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Collisions in Space: A Retrospect of Studies in ISAS

By

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Abstract: A chronological review of studies in ISAS concerning collisions in space is presented. It is shown that collision probability in space with artificial orbiting bodies was estimated, and that Space Traffic Control System was proposed, in the study in 1971. Safety design of space station against collision hazards were discussed in 1972. A trajectory optimization technique for low-thrust multiple rendezvous mission in order to sweep space debris around the earth was developed in 1977. In 1984, collision probability was reestimated using space debris data accumulated for more than a decade.

1. INTRODUCTION

The study of space debris in ISAS is one of the earliest studies in the world. In the early 1970's, we thought that the number of artificial orbiting bodies around the earth might dangerously increase in near future, and our estimation as for probability of collisions of such bodies with each other seemed to verify our apprehensions at the time when space station would come into operation [*1*]. It should be noted that the study was done under assumptions that the space station would be launched in the early 1980's under the circumstances of approximately 4,000 debris existing. On the contrary, in reality, the number of space debris is counted as much as 7,000 in 1989 and the space station, which has a large cross-sectional area, has not been yet launched. In consequence of the estimation of collision probability in future, we proposed a kind of Space Traffic Control System by which we could have reduced collision probability in space.

Along with such a proposal, in 1972, we studied the aspect of safety design of space station against collision hazards [2]. In this study, collision hazards to the space station were categorized into four classes (Fatal, Rescue required, Repairable, and Disturbed), and an onboard search radar to detect space debris was proposed. Feasibility study of Refuge Maneuvering System which would be activated when a big debris approaching to the space station, and a concept of Space Sweeper Mission to reduce the number of existing debris were also discussed.

Since we had recognized that conventional chemical propulsion system was inadequate for the space sweeper mission, we proposed a solar powered electrical propulsion system for such a mission, and an optimization technique for low-thrust multiple rendezvous trajectory was developed in 1977 [*3*].

In 1984, collision probability in space was reestimated using space debris data accumulated for more than a decade, and the debris environment in future was also predicted [*4*].

In this paper, each paper mentioned above is briefly reviewed and major results of these studies are presented.

2. Some Considerations On Utilization Control Of The Near Earth Space In Future

By the time of 1971, more than 2,000 artificial orbiting bodies had already been existing in the near earth space, and their distribution was shown in regard to semi major axis, eccentricity, and orbital inclination (Fig. 1) in a paper titled "Some Considerations on Utilization Control of the Near Earth Space in Future" [*1*]. Two kinds of model for calculating the density of orbiting bodies around the earth were developed as shown in Fig. 2, and by use of these models, probability of collisions of such bodies with each other was estimated as shown in Fig. 3. It led us to the fact that the collision probability for an imaginary space station, which would fly 200 to 500 km of altitude and have 10,000 m^2 of crossectional area, was 0.01 per year under the circumstances of space debris density in 1971. Even if assuming that the incremental rate of orbiting bodies would continue to be about 200 per year as same as the rate by that time, it was easily predicted that the real space station should be launched into the dangerous space surrounded by many artificial orbiting bodies.

In consequence, we proposed a kind of Space Traffic Control (STC) system, in which the altitude range from 200 km to 500 km should be divided into about 30 layers and each layer would be assigned for specific mission flight such as space stations, remote sensing satellites, scientific satellites etc. As shown in Fig. 4, orbital inclination of satellites should also be controlled to reduce the collision probability. Fig. 5 explains how orbital inclination of orbiting bodies contributes to the probability of collision with a satellite which flies 200 to 300 km altitude with 50 deg of inclination, as an example.

The concept of STC was deduced from the air traffic control system and although we thought such a system would be necessary before the space station age would come (at that time, we expected it would come in the early 1980's), any kind of STC system has not been yet adopted except for the stationary positions of geosynchronous satellites allocated by the international agreement.

We also mentioned very briefly about a concept of space sweeper mission which would retrieve dead satellites and orbiting bodies. Fig. 6 shows our prediction for the increment of orbiting bodies up to the end of this century, and also indicated how the STC system and space sweeping would work for the reduction of space debris. It should be noted a mark * in this figure shows the real number of orbiting bodies identified at present.

