SMALL BODY SAMPLE RETURN TO DEIMOS

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ABSTRACT

ESA's Science Payload and Advanced Concepts Office (SCI-A) has recently introduced the Technology Reference Studies (TRS) as a technology development tool to provide a focus for the development of strategically important technologies that are of likely relevance for future scientific missions. This is accomplished through the study of several technologically demanding and scientifically interesting missions, which are not part of the ESA science programme.

The goal of the Deimos Sample Return (DSR) TRS is to study the means of collecting a scientifically significant sample from Deimos' surface and returning it to Earth. The DSR mission profile consists of a small spacecraft, launched on a Soyuz-Fregat 2B. After transferring to the Martian system, the spacecraft will enter into a co-orbit with Deimos where it will perform remote sensing observations and ultimately perform a series of sampling maneuvers. Upon completion of sampling the spacecraft will return to Earth, where the sample canister will perform a direct Earth entry.

This paper will outline the preliminary mission architecture of the DSR TRS, as well as the critical technology drivers. This will include an outline of sampling tools and methods appropriate for a small, low gravity body, as well as planetary protection and re-entry technologies.

1 INTRODUCTION

1.1 Technical Reference Studies (TRS)

The Deimos Sample Return (DSR) is one of ESA's Technology Reference Studies (TRS), which have been introduced to provide a strategic focus for technology development.[1] The TRS have a baseline of a single or a pair of small satellites, with highly miniaturized and highly integrated payload suites. The motivation for this approach is to use low resource spacecraft to create a phased strategic approach to exploration, which will reduce the risk and cost, compared to a single, high resource mission.

Retrieving a sample from a small, low gravity, solar system body is significantly different from retrieving a planetary sample. Whereas a sample return from a larger body, such as a planet, would require a lander, an entry and/or descent system, and a launcher to return to orbit, retrieving a sample from a small body is considerably different. A dedicated launch vehicle after sample collection is not required for such a low gravity environment, and the descent requirements are also significantly altered. The differences and challenges involved in a small body sample return is one of the key reasons that the DSR was chosen as one of ESA's TRS. Deimos specifically was chosen due to the belief that a sample of regolith from the Martian moon contains material from both a class D asteroid and Martian material that was deposited on Deimos during the late heavy bombardment period.

1.2 Deimos

Deimos is one of two moons that are in orbit around Mars. The origins of Deimos and Phobos are unknown, although there are two prevalent theories. One hypothesis states that they are asteroids that were captured into orbit about the planet, while the other theory believes that they were created alongside Mars during the formation of the solar system.

Asteroids are attractive targets for sample return. They are believed to be similar to fossils, retaining some records of the formation of the planets. Deimos is smaller than Phobos, with an acceleration due to gravity less than 0.1 % that of Earth. It is also less irregular in shape than Mars' other moon Phobos and has a smoother appearance due to partial filling of some of its craters. Although Phobos is also of scientific interest, these factors, along with Deimos' larger orbit, make it the more attractive target for such a mission.

Deimos is classified as a D class asteroid. D-type asteroids have low albedos and a generally featureless spectrum. Their spectrums have high values in the infrared region and albedos ranging from 0.04 to 0.07. Deimos' has the highest albedo of any D-asteroid it is 60 % higher than average. This is believed to be cause by the presence of Mars ejecta on the asteroid surface.[2]

The surface mineralogy of a D-class asteroid is inferred to be carbon and perhaps organic-rich silicates. However, current surface mineralogy characterization is not definitive for any of the classes, so D-type asteroids could have differing surface mineralogy. It has been theorized that Deimos' surface is composed of carbonaceous chondrites.[3]

2 SCIENTIFIC RATIONALE

DSR aims to retrieve a scientifically significant sample of material from the Martian satellite and return it to Earth. The recovered sample will provide information about two different solar system bodies, a D-type asteroid, Deimos, and the planet Mars. Modeling demonstrates that approximately 10% of the upper regolith material on Deimos, likely originated from Mars.[2] Deimos has been in orbit around Mars since around the time of its creation and has accreted Martian ejecta. The ejecta were accreted during different eras and came from all over the planet's surface. This material has remained on the asteroid's surface due to Deimos' rubble-pile like structure. This structure efficiently dissipates shock energies and minimizes ejecta velocities, so the majority of ejecta will reaccrete.

The Mars component of the sample will generally consist of Noachian basin forming (4.6-3.8 billion years ago) and late heavy bombardment impacts material (4.0-3.8 billion years ago). This is much older than the material from the SNC meteorites that have been found on Earth, which have been ejected relatively recently. The SNC meteorites are 12 meteorites found on Earth that are believed to have originated on Mars approximately 1.3 billion years ago.

