RESEARCH INTRODUCTION

Cosmic junk — "space debris"

Problems that can't be overlooked lie in the shadows of space development programs

In October 1957, the former Soviet Union launched the artificial satellite "Sputnik I." Though remembered as the opening of a spectacular world of space for humankind, this launch also raised the curtains on the new phenomenon of space debris.

Space debris is a generic term for "cosmic junk," just as the name suggests. Specifically, it refers to manmade objects which orbit the earth but serve no use. This includes artificial satellites which have stopped operation, the upper stages of rockets, and pieces of the same broken apart from explosions or collisions. More than 13,000 pieces of debris are now cataloged(*), all sharing the earth's orbit with artificial satellites in service (Fig. 1).

In January 2007, China conducted an anti-satellite missile test on a decrepit artificial satellite in orbit at an altitude of about 850 km. Many people probably remember the experiment, as it was widely reported by the newspapers, television, and other media as a harbinger of the militarization of space. But the geopolitical concerns weren't the only problem. This test generated more than 2,000 pieces of artificial debris in a wide section of the earth's orbit up to an altitude of about 4,000 km. In fact, collisions between debris have already occurred in orbits where many artificial satellites are now stationed (Table 1).

Given this situation, some may argue that the launch of artificial satellites should be stopped altogether. Yet this would deprive of us of the great conveniences we derive from artificial satellites, such as weather forecasting systems and position navigation systems based on GPS. Disasters caused by abnormal weather conditions or major earthquakes have occurred frequently in recent years, and artificial satellites are helpful for monitoring them. The eyes looking downward from space collect a full picture of disaster conditions, providing crucial information on making decisions on countermeasures.

(*) Cataloged: identified and tracked by ground observation

Table-1 : Collision between debris on the earth orbit

■ A series of collisions between cataloged debris :3 times
• Dec.1991 ; Between Russian used satellite and fragment of its sister satellite • July 1996; Between the French reconnaissance satellite and rocket's fragment • Jan. 2005; Between the upper stage of the USA rocket and fragment of the Chinese rocket (PRC)
■ Examples of debris collisions suspected: About 20 cases (on an increasing trend in recent years)
• Apr. 2002; Debris are released from a Russian satellite, and its orbital period changed at the same time. • Mar.2006; Malfunction of Russian communication satellite • May 2007; Trouble of European weather satellite.
■ Collision with microscopic debris : very frequent
• Window of space-shuttle : average two windows requires replacement for each flight • Many impacts were found on the Space Shuttle and ISS

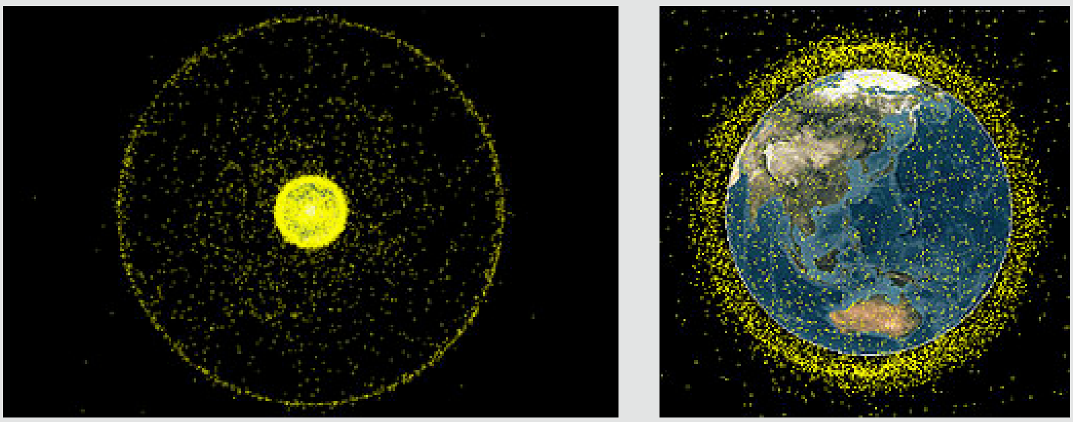

Fig.1 Space debris surrounding the earth

Measures being taken to deal with debris

Awareness of the problem of space debris was considerably enhanced by studies conducted for the realization of the "International Space Station (ISS)," a cosmic house floating at an altitude of 400 km. Because astronauts stay in the ISS at all times, an overriding priority should be placed on human lives. Stringent measures to cope with debris are therefore taken, including thorough monitoring of debris and the installation of a defensive wall.