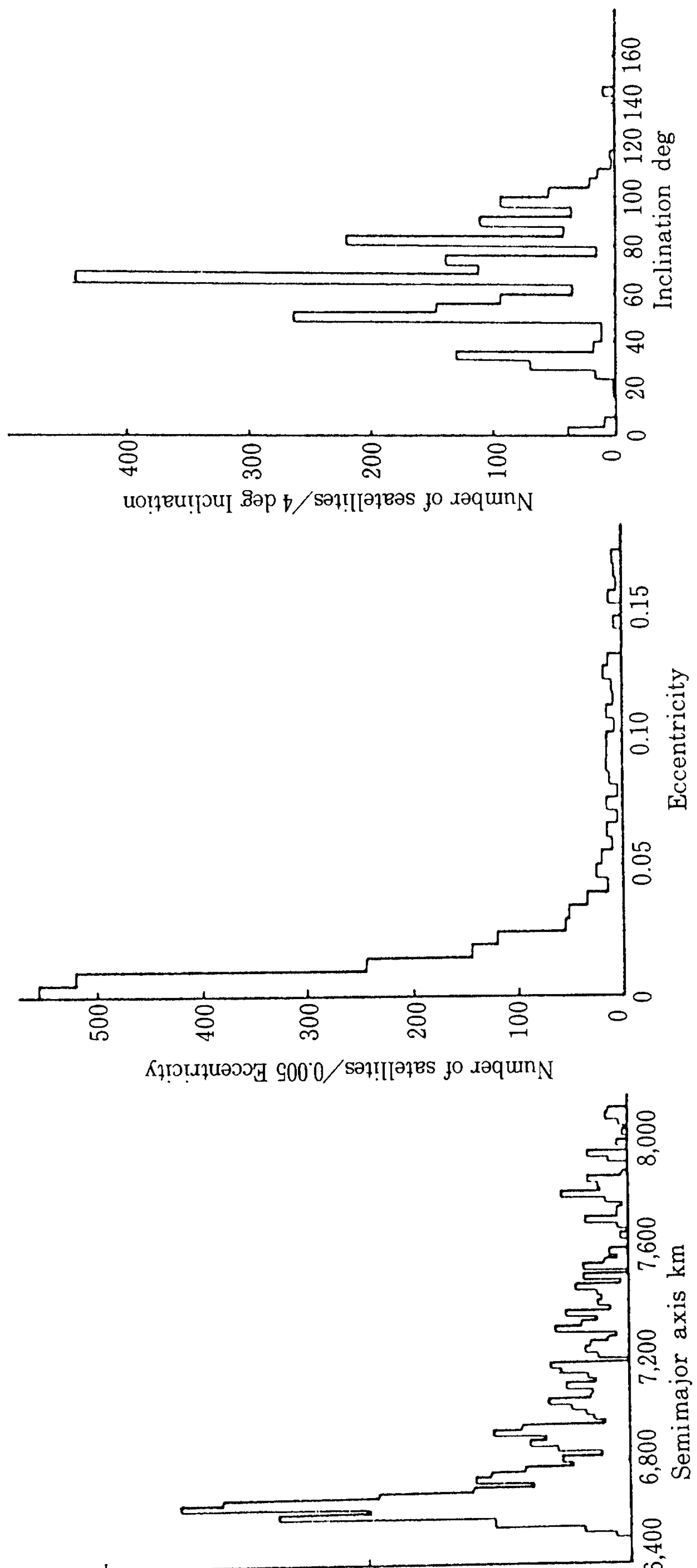
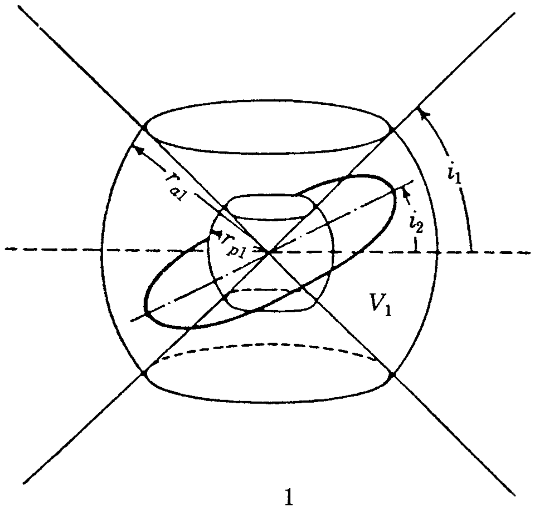


Fig. 1. Distribution of Artificial Orbiting Bodies Identified in 1971



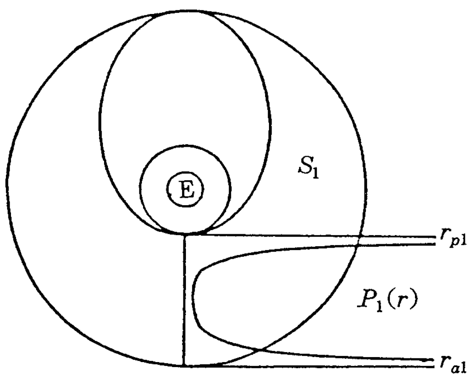
$$p_1 = \frac{1}{\frac{4}{3}\pi\,(r_{a1}^3 - r_{p1}^3)\sin i_1}$$

$$P_{21} = l_2^2 L_2 P_1$$

$$P_j = 1 - \prod_{k \neq j} (1 - P_{jk})$$

$$\approx \sum_{k \neq j} P_{jk}$$

Fig. 2a. Model 1 (Three Dimensional Uniform Density Model)



$$P_1(r) = \frac{1}{\pi^2\,(r_{a1}+r_{p1})\sqrt{(r_{a1}+r_{p1})}}$$

$$P_{pc2} = 2\pi\, r_2 l_2 p_1 (r_2)$$

$$\frac{P_{pc2}}{P_{pc1}} = \frac{1}{\pi}\;\frac{r_{a1}-r_{p1}}{\sqrt{(r_{a1}-r_{p1})\,(r_2-r_{p1})}} > \frac{2}{\pi}$$

Fig. 2b. Model 2 (Two Dimensional Stay Time Model)