Deimos' regolith has been well mixed and it is expected that material from Mars will be found over the entire surface. This is anticipated due to the fact that the albedo of Deimos is about 60% higher than the average D-type asteroid.

The remaining 90% of the returned sample will consist of material from Deimos itself. D-type asteroids contain primitive material, which were not subject to significant alteration after accretion 4.5 billion year ago. This spectral type of asteroid is common in the outer asteroid belt and for the Trojans, but not in the inner solar system.

3 SCIENTIFIC OBJECTIVES

The main objective of the DSR TRS is to examine the feasibility of returning a meaningful sample from the Deimos surface to Earth. Consequently, no additional scientific measurements are currently planned, beyond those required for sample acquisition. This will reduce mission complexity and the resource requirements of the spacecraft. As a result the science objectives focus on the required size of the sample and its composition.

3.1 Sample Size

The amount of material that will be brought back will influence the science that can be performed. It would be advantageous to have enough material to apply all desired measurement techniques and tests. Most instruments require only a very limited amount of material (<< 1 gram) for investigations and those that require more, need only a few grams. The sampling size required for testing purposes is therefore, only several grams. However, a greater amount is required to get a good overview of the sampled area. Some redundancy is also necessary and there should be some additional material if further research is desired.

The areas of investigation that can be pursued vary with regards to the size of the returned sample. The expected sample size required for each area of investigation of interest has been examined.[4] According to expectations a 1 kg sample will contain about 100 g of Martian dust, which is expected to be the minimum required to perform all the desired research. A sample of this size will allow both complete coverage of Deimos and a clear view of several Martian ejecta originating from different episodes and different places. Therefore, the goal of DSR is to return a 1 kg sample of material.

3.2 Sample Composition

The sample should consist of regolith material from the surface. Optimally this should also include several small pebbles. In addition, the sample should not be composed entirely of 'surface dust' and should have some subsurface material, providing a good mix of regolith.

Images of the satellite's surface indicate that Deimos has a regolith zone, which has an estimated mean depth of 10 m. Optical data indicates that this zone is homogeneous across the surface. As evidenced by its many craters, Deimos has been subjected to heavy bombardment by meteorites in its past. The majority of ejecta from this bombardment would reaccrete due to Deimos' rubble-pile like structure that efficiently dissipates shock energies and minimizes ejecta velocities. The surface material thus became widely dispersed. Therefore, the composition of the surface sample does not depend on sampling location. The samples would be similar from any part of the surface.

However, there is one science restriction for the sampling site selection. Newly formed craters by unknown objects should be avoided. Samples from these locations would be likely to contain a high concentration of material from the impacting body and therefore less of the desired material from Deimos and Mars.

4 DSR ARCHITECTURE

The preliminary architecture consists of a small or mini spacecraft, launched into the Mars-Deimos System on a Soyuz Fregate 2B (or equivalent "low cost" launcher). The spacecraft will be launched into a 200 x 25 000 km Earth orbit, after which it will begin its transfer to the Martian system. Upon reaching Mars, the spacecraft will be placed into a highly elliptical orbit (500 x 100 000 km) during orbit insertion, before performing a series of maneuvers to enter into a co-orbiting trajectory with Deimos (20 069 km circular orbit). The spacecraft will then enter into an observation mode, performing measurements of Deimos surface and gravitational properties before obtaining the samples. Once the samples are obtained they will be transferred into a canister inside the Earth Entry Vehicle (EEV). Unnecessary components of the spacecraft, such as the sampling mechanism and empty tanks, will then be separated and left in Martian orbit to reduce propellant requirements for the transfer back to Earth. Upon approaching Earth the EEV will separate and perform a direct re-entry.

Launch Date	Earth-Mars Transfer	Mars Departure Date	Mars-Earth Transfer	Stay Time (days)	Mission Duration (yrs)	Total DeltaV (km/s)
10-Nov-11	0.5 rev.	08-Aug-13	0.5 rev.	331	2.71	2.67
7-Dec-13	0.5 rev.	15-Mar-15	1.5 rev.	169	3.45	3.04
17-Jan-16	0.5 rev.	19-Mar-18	0.5 rev.	515	2.75	3.29
25-Oct-17	1.5 rev.	16-Jun-20	0.5 rev.	122	3.16	3.03
12-May-18	0.5 rev.	21-Feb-19	1.5 rev.	79	3.05	2.73
10-Nov-19	1.5 rev.	10-Jul-22	0.5 rev.	154	3.42	3.08

