Orbit Analysis for the Feasibility Study of the Space Debris Observation System

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Abstract

NASDA has been studying the space debris observation system since 1994. This system is considered as a necessary infrastructure for the manned space activity age in the future. We studied the hardware system which must be prepared and designed the operation conception. In addition, we carried out orbital data processing analysis for the purpose of the feasibility study of the whole system.

In the space debris observation, the most difficult thing is the orbit determination using little observation data.

Owing to cost saving approach, reentry prediction accuracy of the space debris is important on the assumption of a single observation station in Japan.

Then, we carried out the feasibility study from two points described above.

We report the above mentioned analysis method and details of the result in this paper.

1.Introduction

NASDA is studying the space debris observation system to support future manned space activities. This system consists of four subsystems; radio wave observation, optical observation, orbital calculation and integrated management subsystems.

Except for the orbital calculation subsystems, the development of hardware is the principle object. Orbital calculation subsystem requires the study of algorithm to be loaded on this software since this system requires the specific calculation method of its own.

We presumed an unknown apriori orbit which is newly discovered for the particular calculation method for space debris.

Until now, NASDA has been smoothly accomplished the improvement in the precision of the orbit determination with large observation data because high precision was always required to operate satellites. As to the space debris observation, subsequent visibility has to be predicted by poor observation data from radar. Such a technology has not been much discussed precisely in NASDA. Therefore, we concluded that the observation of the technology allows to improve the orbit determination accuracy of unknown debris and to catalog it.

We took another approach by the order estimation which shows how much orbit prediction accuracy of debris is improved if one observation station is developed in Japan. We carried out the post-analysis of the reentry prediction using the prior experience through the Two Lines Orbital Element (TLE) of satellite FSW-1 of China which reentered in March, 1996. Using up to dated data of the TLE, we made simulative observation data in a virtual observation in Japan by just before reentry, and estimated a site and reentry time based on the orbit determination according to this simulative observation data. We compared reentry information estimated in this way with actual reentry imformation. In this comparison, we got the result that the reentry prediction accuracy is about one hour before the reentry.

2. Orbit estimation experiment

In order to catalog the debris through observations, the primary orbit must be determined at first attempt. At least, primary orbit requires as much accuracy as it predicts the following passing visibility information over the ground station on the next day. Because, if it succeeds in the observation of the identical debris on the next day, we can expect the rapid improvement in the orbit determination accuracy by two visible data which is combined with the data in the previous day. Therefore, it becomes important to demonstrate that the orbit determination can be acquired with a single pass. However, NASDA does not possess the possible radar to observe debris. So, we experimented to observe the space debris with Kyoto University's MU radar(Middle and Upper atmosphere radar).

(1) Experiment method

- Using MU radar, we observed the MOS-1b which was tracked by NASDA routine operations, and then determines it by that tracking data.
- By comparing orbit determination value based on observation data from MU radar with highly accurate orbit determination value, we can grasp adoptable orbit determination accuracy by the observation data.
- The observations were carried out on the following schedules.

Stage.1 1995-07-11,12,13(1pass/day)
Stage.2 1995-11-28,29,30(1pass/day)

The MU Radar is located in Shiga Prefecture, and is used not only by Kyoto University, but also by other research institutes at home and abroad. It is a large active phased array radar which can monitor atmospheric phenomena in the middle and upper atmosphere.

The MU Radar transmits signal from 475 Yagi antennas installed in a 103m diameter circular site, and immediately directs a composite radiation beam in a designated direction with active phased array system.

The key parameters of the MU radar are shown in Table 1.

Table 1 MU radar parameters

Center Frequency	46.5 MHz
Beam Width	3.6°
Peak Power	1 MW
sub-Pulse Width	64 μ sec
Accuracy of Angle Detector	0.1°
Accuracy of Range Detector	200 m

(2) Early Orbit Determination (EOD)

In general, high accuracy orbit determinations adopt with the special perturbation method by using the data of many observation passes. However, it must be carry out the orbit determination of space debris in the initial stage based on the geometric orbit determination method.

Because, it must be carried out the orbit determination by only one pass data and there is no initial orbit element for Newton-Lapson method.

The summary of the early orbit determination which is adopted with this experiment is explained below.