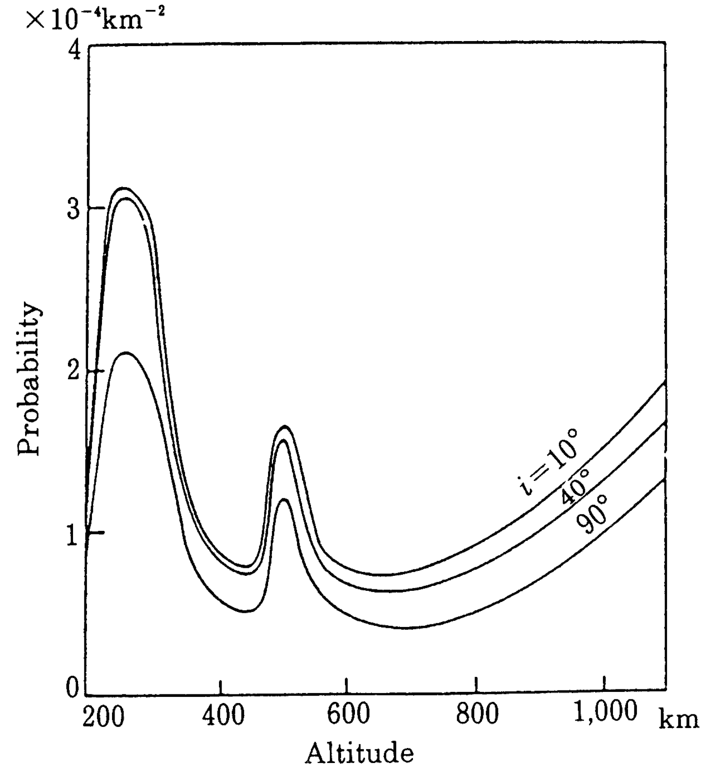


Fig. 3a. Collision Probability in 1971 Estimated by Use of Model 1

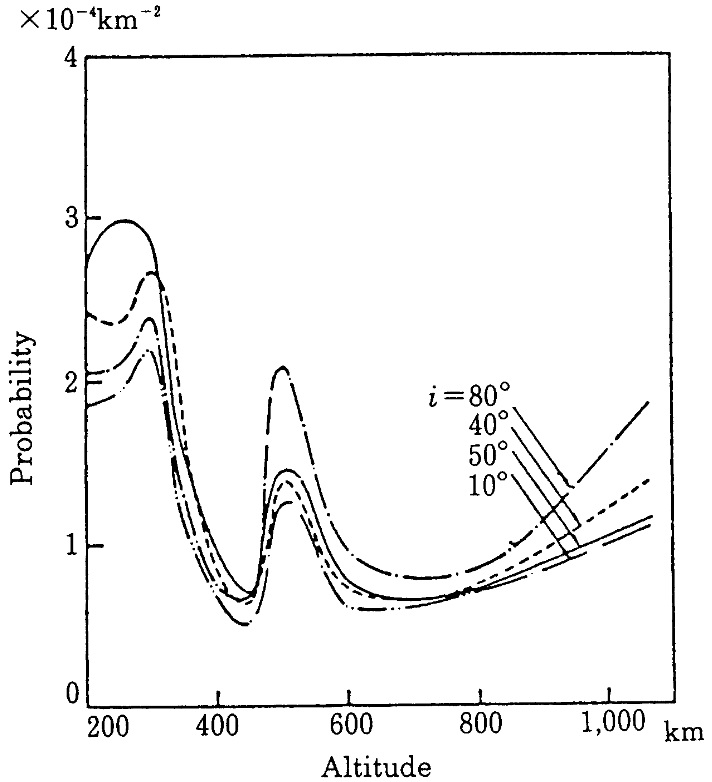


Fig. 3b. Collision Probability in 1971 Estimated by Use of Model 2

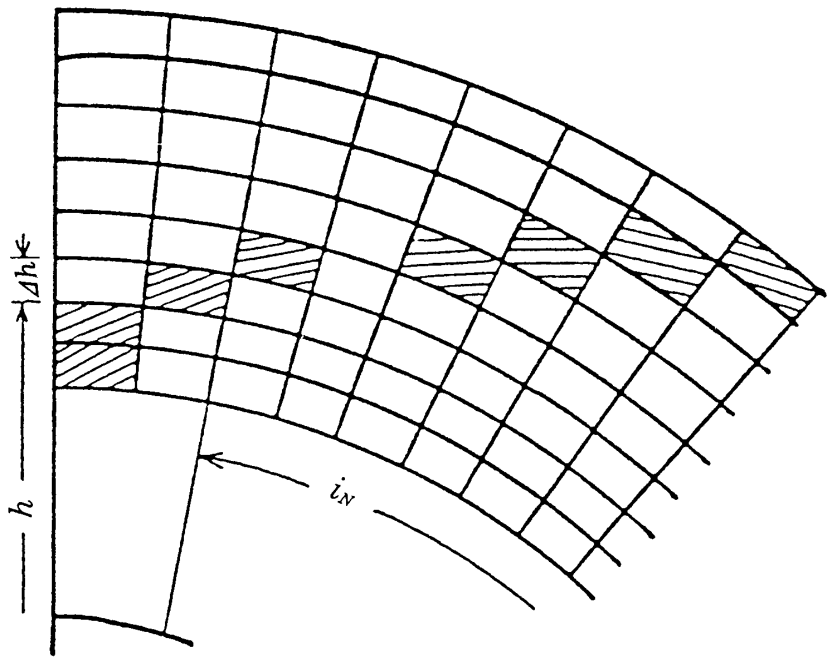


Fig. 4. Concept of STC System

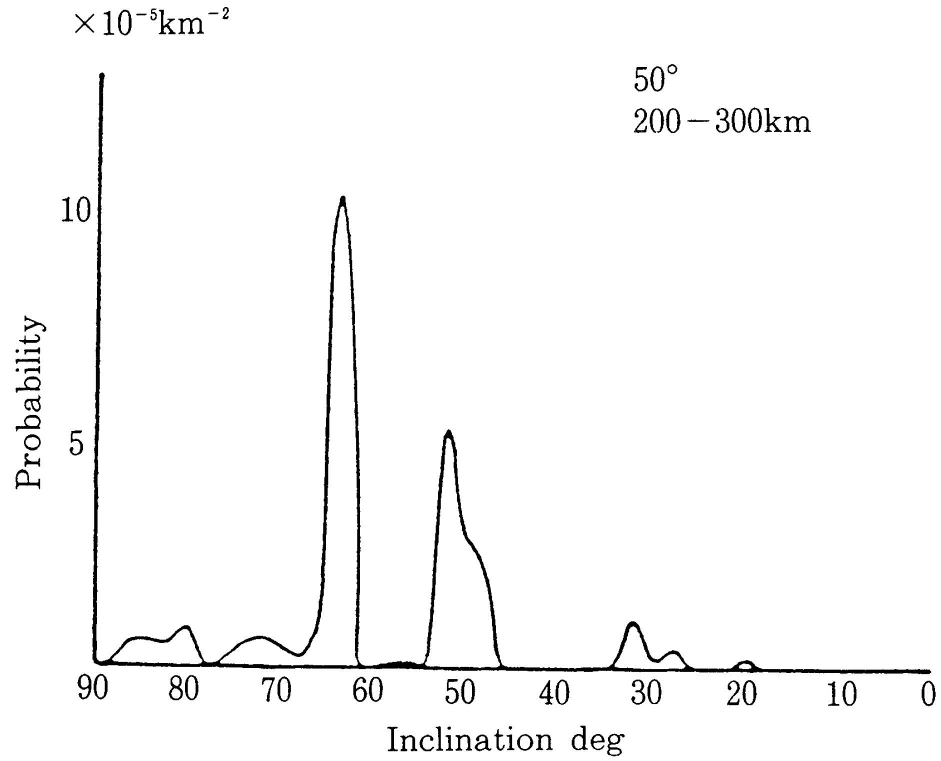


Fig. 5. Contribution of Orbital Inclination to Collision Probability

3. Safety Design Of Space Station Against Collision Hazards With Artificial Orbiting Bodies

Since it had become clear that artificial orbiting bodies might threaten the safe manned space flight in the coming space station age, we considered the aspect of safety design of space station against collision hazards [2].