Large quantities of debris are floating in low Earth orbit (LEO), at an altitude of 2,000 kmor below, and in the geosynchronous orbit (GEO), at 36,000 km. In LEO, the ISS, space shuttle, and various artificial satellites circle the earth, while broadcast satellites, communications satellites, disaster monitoring satellites, etc orbit in GEO (Fig. 2). In addition to LEO and GEO, thousands of pieces of debris, such as the upper stages of rockets, are also floating in transfer orbits (orbits designed to carry satellites to GEO), in orbits with an orbital period of 12 hours (used by GPS satellites), and so forth. These orbits will be the most effective targets for countermeasures against space debris.

Countermeasures against the debris problem are being studied by the Inter-Agency Space Debris Coordination Committee (IADC), a group of which Japan is part. In 2002, IADC established a set of "Space Debris Mitigation Guidelines" to help guide technical measures for debris mitigation. In response, a second set of "Space Debris Mitigation Guidelines" was established in the Science and Technology Subcommittee of the United Nations Committee on the Peaceful Uses of Outer Space (UNCOPUOS) in 2007. Judging from these moves, we can see that the debris problem is viewed a problem on a global scale.

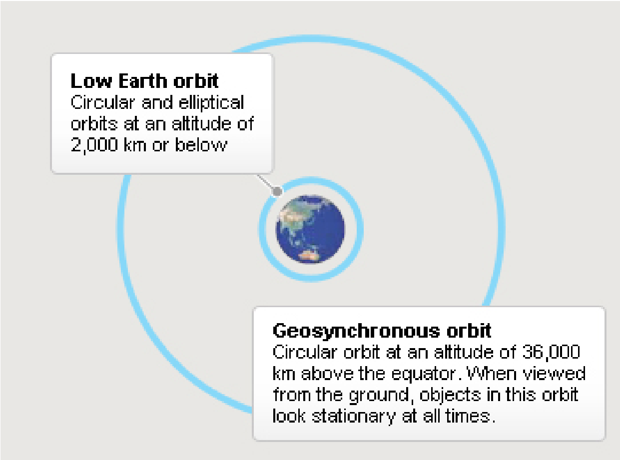

Fig.2 An orbit with abundant debris

How will JAXA deal with the debris problem?

The Japan Aerospace Exploration Agency (JAXA) has established its own "Space Debris mitigation standard" as a guideline for the manufacture and launch of spacecrafts. By following this standards and taking other steps, JAXA is making its best possible efforts to avoid increasing the levels of debris in space.

JAXA set up the "JAXA Space debris committee" in 2006, and since then it has been studying and controlling debris-related problems associated with the operation of artificial satellites and rockets. The agency is also promoting coordination with overseas agencies and its own policy for controlling debris.

On the next page we introduce research projects pursued mainly by the Aerospace Research and Development Directorate, out of the studies now undertaken by JAXA to solve debris problems through "observation," "modeling," "protection," and "mitigation."

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Observe, Predict, Protect, and Mitigate

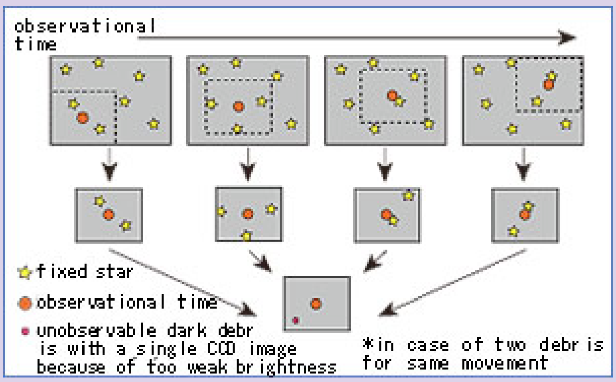
First, knowing what's going on up there

The first step we have to do is to ascertain the conditions of the space debris environment in space. The U.S. Space Surveillance Network (SSN) catalogues and periodically watches more than 13,000 objects in orbit. At this stage, however, the SSN is incapable of detecting objects of less than 50 cm in geostationary orbit (GEO) and objects of less than 10 cm in low earth orbit (LEO). Thus, the objects under these limits have yet to be found. JAXA is developing technologies to detect and catalogue such small objects.

Space objects in GEO seem to be almost unmovable as they travel around the earth once per day above the equator. In contrast, those in LEO move in various directions at velocities of 0.5-degree per second. JAXA is therefore developing observational and cataloging technologies to match each orbital region separately.

■ Technologies for GEO

Two telescopes have been set up at the Nyukasa optical observational site in Nagano. In the future, they will be used in conjunction with technologies to detect unknown space objects and determine their orbits based on observations. One of the most important of these technologies will be the system to control the telescope and CCD camera, then automatically analyze the observation data. This system is presently capable of detecting GEO objects of 30-40 cm in diameter. In future months we will be analyzing data, determining the orbits of detected objects more efficiently, and developing hardware to handle those tasks..