1) Geometric orbit determination method by only head and tail AZ/EL data
2) Determination of initial orbit element for Newton-Lapson Least Square Method
3) Orbit determination by special perturbation method by using whole ranging data

Through these processes, these determined orbits are not osculating elements. Under this experiment condition, however there is no problem for us to regard the determined elements as osculating elements because data arc is far too short.

The determined 6-element by EOD are summarized in Table 2.

The estimated position error between the reference value and the MU value are summarized in Table 3.

(3) Evaluation criteria

The case which this approach experiment assumes that it captures unknown space debris at first, it re-captures the identical object which passes over the observation site in the next time. Therefore, it seems to be possible to re-capture the object if the beam prediction error is within 3 ° which is described from practical observation beamwidth of the MU radar.

Table 2 Early Orbit Determination results

	07-11 12:29:10.031		07-12 12:34:52.401		07-13 12:41:46.721		11-28 01:21:40.471		11-29 01:27:45.761		11-30 01:33:45.971	
	Ref. value	MU value	Ref. value	MU value	Ref. value	MU value	Ref. value	MU value	Ref. value	MU value	Ref. value	MU value
a (km)	7290.383	6995.703	7290.701	7173.189	7289.826	7776.479	7289.210	7159.930	7289.210	7328.950	7289.120	7217.590
e	0.0014	0.0419	0.0014	0.0162	0.0014	0.0632	0.0013	0.0211	0.0014	0.0062	0.0014	0.0098
i (deg)	98.992	98.618	98.991	98.975	98.991	97.884	99.130	97.990	99.130	98.930	99.130	99.350
Ω (deg)	261.379	261.140	262.358	262.377	263.337	262.562	38.910	39.660	39.900	40.030	40.890	40.710
ω (deg)	103.429	219.211	101.826	203.895	106.785	39.642	67.580	294.670	67.390	168.570	66.680	316.200
M (deg)	289.680	173.188	290.163	188.232	288.267	355.735	74.470	208.870	74.650	333.980	75.060	185.800
φ (deg)	33.109	32.399	31.989	32.127	35.052	35.377	142.050	143.540	142.040	142.550	141.740	142.000

*1) Reference value:NASDA operational orbit determination element
*2) MU value:EOD element by MU radar
*3) ϕ :Argument of Latitude(ω + M)
*4) All elements are expressed by osculating element

Table 3 Estimated position error

	07-11 12:29:10.031	07-12 12:34:52.401	07-13 12:41:46.721	11-28 01:21:40.471	11-29 01:27:45.761	11-30 01:33:45.971
ΔR (km)	2.1	4.3	0.6	18.0	3.4	3.9

Most of the prediction error can be replaced by the earth rotation angle which is caused by visibility timing error with Semi-major-axis error. So, the MU radar beamwidth can be replaced by the earth rotation time of 89sec, which is calculated by MOS-1b nominal altitude. It is possible to obtain the criteria for evaluation of permission determination error of Semi-major-axis by this experiment.

The equation of the two-body problem is given by

$$n^2 = \mu / a^3$$

where, n:Mean motion
μ :Earth gravity coefficient
a:Semi-major-axis.

Then n can be calculated from the MOS-1b nominal Semi-major-axis, as

$$n = (2.975540 \times 10^{15} / 7287^3)^{1/2}$$
$$= 87.962 \text{ (rad/day)}.$$

The Semi-major-axis(a') which is included with orbit determination error is derived by Mean motion (n) and it is superposed with 89sec.

The Semi-major-axis(a') can be calculated by the following equation.

$$a' = (\mu / n'^2)^{1/3}$$
$$= (2.975540 \times 10^{15} / 87.782^2)$$
$$= 7282 \text{ km}$$

The permitted Semi-major-axis determination error is given by the difference between a and a', which is ±5 km. As seen from Table 2, all cases do not satisfy acceptance evaluation criteria (Δa=119km, 109km, 372km, 129km, -40km, 72km).

(4) Results of Special Perturbation method

Then, we determined orbit by special perturbation method with the above data and used EOD elements as the apriori value. On this determination, we used Baisian weighted least square method because the observation data quantity is much poor.

In this orbit determination, we estimated caltesian elements without position parameter with fixing the velocity parameter.

The 6-element determined by SP-EST are summarized in Table 4.