Table 1. Categorization of Collision Hazards to Space Station

Hazard class	Damage extent	Damage mode
I	Fatal	Structure damage
II	Rescue required	Decompression Subsystem damage
III	Repairable	Abnormal motion
IV	Disturbance	Space activity interruption

At first in this paper, potential collision hazards to the space station were categorized into four classes as listed in Table 1. The first class hazard caused by collision with another space station, a manned transport vehicle or a large unmanned satellite with high relative velocity should be catastrophic and there are few chances for the crew to be rescued (Fig. 7). The second class hazard includes various damages caused by collisions with smaller artificial or natural orbiting bodies. In this case, it is supposed that airtight compartment is broken or penetrated by debris as shown in Fig. 8 and rescue of crew members should be required. The third category is for lighter damages which could be repaired by the crew though abnormal or undesirable motion of the space station might be induced by the collision. The fourth class hazard is caused by near miss of space debris. In this case, the space station does not suffer from direct damages, but its normal activities and operations would be disturbed.

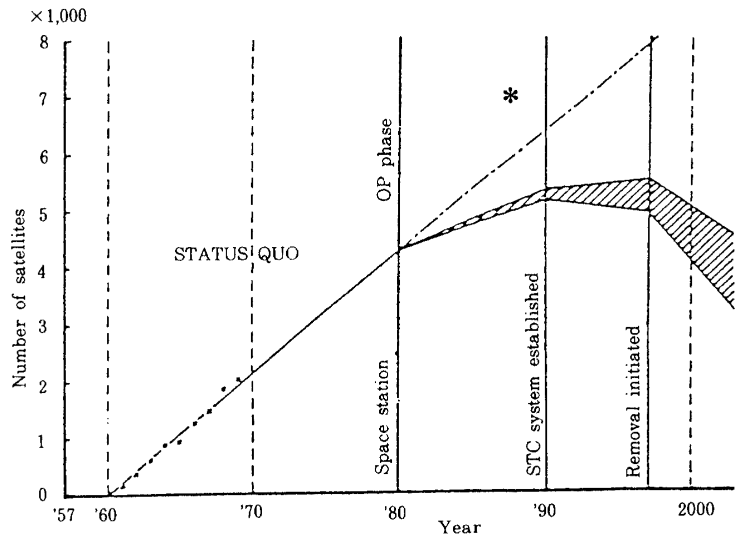


Fig. 6. Prediction of the Number of Orbiting Bodies and Effects of STC System

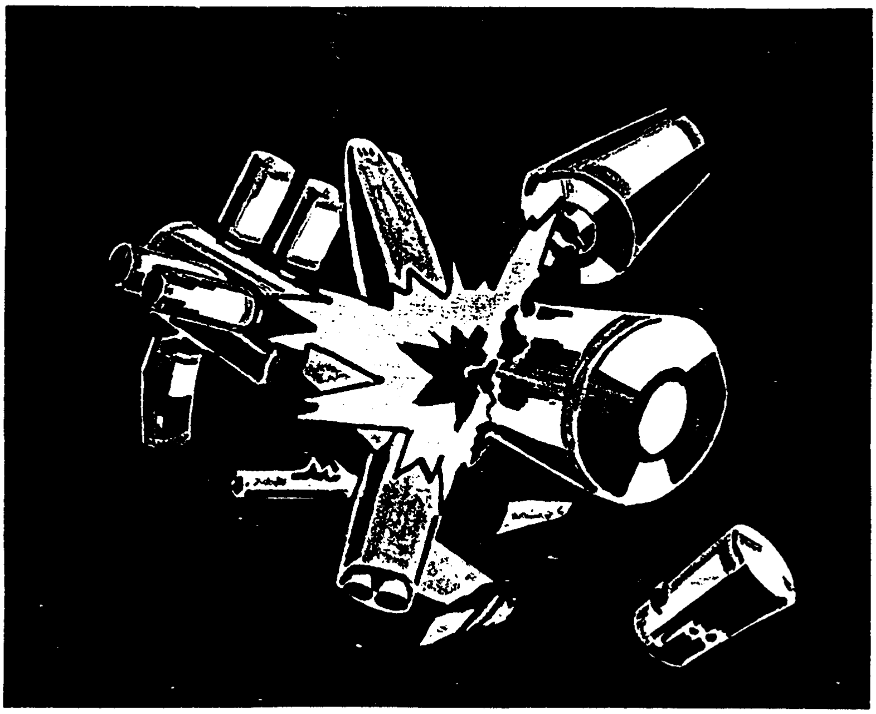


Fig. 7. Collision Hazard Category I

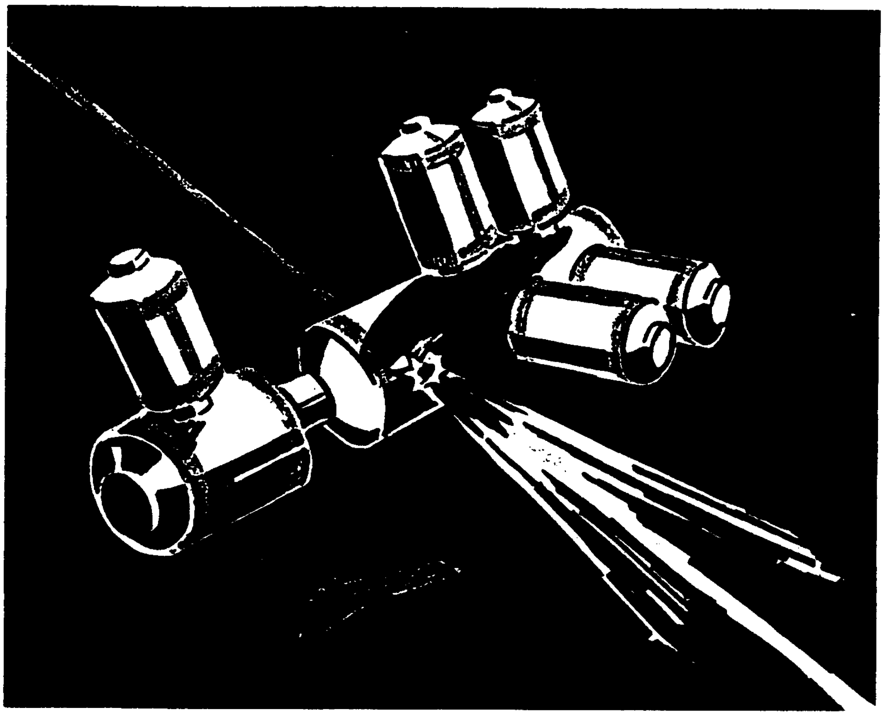


Fig. 8. Collision Hazard Category II

In the paper, two countermeasures to reduce such hazards were mentioned as follows:
1) Onboard detection of space debris and refuging maneuver if necessary,
2) Sweeping dangerous space and establishing Space Traffic Control.

As for the onboard detection of space debris, an active search radar installed on the space station was proposed and its technical problems were discussed. Fig. 9 shows an example of estimated collision probability with debris around the space station which is assumed to fly on a circular orbit with 500 km altitude and 50° inclination. This figure indicates that debris, which is highly probable to collide with the station and therefore should be detected by the search radar, is existing within a region of –45° to +45° in elevation angle and can be divided into two groups as for relative velocity. One group has high relative velocity (7 – 15 km/s) and is concentrated in the forward region with elevation angle less than 15°. Another group spreads sideward with low relative velocity (0 – 7 km/s).

The performance of onboard search radar which could detect such debris were studied, and Table 2 lists a specification of search radar having highest performance conceivable at that time. Using such a radar, it was anticipated that a sphere with 0.3 m could be detected at a distance of 200 km. Fig. 10 describes how much acceleration level is required for the propulsion system of space station for refuging maneuver. Under assumptions that refuging distance is 300 m and that 5 sec of data processing time is necessary to decide whether a debris detected by the radar would collide or not, it is read from the figure that, for example, at least 0.01 g of acceleration is required to avoid collision with debris with 10 km/s of relative velocity and 1 m in diameter. The uppermost line in the figure shows a limit where only the prediction whether collision would occur or not can be done.

In this paper, sizing of airtight compartments was also discussed in order to minimize damages caused by collision of category 2. Also discussed was the space sweeper mission to make the potential manned flight region clean up.

4. Optimum Low-Thrust Multiple Rendezvous

The space sweeper mission inevitably requires multiple rendezvous by a single spacecraft (space sweeper) with several dead satellites or orbiting bodies flying with

Table 2. Specification of Search Radar

Frequency	10 GHz
Peak power	5 MW
Pulse rate	500 ~ 1000 pps
Pulse width	1 ~ 1.5 sec
Measuring characteristics	
Maximum range	1000 km
Range accuracy	150 m
Angular accuracy	0.02°

