Conceptual Study of Space Debris Orbit Analysis Test System

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Abstract

Since 1994, NASDA has studied space debris problems from various viewpoints. This paper presents one of these studies: the conceptual study of the space Debris Orbit ANAlysis Test System (DOANATS). The DOANATS is an experimental system that NASDA plans to develop to maintain the orbital data of space objects (both space debris and operational satellites) and to analyze them. In the conceptual study, NASDA has specified the configuration and the functions of the DOANATS.

1. Introduction

After the launch of the Sputnik-I, space activities have contributed to our lives. However, a large amount of man-made space debris has been left in orbits around the Earth. Recently, the space debris has become a threat to our lives as well as space activities, and some accidents indicating the hazard of space debris (uncontrolled reentry of debris, collision of debris to operating satellite, etc.) occurred (Refs. 1,2).

Today, major space agencies around the world have worked on the space debris problem, in order to perform safe and expanding space activities in the future. The United State Space Command has been operating the Space Surveillance Network(SSN) and observing space debris (Ref.3). Russia has also been observing space debris by Space Surveillance System(SSS) (Ref.4). As a result of these activities, more than 8,000 objects including both operational satellites and space debris are currently tracked with the determination of their orbits. Furthermore, their orbital data are provided widely via Internet.

Although Japan has significant space activities as one of space-faring nations, it has not made sizable contributions to the space debris problem. In order to contribute to countermeasures against this problem, NASDA started various studies about space debris in 1994. This paper presents one of these studies : the conceptual study of the Space Debris Orbit Analysis Test System (DOANATS).

The DOANATS has two major objectives. One is to maintain and update the orbital data of space objects (both space debris and operational satellites are included in these objects). Another is to analyze these orbital data. To achieve these objectives, the DOANATS consists of a Data Base Subsystem and an Orbit Analysis Subsystem. All the data in the data base and analysis functions can be provided to other space agencies.

In the following sections, we describe the overview of the DOANATS and specify each function in this system.

2. Overview of the DOANATS

The DOANATS consists of the following subsystems.

— Data Base Subsystem : This subsystem receives the orbital data of space objects from other systems and maintains them with the additional data that are estimated based on these orbital data.

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— Orbit Analysis Subsystem : This subsystem has the functions that perform various analyses of the orbital data maintained in the data base subsystem.

All the data in the Data Base Subsystem and all the functions of the Orbit Analysis Subsystem can be provided to users via Internet.

Figure 1 shows the configuration of the DOANATS.

3. Data base subsystem

The Data Base Subsystem performs the following processes to maintain and update the orbital data.

- Receiving the orbital data
- Estimating the additional data
- Maintaining the data
- Providing the data

Figure 2 shows the constitution of the Data Base Subsystem and its data flow. As Figure 2 shows, four processes described above are offered by five functions : Data Update Function, Format Transformation Function, Data Estimation Function, Data Base, Data Search Function.

3.1 Receiving the orbital data

The Data Base Subsystem obtains two types of orbital data, each of which has a different source.

One is the orbital data in the format of the Two Line Element (TLE) provided by the Remote Bulletin Board System (RBBS). Managed by Goddard Space Fright Center (GSFC), the RBBS maintains the TLE data of more than 8,000 space objects (including NASDA's space objects). A user can access the RBBS as a general user or a super user and obtain the latest orbital data (a super