Table 4-1: Optimal High Thrust Transfers

The instrumentation on-board the spacecraft will be composed of a Highly Integrated Payload Suite (HIPS) in order to reduce resource and size requirements.[5] In order to safely obtain a sample from the surface, if any kind of close approach or touch down is to be made, the gravitational and surface characteristics of Deimos must be known. Therefore the payload will likely contain a set of remote sensing instruments in order to characterize the asteroid and sampling sites to aid in determining the navigation and control sequences for the sampling maneuvers. In addition to those required for characterization activities before sampling, imaging and range finding instruments will be required during the maneuvers.[6]

4.1 Mission Analysis

The mission analysis for a sample return to Deimos has been examined for launch in the 2010-2020 time frame.[7] Both low and high thrust scenarios were analyzed along with gravity assists, optimal stay times and Martian orbits, as well as other ΔV reducing measures. The study has determined that it is feasible to return a significant mass using both chemical and combined chemical and Solar Electric Propulsion (SEP) scenarios. However, due to the higher cost of a SEP system, the baseline will be a Chemical Propulsion (CP) system.

4.1.1 High Thrust Transfers

The baseline scenario for high thrust transfers uses half revolution transfers to and from Mars. A direct entry is envisioned at Earth return since an Earth orbit insertion would not be feasible with the mass constraints of using a Soyuz Fregate 2B launch vehicle. The main concern of this scenario is the long required stay times at Mars of about 450 days. These can be decreased with a 1.5 revolution transfer scenario, however the transfer time is increased and the overall mission time remains relatively unchanged.

For the nominal high thrust scenarios the optimum total ΔVs are around 7 km/s and the optimum stay time ranges between 330 and 550 days. The optimum transfers are outlined in Table 4-1. The type of transfer is also noted for each segment, whether it is a 0.5 (short) or 1.5 (long) revolution transfer.

4.1.2 Transfer Mass Analysis

The useful masses available at Earth return were also analyzed for the optimum transfers and can be found with the mass breakdown in Table 4-2. The analysis assumes the use of a CP system with a specific impulse of 320s and that the maximum capacity of the Soyuz Fregat 2B, 2890.8 kg, is employed to launch into a HEO (200 x 25 000 km). The transfers have two CP stages in order to maximize the Earth returned mass as it was found that the CP-CP staged transfer has a mass advantage over a single CP transfer.

The masses at atmospheric entry in Table 4-2 represent the maximum spacecraft dry mass remaining upon reaching the Earth's atmosphere. For these transfer scenarios, the masses range between 200 and 300 kg. Leaving mass behind at Mars or increasing the performance of the CP system (i.e. increasing Isp) could increase this mass. However, preliminary analysis indicates that the mass at atmospheric entry for these transfer cases should be adequate for the needs of DSR.

Launch Epoch	2011	2013	2016	2017	2018	2020
Chemical Stage 1 Dry Mass (kg)	746	757.7	805	761	724.8	746.2
Chemical Stage 1 Fuel Mass (kg)	162.5	164	170	164.4	159.7	162.5
Chemical Stage 2 Dry Mass (kg)	1065.3	1114.3	1101.5	1110.4	1160.3	1132.6
Chemical Stage 2 Fuel Mass (kg)	198.3	203.1	201.9	202.7	207.6	204.9
Transfer Rate (kg/year)	121.2	75.9	80.9	82.9	79.3	74.4
Mass at Atmospheric Entry (kg)	**328.7**	**261.7**	**222.4**	**262.2**	**248.3**	**254.5**

Table 4-2: Mass at Atmospheric Entry for High Thrust Transfers

4.2 Deimos Observational Orbit

Once the spacecraft has entered into a co-orbiting trajectory with Deimos it will be placed into an observational orbit in order to observe the surface before performing sampling maneuvers. This observational orbit will be achieved by slightly modifying the eccentricity and inclination of the spacecraft's orbit, with respect to that of Deimos (see Table 4-3).

Orbital Characteristics	Deimos	Spacecraft
Eccentricity	0.0005	+ 0.0005
Inclination (deg.)	1.79	+/- 0.05

Table 4-3: Orbital Characteristics for Observation Orbit

The difference in eccentricity will produce a relative circular motion about Deimos with a distance of ~11.5 km from the surface and a 30 hour period. The slight difference in inclination will allow observation of the North and South Poles. This relative circular motion can be seen in Figures 4-1 and 4-2.