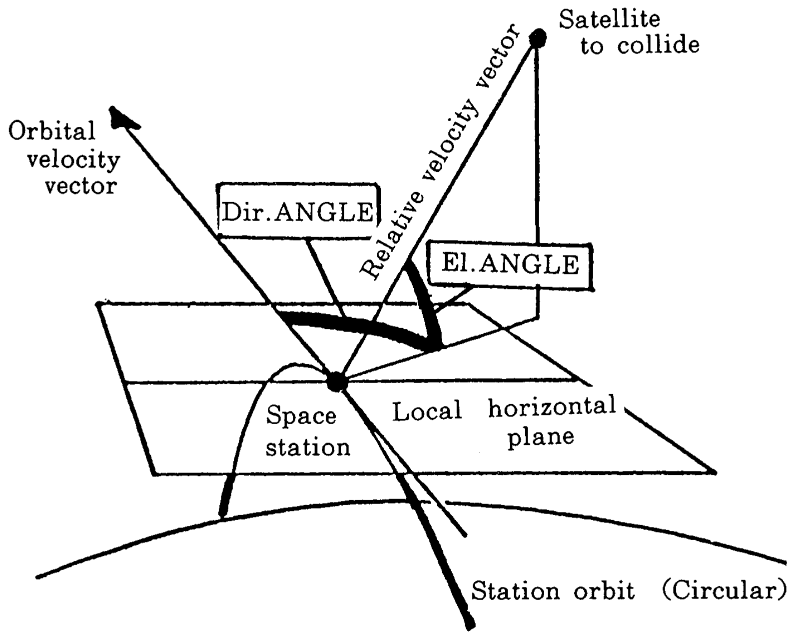


Fig. 9a. Coordinate System for Search Radar

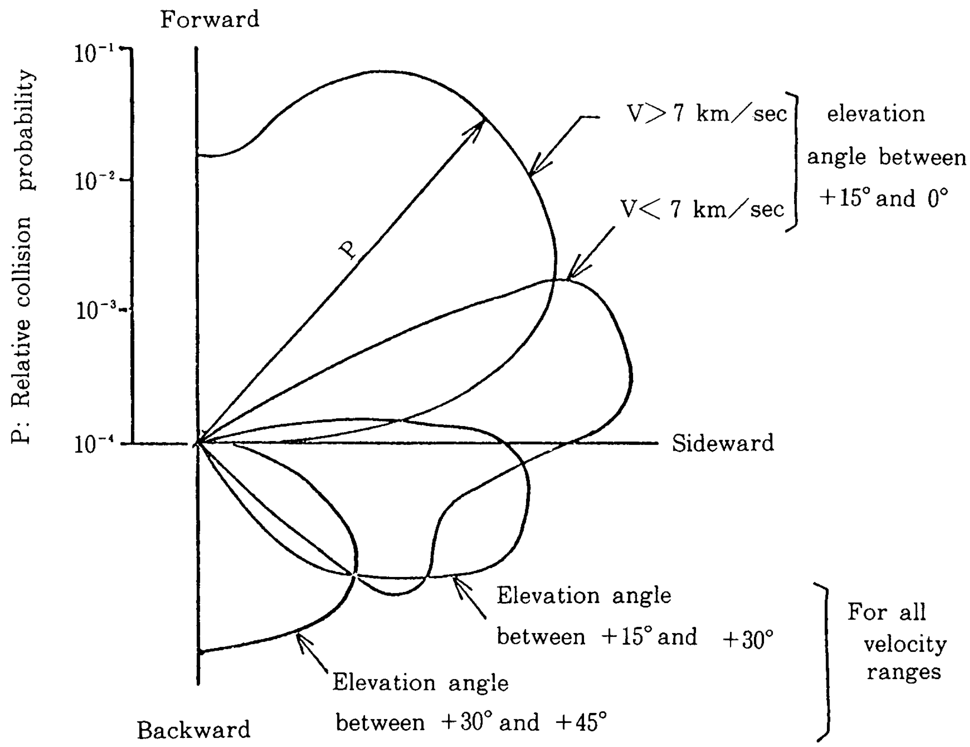


Fig. 9b. Directional Collision Probability Projected on Local Horizontal Plane

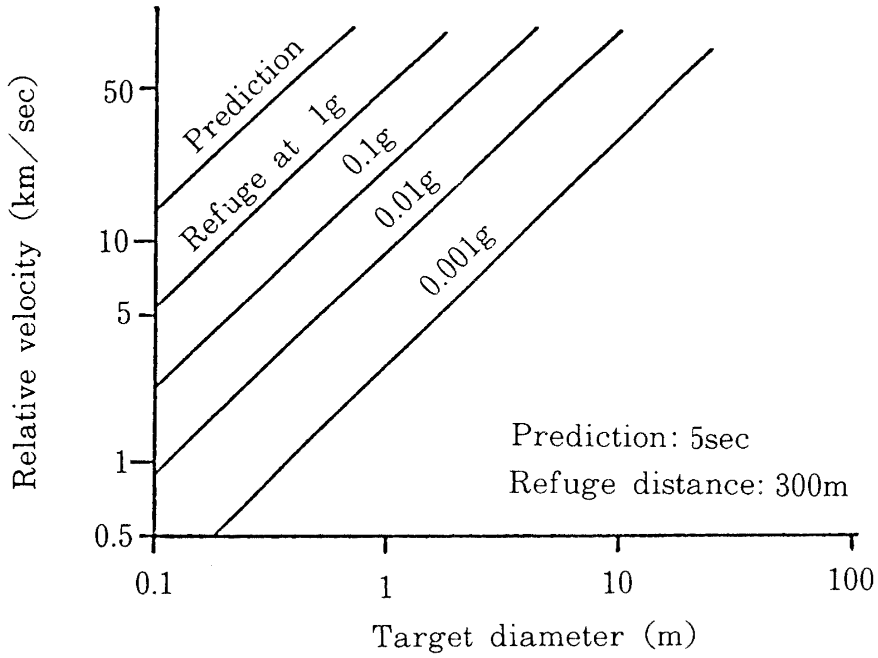


Fig. 10. Required Acceleration Level for Refuging Maneuver

different orbital elements. Since the conventional chemical propulsion system is, as well-known, inadequate to such a mission, we proposed space sweeping by use of solar powered electrical propulsion system and developed a trajectory optimization technique for low-thrust multiple rendezvous problem [*3*].

A simple equation representing a performance index to evaluate fuel consumption required for low-thrust rendezvous was developed and the optimum multiple rendezvous problem was solved by applying a solution for so-called travelling salesman problem.

Table 3 shows an example of optimized sequence, flight time allocation and fuel consumption when a low-thrusted space sweeper pursues 10 orbiting targets which have typical orbital elements in a region dangerous against the space station as listed in Table 4.

5. Collision Probability In Space And The Debris Environment In Future

During more than a decade since 1971 when our first calculation of number density of artificial orbiting bodies and estimation of collision probability in the near earth space done [*1*], the number of space debris had continued to increase as predicted. So, in 1984, the collision probability at that