By stacking CCD images after shifting them on simulating the movement of debris, it becomes possible to observe even such dark debris as is impossible to catch with a single CCD image because of too weak brightness.

Fig.1 Automatic detection of moving stellar body by application of "Stacking Method"

■ Technologies for LEO

- cataloging faint debris
  Technologies for unknown objects are being developed for LEO as well as GEO. Object in LEO require complex image-processing, as they move in various directions at variable speeds. Data analysis hardware will be developed to reduce the huge amounts of time spent on calculation.
- Determining the shapes of cataloged debris
  The shape of LEO objects is difficult to figure out based solely on ground observation. Yet in many case, LEO objects rotate as they orbit and reflect the sun at variable brightness. A technology to determine the shapes of LEO objects based on changes in brightness is also being developed. This technology will be useful for debris-removal systems in the future.
- Direct observation in space
  Our team launched three dust collectors (equipment to capture debris) on the Russian Service Module of the International Space Station (ISS) in 2001. The first of three was kept in space to measure (capture) debris for about a year; the second and third, for two and a half years and four years, respectively, from 2001 to 2005. Now we are proceeding with the analyses of the captured debris. Also, as a plan for the future, we are scheduled to install a dust collector on the Exposed Facility (EF) of the Japanese Experiment Module (JEM) "Kibo," a module located on the front surface in the traveling direction of the ISS, for direct observations.

(Persons in charge: Toshifumi Yanagisawa, Hirohisa Kurosaki, and Atsushi Nakajima, Innovative Technology Research Center, and Yugo Kimoto, Shoichi Ichikawa, and Riyo Yamanaka, Advanced Materials Group)

Predicting how the situation with space debris will change in the years to come

Once we understand the present state of debris, we need to accurately predict how it will change in the future. As an analytical tool for this purpose, we are developing a "debris evolutionary model" in collaboration with Kyushu University. We have also developed two other types of analytical tools, a "debris mitigation standard support tool" and a "debris collision risk analysis tool," in order to take adequate debris-mitigation measures for the spacecraft to be launched in the future while protecting the spacecraft from the threat of debris.

■ Debris evolutionary model

The models at our disposal today allow us to predict how debris will increase or decrease in the future, based on the status of debris now.

Even if humankind were to stop launching all spacecraft such as artificial satellites, exponential increases in the number of debris particles around the earth would still be inevitable. The inevitable increases result from the collision between objects strewn in low orbit, mainly from about 1000 km to 1500 km. What measures should be taken to preserve the on-orbit environment? The debris evolutionary model can evaluate the effectiveness of the debris mitigation measures.

■ Support tools for the debris mitigation standard

When JAXA plans, designs, and operates spacecraft, it relies upon a "space debris mitigation standard" to clarify the matters to be considered in its efforts to keep the generation of debris to a minimum. The support tools for the debris mitigation standard are designed to evaluate whether a spacecraft to be launched meets the standard and supports the adaptation. The tool can evaluate the probability of debris colliding in orbit and investigate whether measures to cope with debris can be implemented in accordance with the standard.

The standard stipulates, for example, that if a spacecraft in low earth orbit stops operating, it must reenter the earth atmosphere and burn out within 25 years. Using the tool, we can determine whether a spacecraft meets this standard. If we find that the aircraft won't meet this standard, we can then use the tool to determine how much extra fuel should be loaded in order to force a descent from orbit.

■ Debris collision risk analysis tool

This tool is designed to determine the probability of debris collision with a satellite whose design specifications have been fixed to some extent. Specifically, it estimates how much debris will collide with which part or parts of the satellite, in consideration of the shape of the satellite, its attitude in orbit, and other factors. If, for example, the wall surface of a satellite is under the shadow of an antenna, etc., debris will rarely collide with it. Thus, we can determine the probability or amount of debris collision with each position (Fig. 2). Based on the analysis result, we can then study specific measures, such as protective measures for equipment at positions where debris collision are expected to be frequent.