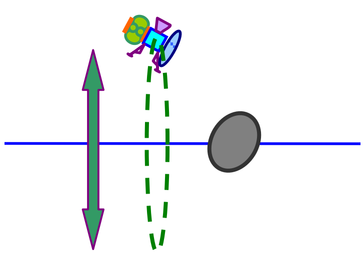

Figure 4-1: Spacecraft Relative Motion

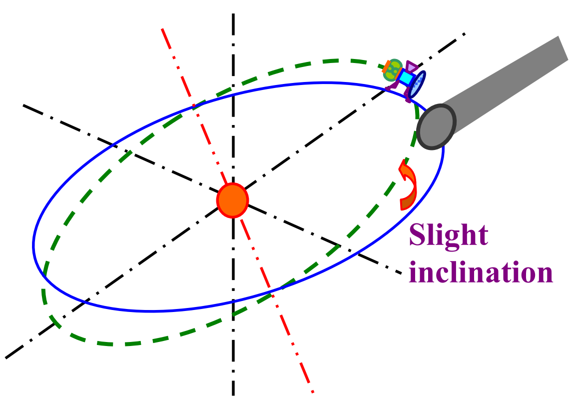

Figure 4-2: Spacecraft's Modified Orbit

This observational orbit will permit the examination of a large number of sampling sites on the surface, enabling the selection of the most optimal locations for sampling maneuvers. The repetitive motion about Deimos will also aid in the accurate mapping of its gravitation field, which will be key in the determination of the navigation sequence for sampling maneuvers.

5 PLANETARY PROTECTION

"The Outer Space Treaty of 1967 specifically requires that all space exploration must be done in a way that avoids harmful contamination to celestial bodies or adverse changes in the environment of the Earth from the introduction of extraterrestrial materials."* The impact of both back and forward contamination during this mission must therefore be addressed.[8]

It has been determined that there is little danger from contaminating Deimos with Earth materials, however it would compromise the scientific integrity of the returned sample. Therefore, forward contamination of the samples and sample sites must be prevented.

It has also been determined that the prevention of back contamination is not strictly required for bodies such as Deimos. Specifically, a report by the US Space Studies Board states that containment is not warranted for samples returned from the Martian moons, Phobos and Deimos.[9] However, the current COSPAR Planetary Protection Policy recommends further study before any such mission is undertaken.

If it were concluded that the prevention of back contamination is warranted, several stringent requirements would be necessary for DSR. The exterior of the re-entry vehicle would need to remain uncontaminated by the sample or any other Deimos material during sample collection. The containment of the sample would also have to be verifiable before re-entry and the sample capsule would need to be sufficiently robust in order to withstand a crash landing. All of this must be done in accordance with current Planetary Protection guidelines.

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* http://www.astrobiology.com/adastra/bring.em.back.html

The current strategy for the DSR TRS is to adopt the more stringent requirements, protecting against back contamination. This will ensure the feasibility of the design in the case that further studies of Deimos determine that a returned sample could be hazardous. This approach also has the benefit that such a DSR mission could potentially act as a technology demonstration mission for several Mars Sample Return technologies.

6 ENABLING TECHNOLOGIES

Several technologies have been identified as enabling for a DSR mission. These technologies fall into two categories, those required to collect a sample from Deimos' surface and those required to insure protection against back contamination. The enabling technologies for sample collection include a highly autonomous guidance navigation and control system, as well as the sampling mechanism itself. The technologies required for planetary protection compliance include a sample containment mechanism, to break the contamination chain, and a robust Earth entry vehicle.

6.1 Sampling Mechanism

There are various methods that can be used to retrieve a sample from a small solar system body such as Deimos. The two main options involve whether or not the spacecraft will make contact with the surface. The sample could be obtained through: collecting the sample directly from the surface or creating a debris cloud of asteroid material and collecting a sample from that cloud. Both of these options will necessitate the development of new technology in order to optimize the sampling method for a small body and to accommodate its use on a small or mini spacecraft. However, collecting samples from a debris cloud is extremely limiting in possible sample size and it would be difficult to collect the required 1 kg sample.

One option for a rendezvous sample collection would be a touch-and-go. The spacecraft would briefly make contact with the surface; collect the sample and return to orbit. Anchoring of the spacecraft would not be required which would simplify operations and reduce spacecraft mass. In addition, for a touch-and-go methods the relative speed between the spacecraft and the asteroid would not necessarily need to be as low as for a precision landing, thus decreasing the required ΔV. It also might be possible to conserve the momentum of the spacecraft while reversing the direction of travel. This would further decrease the ΔV needed to return to orbit.

A touch-and-go sampling maneuver could prove optimal in terms of spacecraft and mission requirements, however it introduces several challenges in collecting the actual sample. The sample would have to be collected in a very short time frame and this could prove exceedingly difficult considering the amount of sample required. It is unlikely that a 1 kg sample could be collected during a single maneuver so several maneuvers would have to be performed. However, this produces the added benefit of providing multiple sampling sites.