time was reestimated [*4*]. Fig. 11 shows the results and it is read from the figure that the collision probability of a space station, which flies within an altitude range of 200 to 500 km and has a cross-sectional area of 10,000 m^2, is about 0.01. Surprisingly, it became clear that this value had been maintaining the same level for more than a decade. However, it should be noted that the collision probability around 1,000 km height is about ten times higher than at 500 km height.

Table 3. Optimum Sequence and Costs for Multiple Low-Thrust Rendezvous Pursuing Targets Listed in Table 4

I_{SP} = 5000 sec.

sequence	*i* (deg)	n_{fj}	a_{oj} (km/s²)	ΔV_j (km/s)	m_{fj}/m_{oj}
0–9	3.1	28.87	$3.4318 \cdot 10^{-6}$	0.6002	0.9878
9–1	2.4	22.12	3.4741	0.4648	0.9906
1–10	11.9	104.06	3.5072	2.2479	0.9552
10–2	3.9	33.01	3.6717	0.7353	0.9851
2–5	16.0	131.55	3.7272	3.0445	0.9398
5–8	5.7	43.89	3.9660	1.0595	0.9786
8–3	5.2	39.43	4.0526	0.9716	0.9804
3–7	5.2	38.42	4.1337	0.9656	0.9805
7–4	7.5	54.40	4.2159	1.4006	0.9718
4–6	5.0	35.80	4.3381	0.9441	0.9809
6–0	2.7	18.45	4.4224	0.4938	0.9900
Total		550.00		12.9279	0.7682

Table 4. Typical Targets To Be Swept

orbit No.	*a (km)*	e	ω (deg)	Ω (deg)	*i* (deg)
0	7078.	0	–	0.	30.
1	7103.	0.0246	80.	10.	28.
2	7078.	0.0071	−100.	30.	32.
3	7228.	0.0138	150.	−20.	31.
4	7278.	0.0137	30.	−15.	30.
5	6978.	0.0072	0.	0.	33.
6	7028.	0.0071	60.	−5.	29.
7	7303	0.0034	−60.	−30.	30.
8	7003.	0.0178	−120.	−10.	31.
9	7353.	0.0034	90.	5.	28.
10	7253.	0.0034	−150.	35.	29.