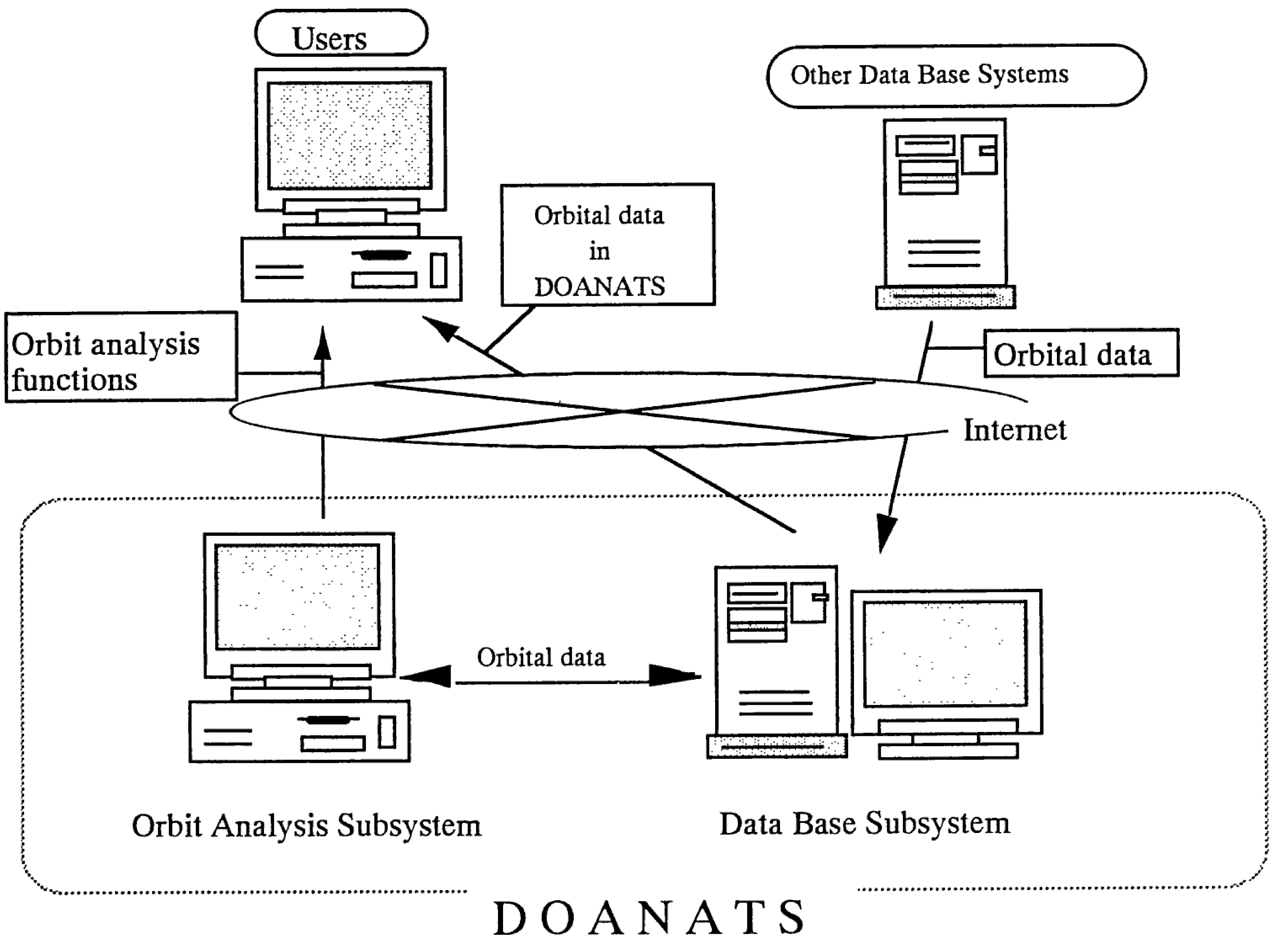

Figure 1 : Configuration of the DOANATS

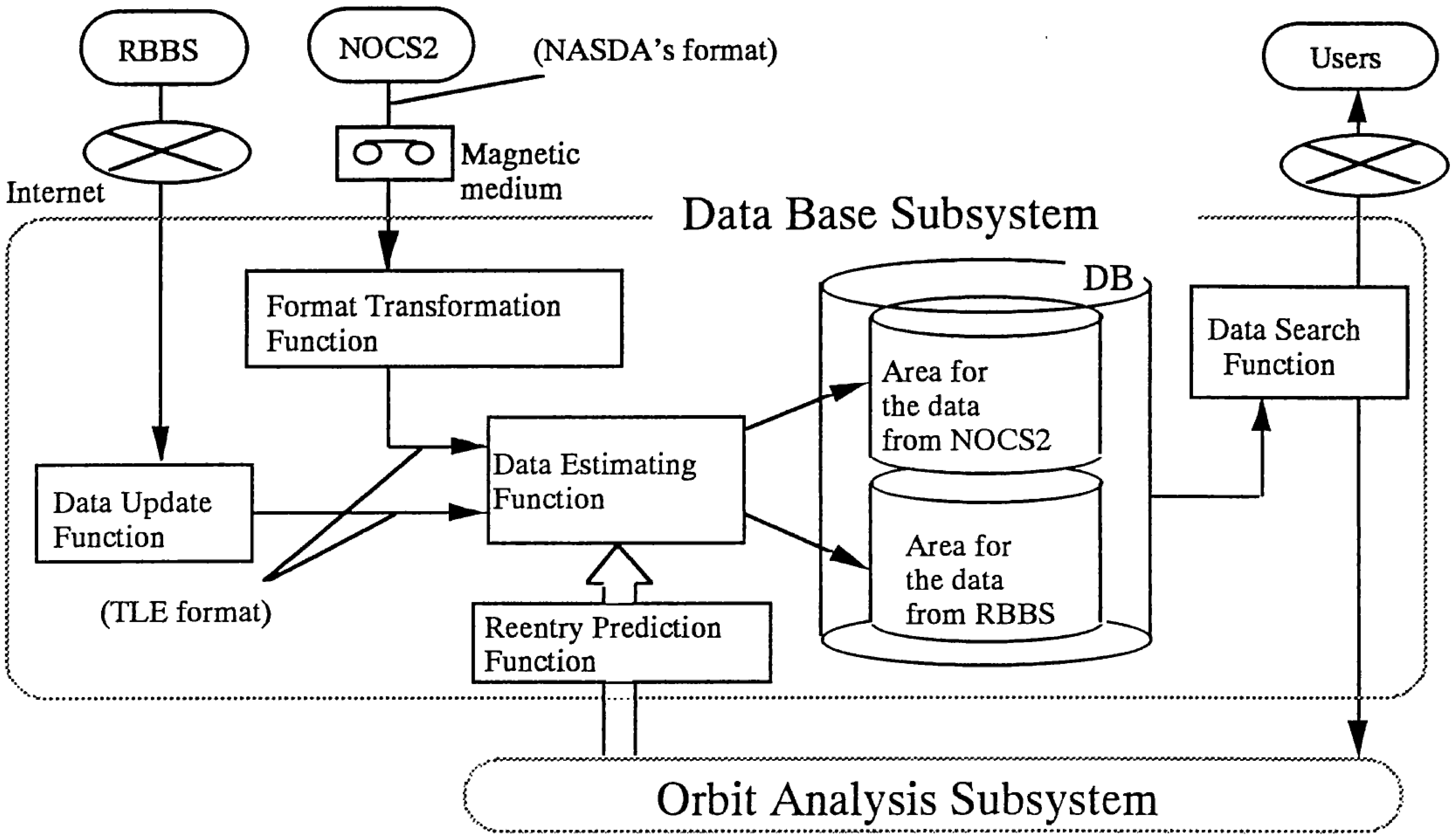

Figure 2 :Constitution of data base subsystem and data flow

user can obtain all the data in the RBBS but a general user can not). The Data Update Function accesses the RBBS as a super user (NASDA has the super user access level) and receives all the TLE data automatically .

The other is the orbital data on NASDA's operating satellites that is estimated by NASDA Orbit Computation System2 (NOCS2). The NOCS2 is the operation support system for NASDA's satellites, which determines orbital data (orbital elements, atmosphere drag coefficients, and so on). The data base subsystem obtains these orbital data. Because the NOCS2 is not allowed to have a connection to the Internet, the operator of the DOANATS transports the orbital data from the NOCS2 to the Data Base Subsystem by using magnetic medium. Then, the Format Transformation Function transforms the format of the NOCS2 data to the TLE format.

As described above, the Data Base Subsystem obtains the two types of orbital data, RBBS data and NOCS2 data, and then, the format of the NOCS2 data transforms to the TLE format. Finally, both data are forwarded to the next stage, the Data Estimation Function.

Here, we explain the reason why the DOANATS maintains the NOCS2 data, although the RBBS data include the NASDA's operational satellites data.

Most of the space agencies are fully aware that the information sharing will make more effective countermeasures against the space debris problem. Currently, the information that NASDA can provide is only the orbital data of NASDA's operating satellites: the NOCS2 data. Therefore, in terms of the information sharing, the DOANATS maintains the NOCS2 data and provides them to other space agencies.

3.2 Estimating the additional data

After the TLE data are obtained from the RBBS and the NOCS2, the Data Estimation Function estimates additional data by using the TLE data. Table 1 shows the items of the TLE data and the additional data.