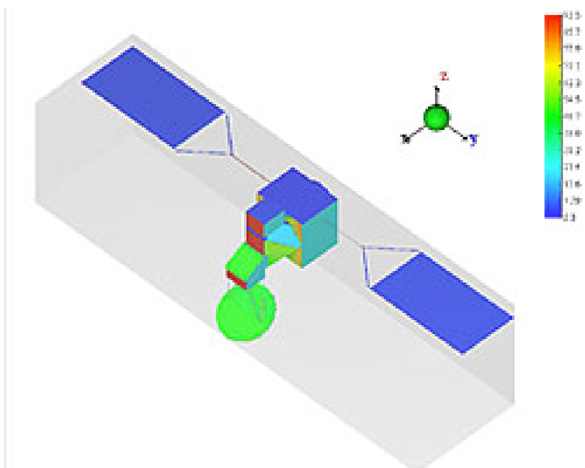
Spacecraft designers will have a great advantage if they can analyze how much damage will be incurred when debris collides against a given part of a spacecraft, in addition to estimating the frequency of collision. This year, we are therefore developing a debris damage risk analysis tool based on the results we have gleaned from our research on "protective" tools.

(Person in charge: Satomi Kawamoto, Innovative Technology Research Center)

How can we protect artificial satellites in the prime of their lives from debris?

Objects in earth orbit travel at slower speeds as their altitudes rise. And debris in low orbit flies about in various directions, posing a higher danger of collision. The average speed of debris in low orbit is 7,000 m/s. When objects at this altitude collide head-on with each other, the relative speed is 14,000 m/s. Even when they collide from the side, the relative speed is still very high, at 10,000 m/s. For a rough idea of the destructive power by comparison, remember that the speed of live ammunition shot from a rifle is about 800 m/s.

To protect artificial satellites from the threat of debris, it can be helpful to closely examine the condition when debris actually hits an artificial satellite. Until several years ago, metallic materials such as aluminum and titanium were adopted for the structural parts of artificial satellites. More recently, however, aerospace manufacturers have



(Red: Collision danger areas Blue: Collision safety areas)

Fig.2 Results of analysis by a debris collision analysis tool adopted a strong, lightweight material called "carbon fiber reinforced plastic (CFRP)" as the mainstream. Because CFRP is relatively new, little or no systematic data on debris collisions has been accumulated even on a global basis. Our group is therefore conducting experiments and analyses to construct a database helpful for satellite design (Fig. 3).

When debris collides with satellites, it can penetrate the wall and even break up into a cloud of particles inside the satellite. Penetrated debris and debris clouds can both be expected to affect the equipment installed within the satellite. Moreover, there is a high probability of debris collision against the solar cell panels and electric power harnesses used to supply electricity, as both are exposed to the space environment. This raises another concern about the effect of debris collisions. Based on the research been done so far, we have confirmed that even if debris of a certain size collides with a solar panel, the panel would probably not work. Regarding the electric power harnesses, it might be necessary to reduce the probability of debris collision by protecting the harnesses with aluminum plates when the collision effects on the satellite system are a matter of concern.

General debris-collision experiments are conducted with a "two-stage gas gun," a device designed to accelerate the aluminum objects used to simulate debris. Actual collision speeds are still unobtainable with this device, which only obtains a maximum speed of about 7 km/s. We and other researchers in Japan have been seeking to improve on this speed by applying a method of acceleration via "shaped-charge system (Fig. 4)." Since developing this method 15 years ago, we have repeatedly conducted experiments with progressively improved versions. At this point we have improved the technology far enough to eject aluminum at a speed of 11 km/s. In the future we plan to conduct experiments in parallel. On the one hand, we will be using a two-stage gas gun owned by the JAXA Institute of Space and Astronautical Science. On the other, we will be moving ahead with the performance verification of the shaped-charge system, while accumulating data.

(Persons in charge: Shin-ichi Takeda, Innovative Technology Research Center; Yosuke Nagao and Masumi Higashide, Advanced Materials Group; and Shiro Kawakita, Space Power System Group)

The final goal is to beautify the space environment

The most effective method for reducing debris is to remove debris directly. By the same thinking, it is especially effective to remove large residua, such as the artificial satellites which have completed their operations but still circle in low earth orbits crowded with debris. To develop such a method, we are moving forward with studies and R&D by inviting members of the groups within the Aerospace Research and Development Directorate, specialists in space technology, to work with us.

Specifically, we are studying a method for capturing debris directly with a removal system and lowering its orbital altitude, thereby forcing it to reenter the atmosphere and burn out. For this purpose, we need to have a "cleaning robot" spacecraft with the functions of an "eye" for grasping the position and condition of debris, a "leg" for coming close to the debris, and an "arm" for capturing the debris. So far, we have been moving forward with R&D on technologies for an optical sensor system

External appearance of a test specimen after an experimentcollision-simulation experiment

Condition of inside damage inspected by ultrasonic scanning system

Fig.3 Results of analysis of a debris-collision-simulation experiment


Fig.4 External appearance of shaped-charge system

used as the eye of a robot, on a navigation and guidance system used as the leg (for approaching and guiding uncooperative targets), and on a robot arm (Fig. 5).