We considered such phenomena were caused by the fact that the lifetime of debris in low earth orbit was relatively short because of air drag. Then we estimated the lifetime of debris in consideration of the change in atmospheric density caused by periodic variation of solar activity. Fig. 12 describes the lifetime of debris injected into a circular orbit in 1980 as a function of debris mass and initial altitude.

Using such results and assuming launch frequency maintained, the number density of space debris in the next 50 years and collision probability in future were predicted as shown in Fig. 13 and Fig. 14. It is read from these figures that collision probability in the low earth orbit region in 2030 looks like maintain as same level as in 1980, but that, at the height of around 1,000 km and 1,400 km, the number of space debris will continue to increase.

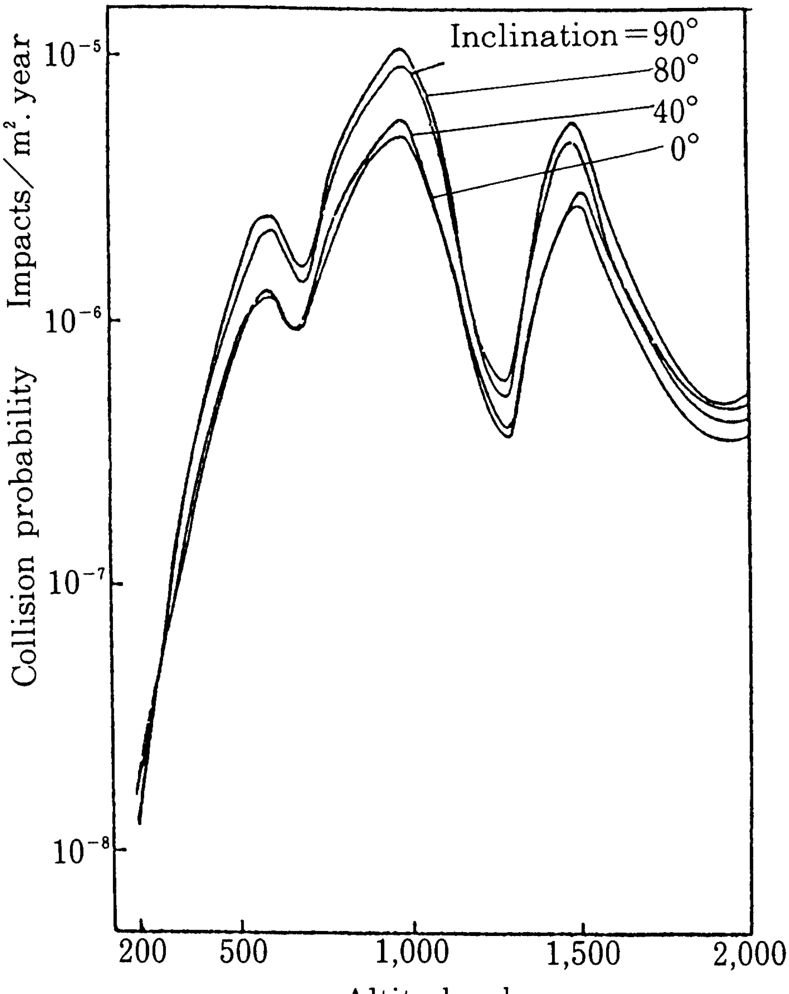


Fig. 11. Collision Probability in 1982

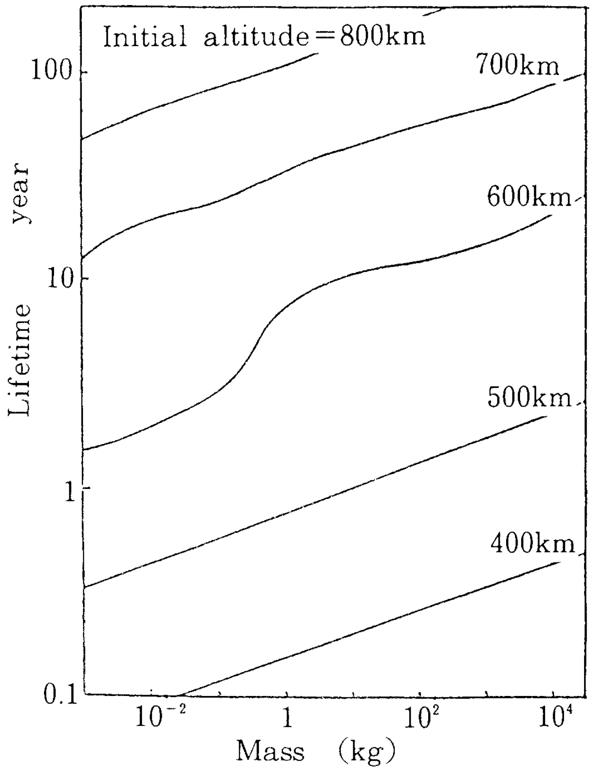


Fig. 12. Lifetime of Space Debris

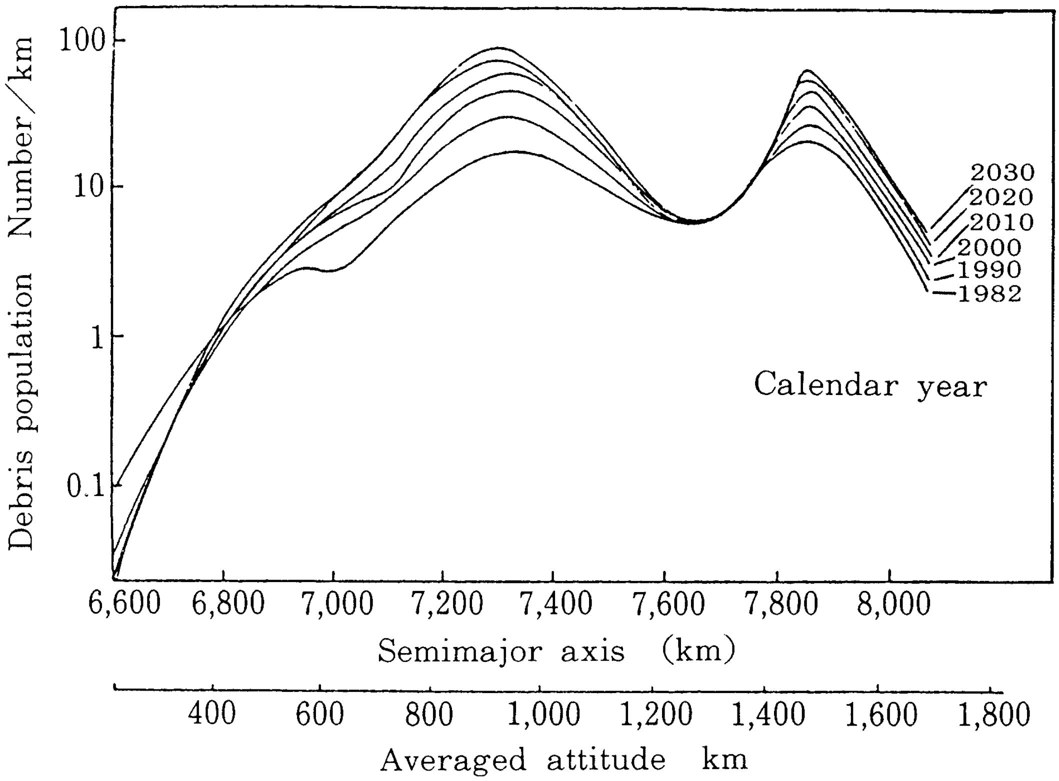