Table 1 : Items of the TLE data and the additional data

TLE data	Additional data
Satellite number	Orbital data
International designator	Semi−major axis
Epoch	Apogee height
First time derivation of the mean motion	Perigee height
Second time derivation of the mean motion	Apogee radius
BSTAR	Perigee radius
Ephemeris type	Rotating period
Element number	Type of orbit
Inclination	Reentry time data
Right ascension of the ascending node	Reentry time
Eccentricity	(estimated by simple prediction)
Argument of perigee	Reentry time
Mean anomaly	(estimated by rough prediction)
Mean motion	Reentry time
Revolution number at epoch	(estimated by accurate prediction)

Table 1 categorizes the additional data into two groups: orbital data and reentry time data. All the orbital data are easily calculated by using simple equations. On the other hand, the reentry time data are difficult to estimate, because the orbit generation process is necessary for this estimation.

The Data Estimation Function estimates the reentry time data by using the Reentry Prediction Function in the Orbit Analysis Subsystem. In this estimation, the reentry time is roughly estimated by the Simple Reentry Prediction first. Although the Simple Reentry Prediction is able to estimate the reentry time quickly, the accuracy of the estimation is low. Next, for the space objects that are estimated to reenter into the Earth atmosphere within a year, the Rough Reentry Prediction is performed to estimate more accurate reentry times. The Rough Reentry Prediction is able to estimate the reentry time more accurately than the Simnle Reentry Prediction, although it takes more time for estimation. Finally, for the space objects that are estimated to reenter within 60 days, the Accurate Reentry Prediction is performed to estimate the most accurate reentry time. The Accurate Reentry Prediction is able to estimate the most accurate reentry time among these three reentry predictions, but it requires considerable amount of time for estimation.

The three types of reentry predictions, graded by prediction accuracy, estimate the reentry time of each space object, depending on the danger of the reentry. Figure 3 shows the process of the estimation of the reentry time data. (Details of the Reentry Prediction Function are explained in 4.1)