As seen from Table 4, all cases Semi-major-axis error are decreased considerably, and case-1 satisfies the aforesaid evaluation criteria.

Table 4 Special Perturbation Method estimation results

	07-11 12:29:10.031		07-12 12:34:52.401		07-13 12:41:46.721		11-28 01:21:40.471		11-29 01:27:45.761		11-30 01:33:45.971	
	Ref. value	MU value	Ref. value	MU value	Ref. value	MU value	Ref. value	MU value	Ref. value	MU value	Ref. value	MU value
a (km)	7290.333	7285.677	7290.701	7275.137	7289.826	could not be estimated	7289.210	7187.710	7289.210	7328.090	7289.120	7261.450
e	0.0014	0.0017	0.0014	0.0032	0.0014		0.0013	0.0182	0.0014	0.0062	0.0014	0.0042
i (deg)	98.992	98.803	98.991	99.127	98.991		99.130	97.990	99.130	98.930	99.130	99.310
Ω (deg)	261.379	261.255	262.358	262.472	263.337		38.910	39.660	39.900	40.030	40.890	40.750
ω (deg)	103.429	135.536	101.826	155.055	106.785		67.580	286.280	67.390	170.230	66.680	291.030
M (deg)	289.680	257.600	290.163	237.137	288.267		74.470	217.370	74.650	332.340	75.060	211.110
φ (deg)	33.109	33.136	31.989	32.192	35.052		142.050	143.650	142.040	142.570	141.740	142.140

3. The reentry prediction analysis

(1) The purpose of this analysis

The reentering of the spacecraft such as the space debris was recently taken up as a social problem. Especially, reentering of the large spacecraft happened successively in 1996 and these phenomena drew attention in Japan.

Those were FSW-1 satellite of China which reentered in the last spring and MARS96 which was failed to inject to the Mars exploration orbit in the last winter.

Over 10 years NASDA has predicted possible spacecrafts which could fall to the Earth without complete combustion. As NASDA does not track spacecrafts by radar, we can not use the observation data of reentering objects.

So, we compute reentry prediction based on the TLE which can be obtained from NASA Goddard Space Flight Center.

Spacecrafts on the point of reentering is greatly affected by the atmospheric drag force because spacecrafts orbit in low altitude where atmospheric density is very high. Thus, NASDA estimates parameters related to ballistic coefficient on the condition of orbit generation for reentry prediction.

The estimation method for optimizing the ballistic coefficient are shown below.

1) Obtain two TLE of (o1) and (n1). (o1) represents the last element, and (n1) represents the latest element.
2) Shift the element(o1) to the element (n1) epoch.
3) In this process,scan the parameter of the ballistic coefficient to agree between the argument of latitude of the generated element(o2) and the argument of latitude of (n1).
4) If two arguments of latitude coincide the calculated ballistic coefficient with parameter scanning is defined as the optimum value.
5) Generate the element(n1) with the above mentioned optimum ballistic coefficient.

The above is the NASDA method for predicting the reentry which has long been adopted. The pivot of the problem of this method is shown below.

- Determination error of the TLE and the transitory fluctuation of atmospheric density are courses of large error in the prediction accuracy.
- The TLE determination error and the perturbation model error are feedbacked to the estimated optimum ballistic coefficient.

The reentry of the spacecrafts recently became a part of the crisis management in Japan, and the improvement in the accuracy of the reentry is an urgent matter. Therefore, the reentry prediction error which leads the above mentioned two problems must be improved. This circumstances suggests us to have the radar to observe the reentering object to conclude the problems drastically. This analysis is done for feasibility study concerning the accuracy of the reentry prediction on the assumption that Japan has one radar site.

(2) The limit to reentry prediction without observations

The above mentioned example of prediction results are shown in Table 5.

As can be seen in the Table 5, that is impractical because the prediction error is a few hours when it was done before 1-2 days of the reentry, but 0.5-1 day before 4-5 days of it. When the reentry prediction should be done as the crisis management, the required accuracy is ±1 hour before 4-5 days of the reentry and ±0.25 hour before a day of it. Because the reentry tracing pass ca be almost specified when the ±1 hour error can be secured, then danger which affect a land is easily grasped.

Then we made the above mentioned permitted value as a evaluation criteria for the feasibility study here.