Once we capture debris, we have to apply the brakes to it in order to force it back down into the atmosphere (i.e., reentry). The method we hope to use for this function is based on an EDT, or Electro Dynamic Tether (Fig. 6).

For our cleaning robot with these functions, we are studying two separate systems. In the first, one robot removes one piece of debris. In the second, one robot removes more than one piece of debris.

■ Small satellite type removal system (Fig. 7)

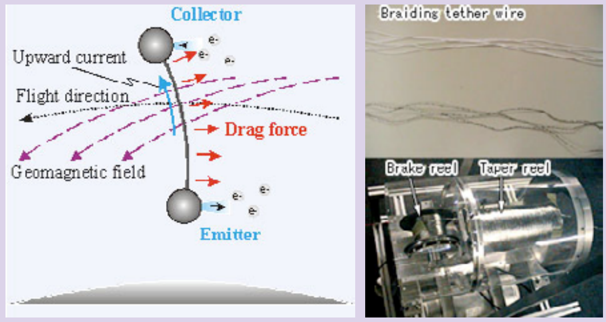
This is a small cleaning robot that can be launched by the piggyback method. An extension-type robotic arm shaped like a large hand reaches out to the debris and closes its fingers around it. With a satellite itself serving as a weight at the end of the tether, the robot reenters the atmosphere together with the debris as the EDT applies a braking force. The adoption of components with a limited period of operation can help to curb the manufacturing cost.

■ Multiple-debris removal system

This is a large cleaning robot equipped with numerous EDTs. After using its robotic arm to capture debris, it mounts an EDT on the debris. By stretching the tether of the mounted EDT mechanism, the debris is forced into reentry. This is a general-purpose system capable of moving between orbits and removing more than one piece of debris.

Japan excels at both the "rendezvous technology" for approaching debris and the "robot arm technology" for capturing debris, thanks to its accumulated experiences with the Engineering Test Satellite VII (ETS- VII), etc. Backed by this skill and know-how, JAXA is the first space agency in the world to research and develop debris-removal technology.

JAXA has also carried out successful demonstration tests on the ground to develop its technologies for the eye, leg, and hand of a cleaning robot. The tether system, on the other hand, can only be researched through analytical verifications, as on-ground tests pose prohibitive challenges. In the future we would like to develop a "cleaning robot" satellite with our sights set on verification in space as well.
(Person in charge: Shinichiro Nishida, Satomi Kawamoto and Yasushi Okawa, Innovative Technology Research Center)



A magnetic field is formed around the earth. Because the electrically conductive tether is made of metal, electromotive force is generated when the tether passes transversely across the magnetic field. Therefore, an electric current continues to flow through the tether if electrons are exchanged with the space plasma. Due to the interaction between the electric current and magnetic field, a backward force (Lorentz force) acts in the tether, decreasing the speed of travel as a result.

Fig.6 Principle of the electro-dynamic tether and a prototype tether

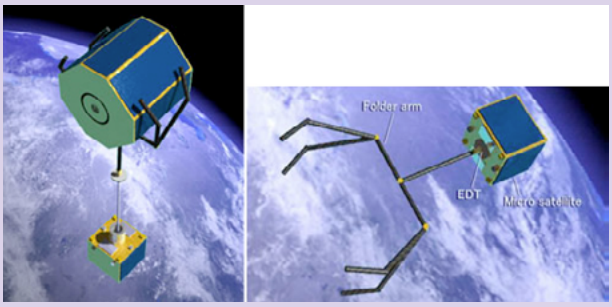
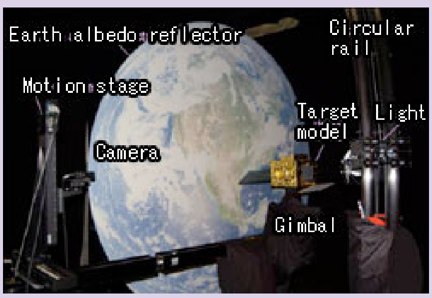
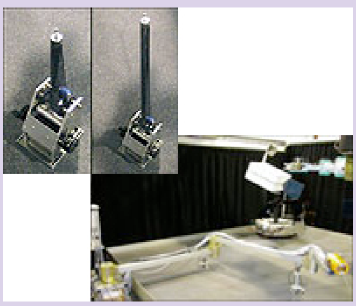


Fig.7 Small satellite type removal system



Experiment on the visual measurement technology for capturing debris



Experiment on debris capture by a robotic arm

Fig.5 Demonstration experiments on the eye, leg, and arm