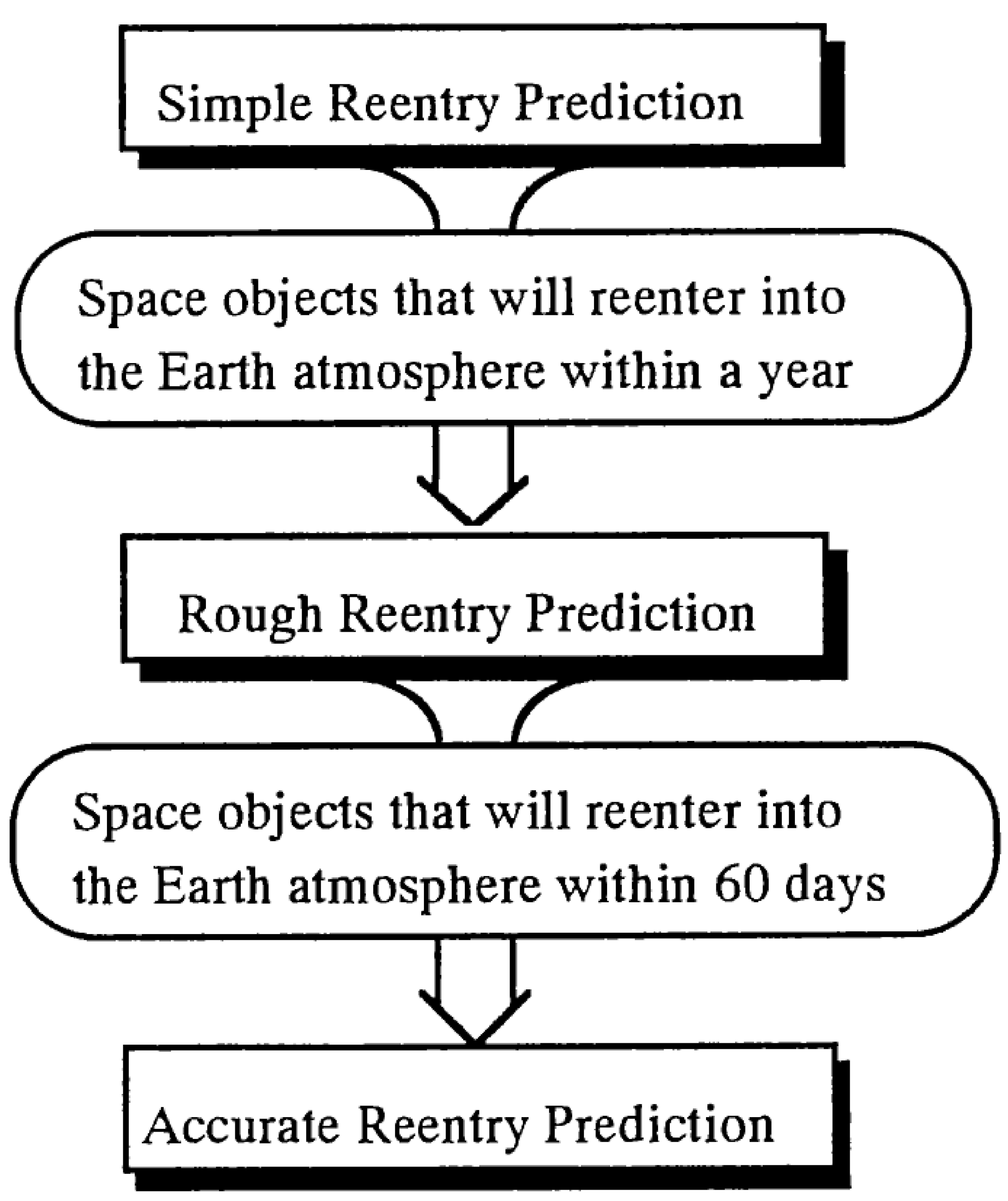

Figure 3 : Process of the estimation of the reentry data

3.3 Maintaining the data

After the additional data are estimated by the Data Estimation Function, both the TLE data and the additional data are maintained in the Data Base. As Figure 2 shows, the Data Base has two areas for maintenance. One is the area in which the Data Base Subsystem maintains the TLE data received from the RBBS and the additional data estimated from these TLE data. The other is the area in which the subsystem maintains the TLE data received from the NOCS2 and the additional data estimated from these TLE data.

3.4 Providing the data

All the data maintained in the Data Base are provided to the users who are allowed access to the DOANATS. NASDA plans to give access to the DOANATS to only public agencies, because the DOANATS has the RBBS data and the owner of the RBBS (GSFC) allows NASDA to provide them to only public agencies.

Users enter the DOANATS by using their password, and obtain the data. The Data Search Function provides users with a search menu. Users can search their data by specifying the items in the search menu.

4. Orbit Analysis Subsystem

The orbit analysis subsystem has following four functions.

- Reentry Prediction Function
- Collision Analysis Function
- Debris Dispersion Simulator
- Orbit Analysis Function

Users can use these functions via Internet and analyze debris' orbit.

4.1 Reentry Prediction Function

The Reentry Prediction Function estimates when a space object reenters into the Earth atmosphere. This function has three prediction algorithms according to the accuracy of the estimation. They are the Simple Reentry Prediction, the Rough Reentry Prediction, and the Accurate Reentry Prediction. A user can select these predictions for their purposes.

4.1.1 Simple Reentry Prediction

Placing an emphasis on a quick estimation rather than an accurate estimation, the Simple Reentry Prediction performs the order estimation of the reentry time without orbit generation process.

To meet this requirement, we use the King-Hele's equations (Ref.5) for the estimation. The King-Hele's equations consists of three equations, each of which corresponds to the range of the eccentricity. Each equation estimates a reentry time by using orbital elements, first time-derivative of mean motion, and a parameter named density scale height which is a function of the height of a space object and the atmosphere density at this height (we use the U.S. standard atmosphere density model to estimate the atmosphere density). The characteristics of the King-Hele's equations are (1) they require only density scale height in addition to parameters estimated by the orbit determination process, and (2) the results of these equations are not sensitive to the ambiguity of the solar activity.

Without the orbit generation, the Simple Reentry Prediction performs the order estimation of the reentry time quickly.

4.1.2 Rough Reentry Prediction

The Rough Reentry Prediction estimates the reentry time more accurately than the Simple Reentry Prediction. This prediction is suitable for the reentry prediction of the space objects that are considered to reenter into the Earth atmosphere within a year according to

the Simple Reentry Prediction.
The Rough Reentry Prediction generates the orbit until the space object reenters into the Earth atmosphere, and estimates the reentry time accurately. Because the Rough Reentry Prediction is performed for the space object that will reenter months later, this prediction has to generate the orbit for a long time. Therefore, taking the estimation time into account, we use the general perturbation method for orbit generation.