Table 5 Example of reentry prediction results

Progress M17 (Rassia)			FSW - 1 (China)		
Reentry Day 1994-03-03 03:49 (UT)			Reentry Day 1996-03-12 04:05 (UT)		
Prediction day	Predicted result	Prediction error	Prediction day	Predicted result	Prediction error
X - 6	03-01 22:33	29 hours	X - 6	03-01 22:33	40 hours
X - 5	03-03 23:03	19 hours	X - 5	03-03 23:03	17.5 hours
X - 2	03-03 02:08	1.5 hours	X - 1	03-03 02:08	0.5 hour
X - 1	03-03 04:40	1 hour.	X - 0	03-03 04:40	0.5 hour

(3) Analysis method

Since NASDA does not have the actual observation data of the spacecraft data on the point of the reentry, we analyzed it by simulated data. From the reentry of FSW-1, over 7 days the simulated observation data regenerates with fidelity the observation data from the hypothetical site based on approximaely 40 TLE obtained from NASA every several hours. FSW-1 orbit is determined according to each case setting by this simulation data, and the reentry prediction is done by the determined orbit and ballistic coefficient estimated concurrently. We arranged the Masuda Tracking and Data Acquisition Station(MTDS) in Tanegashima Space Center as the hypothetical site for this analysis.

The case setting is shown in Table 6.

Table 6 Analysis case setting

Case \ Date	03-06 (X - 6) 4 passes	03-07 (X - 5) 4 passes	03-08 (X - 4) 4 passes	03-09 (X - 3) 4 passes	03-10 (X - 2) 4 passes	03-11 (X - 1) 4 passe
a	○	○				
b		○	○			
c			○	○		
d				○	○	
e					○	○
f	○	○	○			
g		○	○	○		
h			○	○	○	

Case \ Date	03-06 (X - 6) 4 passes	03-07 (X - 5) 4 passes	03-08 (X - 4) 4 passes	03-09 (X - 3) 4 passes	03-10 (X - 2) 4 passes	03-11 (X - 1) 4 passe
i				○	○	○
j	○	○	○	○		
k		○	○	○	○	
l			○	○	○	○
m	○	○	○	○	○	
n		○	○	○	○	○
o	○	○	○	○	○	○

As seen from Table 6, FSW-1 could be observed for 3~ 4 passes every day just before reentry from the hypothetical site. We evaluated the reentry prediction accuracy by orbit by using visible simulated observation data which is based on 2 days from 6 days.

(4) Results

The orbit determinations and reentry prediction were carried out respectively with case setting which is mentioned above. By comparing the difference in the reentry prediction time with this analytical method and FSW-1 actual fall time, we can know whether the prediction error satisfies the evaluation criteria.

Provided that reentry prediction time by NASDA means altitude in 90 km of FSW-1 crossing time, since NOCS(NASDA Orbit Computation System) has been adopted to the atmospheric density model at the altitude of 90km over.

However, FSW-1 the actual reentry time means the time which NASDA obtained from USSPACECOM in those days.

The prediction error of the each case is shown in Table 7.

Table 7 Reentry prediction error by this analysis

Case	Analysis Method(h)	Conventional method(h)	Case	Analysis Method(h)	Conventional method(h)
a	0.5	17.5	i	0.5	1.0
b	-1.0	23.0	j	0.0	4.0
c	0.5	4.0	k	——	3.5
d	-0.5	3.5	l	1.0	1.0
e	——	1.0	m	0.5	3.5
f	-1.5	23.0	n	0.5	1.o
g	0.5	4.0	o	0.5	1.0
h	0.5	3.5			

As seen from Table 7, there is remarkable improvement in the reentry prediction results with the simulated observation data as compared with conventional NASDA prediction method. Also, it was possible to verify that the reentry prediction error had sufficiently satisfied the evaluation criteria.

Figure 7 shows the world map which plots the predicted reentry points by this analysis for every case setting.