Fig. 13. Predicted Number Density of Space Debris in Next 50 Years

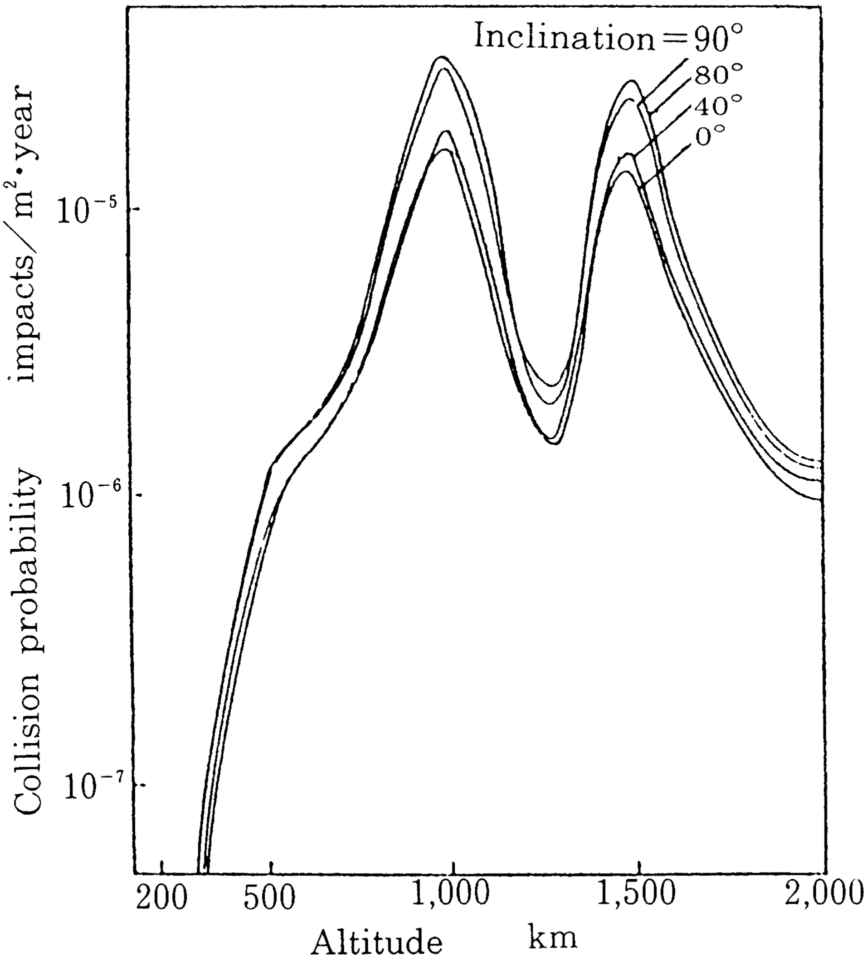


Fig. 14. Predicted Collision Probability in 2030

6. Concluding Remarks

Studies in ISAS concerning collisions in space have been reviewed chronologically and the major results of each paper have been presented. We started our studies in this field in 1971, however, not all studies are of course necessarily complete and we should continue further investigations. Especially it is expected hereafter not only to carry out paper works but also to take actions in controlling and reduction of space debris in a framework of international cooperations. Finally it should be pointed out that international agreement and establishment of several kinds of the space law as for space debris are quite important and necessary along with technical solutions in this field.

References

[*1*] M. Nagatomo, H. Matsuo and K. Uesugi, Some Considerations on Utilization Control of the Near Earth Space in Future, *Proc. 9th ISTS*, pp. 257–263, 1971.

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