The perturbation considered in this orbit generation are the Earth gravity potential, the gravity by the Sun and the Moon, and atmosphere drag. Regarding the Earth gravity potential and the gravity by the Sun and Moon, the J_2 term and the P_2 term[1] are considered. On the other hand, the perturbation functions based on the atmosphere model are used for atmosphere drag. In this orbit generation, the U.S. standard model and the MSIS model are used depending on the height of the object.

As described above, the Rough Reentry Prediction estimates the reentry time by generating the object's orbit with the general perturbation method that considers only major perturbation terms.

4.1.3 Accurate Reentry Prediction

The Accurate Reentry Prediction estimates the reentry time most accurately among these three predictions. Moreover, this prediction estimates the reentry area as well. Targets of this prediction are the space objects that will reenter within 60 days.

To estimate the reentry time and area as accurately as possible, the Accurate Reentry Prediction generates the space object's orbit until the object will reenter into the Earth atmosphere by using the special perturbation method that considers perturbations as many as possible. Furthermore, to estimate the reentry time and area in different conditions, users can set up the perturbation conditions as they like

When a satellite reenters into the Earth atmosphere, the Accurate Reentry Prediction is used to predict the reentry time. Therefore, this function will contribute to the alleviation of the space debris problem.

4.2 Collision Analysis Function

The Collision Analysis Function identities the space objects that have possibility of the collision with a target of this analysis (rocket or satellite). For example, in case of a rocket launching, the Collision Analysis Function determines whether or not the space objects that may collide with the rocket exists in the Data Base Subsystem.

Figure 4 shows the process of the Collision Analysis Function. The Collision Analysis Function consists of three stages (Orbit Comparison Stage, Rough Collision Analysis Stage, Accurate Collision Analysis Stage) and identifies the space object that have high probability for collision with a target spacecraft.

In the Orbit Comparison Stage, the space objects that could collide with the target spacecraft are identified by the geometric comparison of the space object's orbit in the Data Base Subsystem and the target's orbit (in case of a rocket, it is a trajectory). In this stage, the Collision Analysis Function finds the points of close encounter in the intersection of the target's orbit plane and the space object's orbit plane (*i.e.*, p1, p2, q1, and q2 in Figure 5). Then, the distances between p1 and p2 and between q1 and q2 are calculated. If any of the distances is shorter than a threshold (users can input this threshold), the space object is considered to be a potential hazard that could collide with the target. Note that,

[1] P2 term is the first term of the Legendre expansion for the perturbation function that describe the Sun and the Moon gravity.