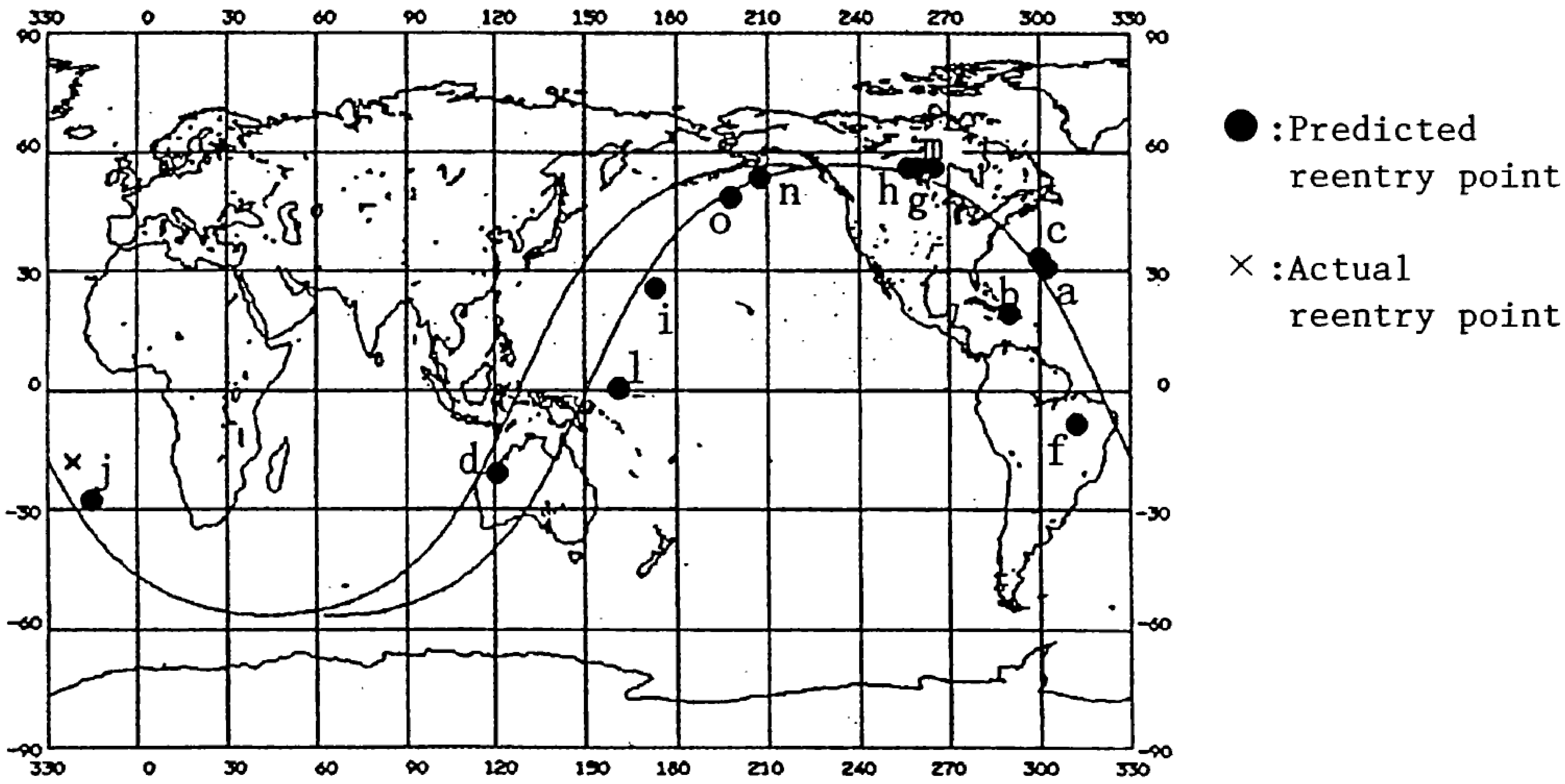

Figure 1 Reentry prediction results on the World Map

4. Conclusion

The analysis and study shown in this paper was made within the scheme of " The research of the space debris ground observation system " in NASDA, and shows the feasibility of the concept of the development in Japan in the future.

As to the space debris observation, USA and Russia are in the stage which can perform actual observations, and Europe has already performed actual experiments on a full scale. Under these circumstances, we are in the standpoint that the international contribution will be required as a member of the space development nations in the future.

Therefore, we want to lead the conceptual study phase to the development stage, accumulating satisfactory results of the verification about the feasibility of the debris observation system based on the analysis presented in this paper.

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