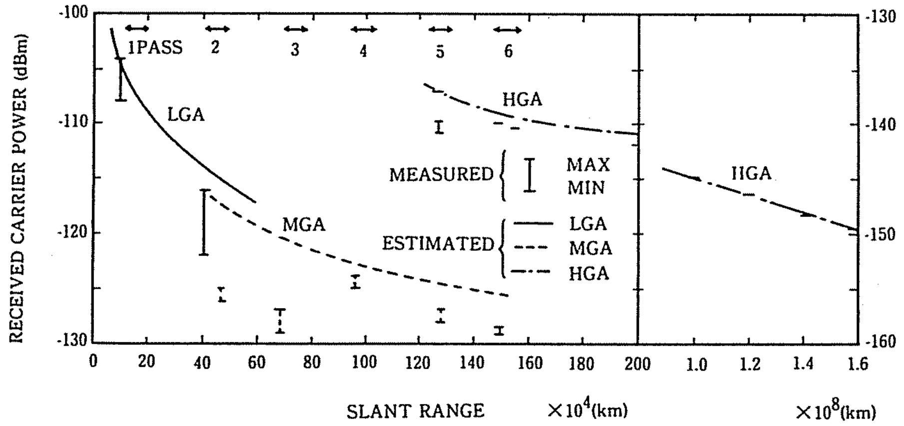

Fig.6 Slant range versus received power level (SUISEI)

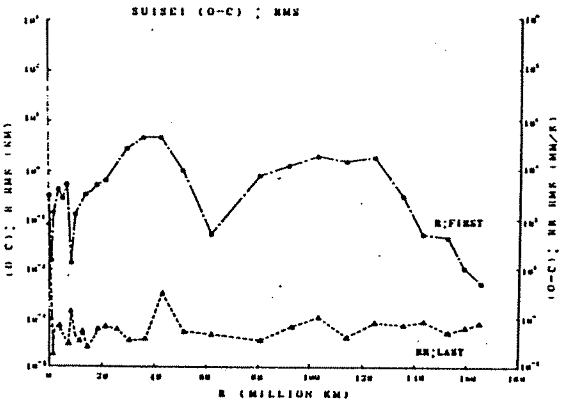

Fig.7 (O-C) (rms) of range and range-rate data (SUISEI)

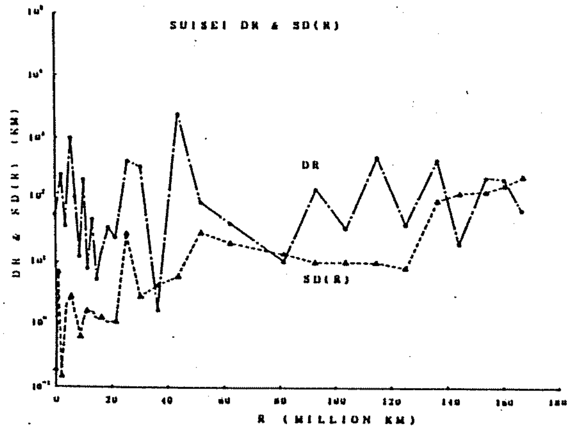

Fig.8-a Estimation error of distance(rms) and standard deviation (SUISEI)

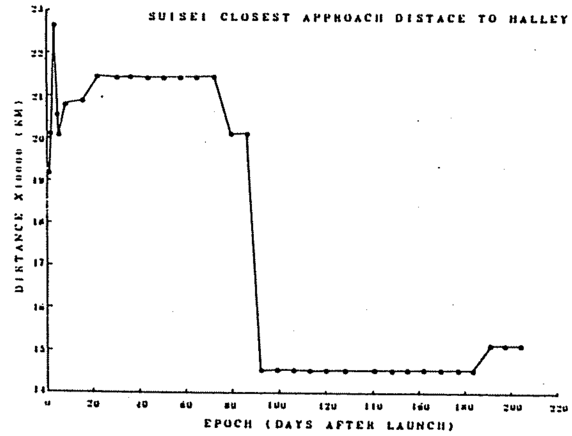

Fig.9 Closest approach distance of SUISEI to Halley's comet

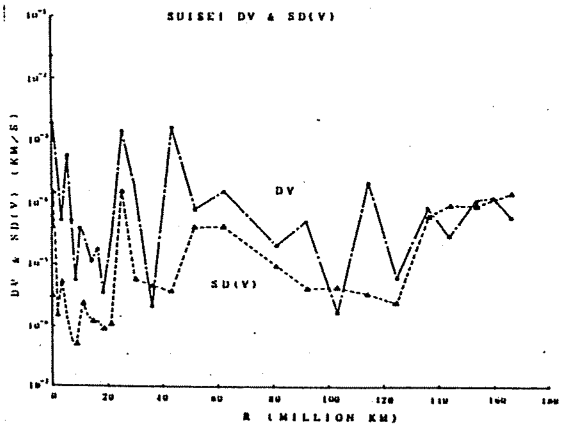

Fig.8-b Estimation error of speed (rms) and standard deviation (SUISEI)