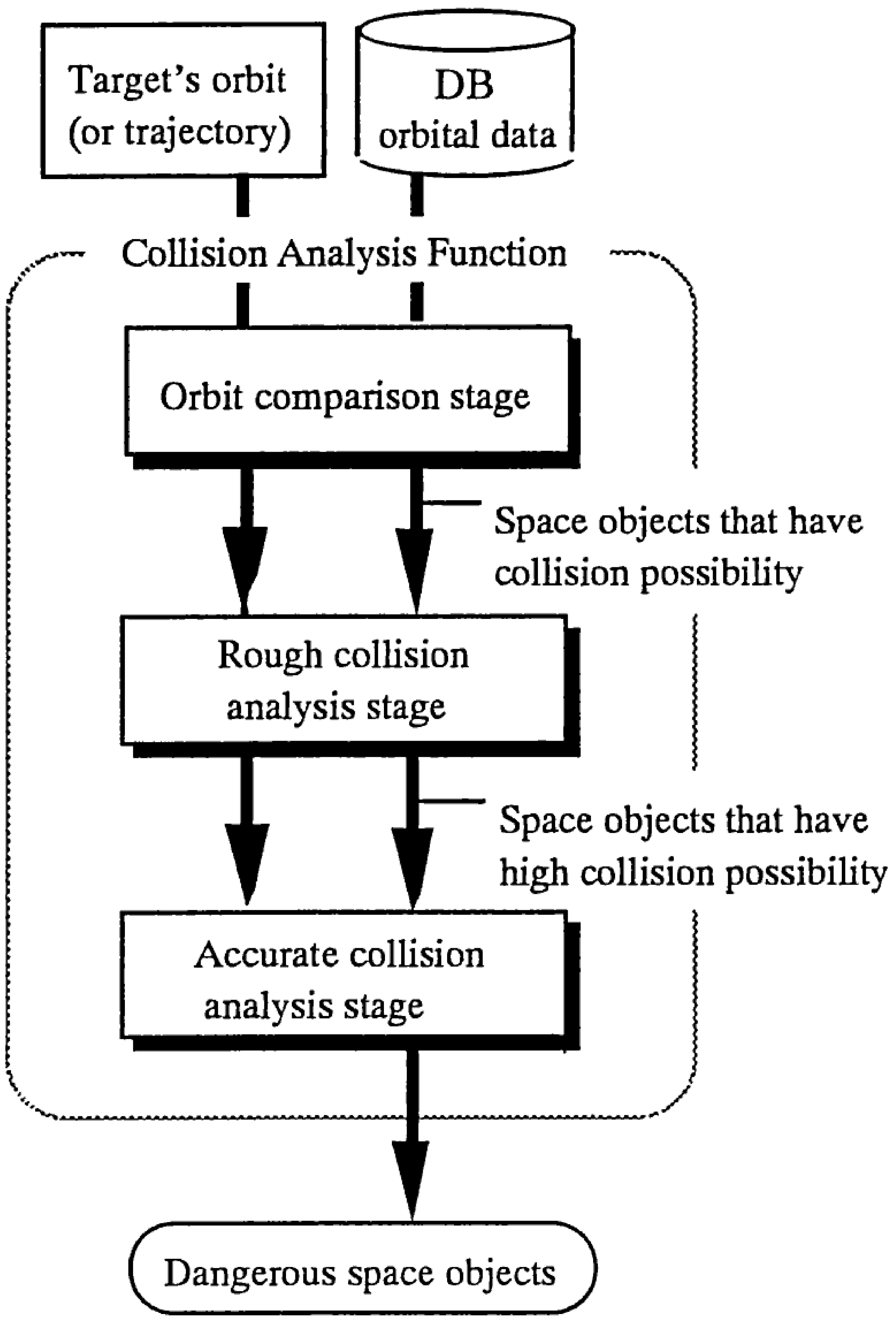

Figure 4: Processes of the collision analysis function

in this stage, time-consuming orbit generation is not used, but two orbits are compared only geometrically.

Once a space object is identified as a potential hazard for the target spacecraft, a collision analysis is performed introducing time into the analysis. In the Rough Collision Analysis stage, target's position and space object's

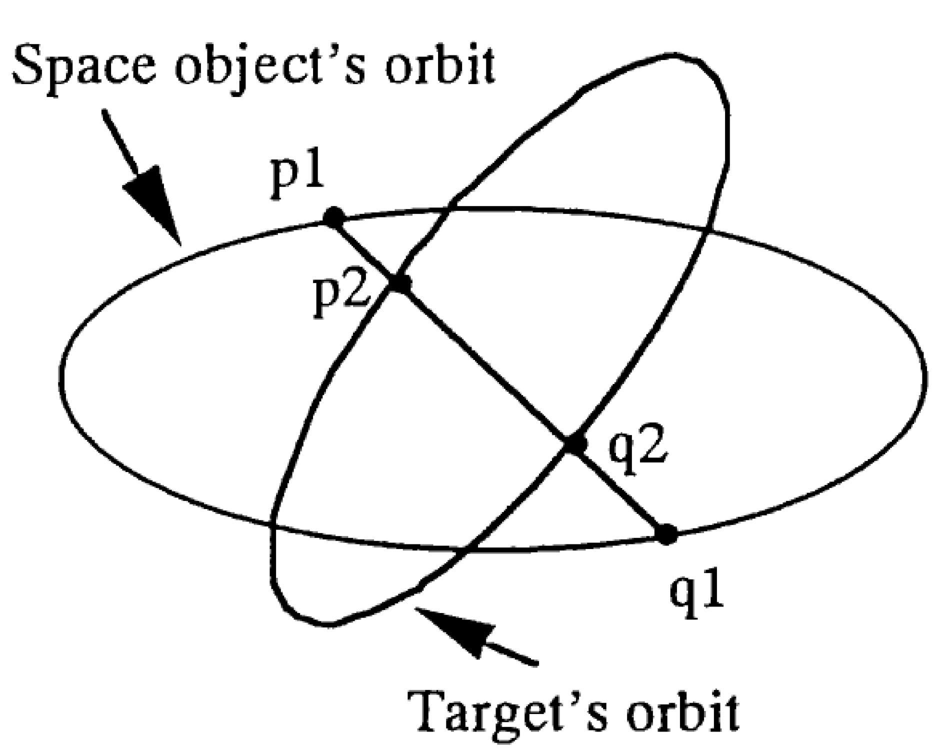

Figure 5: Geometrically comparison of two orbits

position are calculated by orbit generation with a time step of one minute. Then, the corresponding positions are compared. If the distance between the target and the space object is shorter than a threshold at their closest approach, this function considers the space object to have high probability for the collision. Such objects will be analyzed further in the next stage: Accurate Collision Analysis Stage.

The Collision Analysis Function performs the most detailed collision analysis for the space objects that have high collision possibility. In this Accurate Collision Analysis stage, positions of the target and the space objects are estimated with a tinier time step than the previous stage (*i.e.*, every one second). If the space object approaches the target closer than a threshold, this function considers the space object to be dangerous.

In summary, the Collision Analysis Function identifies the dangerous objects that have high probability for collision with a target, by the staged identification process. This function provides the number of dangerous objects, international designators of these objects, and closest distances between the target and dangerous objects.

4.3 Debris Dispersion Simulator

An explosion of satellite and a collision of satellites result in space debris. Debris created by such events form a debris cloud and spread around orbits gradually. The Debris Dispersion Simulator simulates the debris' evolution.

The Debris Dispersion Simulator consists of a debris breakup model and the orbit generation process. The debris breakup model estimates how objects divide into fragments due to a breakup. The model is usually built from breakup experiments on the Earth (See Refs.6,7).

A user enters a set of parameters describing a breakup condition into the Debris Dispersion Simulator. The breakup model estimates the mass and the velocity of each fragment under this condition. Then, based on the mass and the velocity, each fragment's orbit is generated. The simulator displays how all the fragments spread in the orbit.

4.4 Orbit Analysis Function

The main role of the orbit analysis function is the comparison of plural orbits. A user selects some space objects from the data base and enters their orbital data to this function. Then, this function generates the orbits and displays the changes of each set of orbital elements graphically. In this analysis, a user has a freedom to choose the condition for the orbit generation.

In addition, the orbit analysis function has useful analysis tools such as a tool for transformation between mean orbital elements and osculate orbital elements.

A user can analyze orbital data by using these tools.

5. Conclusion

This paper described the conceptual study of the DOANATS. The DOANATS maintains orbital data of space objects and analyzes them. The outline of this system has been specified in this study. Now, NASDA is performing the detailed study about the DOANATS and has started the development of this system. NASDA plans to finish the development in two years and start the test operation in 1998.

In future, the DOANATS is to be connected with the space debris observation system that NASDA is planning to develop, and expand into a part of the worldwide debris data base system.

Reference

1. *US SPACE COMMAND NEWS Release*, 11 Mar, 1996.

2. *SPACE NEWS*, AUG 26-SEP, 1996.

3. S. A. Chamberlain and T. A. Slauenwhite, United States Space Command Surveillance Network Overview, *Proceeding of the First European Conference on Space Debris*, pp37-42, 1993.

4. G. Batyr, et.al., The Current State of Russian Space Surveillance System and its Capability in Surveying Space Debris, *Proceeding of the First European Conference on Space Debris*, pp43-47, 1993.

5. D. King-Hele, Satellite Orbits in an Atmosphere: Theory and Applications, *ISBN 0-216-92252-9, Blackie and Son Ltd, UK*, 1987.

6. V. Chobotov and D. Spencer, Debris evolution and lifetime following an orbital breakup, *Paper AIAA-890085, 28th Aerospace Sciences Meeting*, 1990.

7. T. Yasaka and N. Ishii, Breakup in Geostationary Orbit: A Possible Creation of a Debris Ring, *Acta Astronautica*, Vol. 26, No.7, pp.523-530, 1992.