Several mechanisms could be used in such a touch-and-go maneuver, where the spacecraft briefly makes contact with the surface before returning to orbit. A scoop could be used to collect the sample, scooping a quantity of regolith into a collector when the spacecraft touches the surface. A compressed collector device could also be used. It would imbed itself into the surface as the spacecraft impacts and then, as the spacecraft returns to orbit, the collector would be withdrawn from the surface with the desired sample contained within. Hyabusa, the Japanese asteroid sample return mission uses a touch-and-go sampling approach. Upon a brief contact with the surface, a projectile is fired and the debris is then funneled up a cone as the spacecraft retreats from the surface.[10] A similar device could also be useful for DSR, however the means of collecting a sample of sufficient size would need to be addressed.

The design and development of a sampling mechanism capable of collecting a 1 kg sample of regolith from a small body is critical for the feasibility of a DSR mission. The mechanism should also be compatible with the optimal touch-and-go type-sampling maneuver.

6.2 Highly Autonomous Guidance, Navigation and Control System

Performing a rendezvous or landing maneuver on the surface of a small body, with only a small gravitational field, presents several challenges. The requirements for the approach and rendezvous or landing will largely depend on the sampling method selected. However, the survival of the spacecraft after the sampling maneuver is critical, so the approach towards and any contact with the surface must be strictly controlled.

Due to the lag time in communication between the Earth and the Martian system, real time control during these critical maneuvers will not be possible. Therefore a highly autonomous guidance, navigation and control system must be developed to ensure feasibility of such a mission.

6.3 Earth Entry Vehicle (EEV)

In order to comply with back contamination protection requirements the Earth Entry Vehicle (EEV) must ensure containment of the sample, in addition to bringing it safely to Earth. The containment seal on the EEV door must be verifiable before Earth entry will be permitted and containment of the sample must be ensured during entry and landing. The EEV will also need to enable rapid localization and recovery of the sample. Several current and past studies have examined potential designs of re-entry vehicles for Mars Sample Return (MSR) missions. These studies could prove beneficial for the design and development of the EEV for a DSR mission. There also exists the potential for a DSR mission to provide technology demonstration for a MSR Earth re-entry vehicle.

6.4 Sample Handling/Containment

In order to comply with the planetary protection requirements to prevent back contamination, the sample must be contained and the exterior of the EEV cannot come into contact with any foreign material. Therefore a break in the contamination chain is required where the EEV is separated from any sections of the spacecraft that have made contact with Deimos material. Figure 6-1 shows a method for this contamination break during transfer of the sample to the EEV. The red outer casing provides a shield that prevents contamination of the exterior surface of the EEV. It will prevent contamination from any contact with the sample material as well as contact with any debris or dust cloud created when the spacecraft impacts the surface.

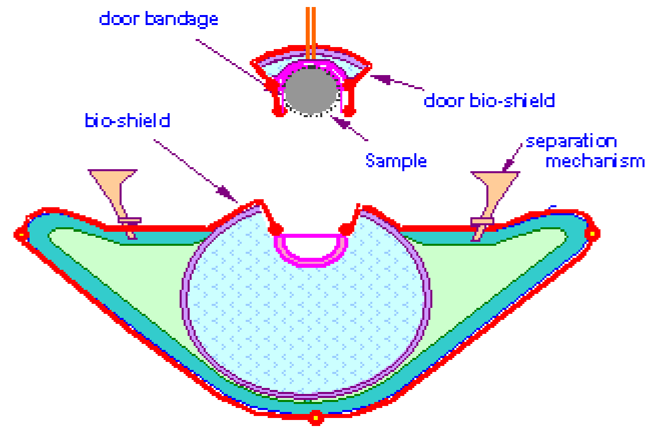

Figure 6-1: EEV Contamination Protection and Sample Containment*

As in the case of the EEV, sample handling and containment mechanisms have been studied for MSR missions. These studies could prove beneficial to DSR and such a mission could also provide technology demonstration for these technologies.

7 CONCLUSION

The Deimos Sample Return Technology Reference Study aims to focus the development of technology required for returning a sample from a small solar system body. In the preliminary stages of the study several enabling technologies have been identified. The sampling methodology and mechanisms required for DSR have the potential to be used in collecting a sample from any small solar system body. The sample containment mechanisms and entry vehicle could be used for any sample return mission requiring back contamination protection. The continuing study of the DSR TRS will continue to define a mission profile in order to examine feasibility and to refine technological requirements for such a mission.

* Figure courtesy of Alcatel Space (Cannes)

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REFERENCES

1. Lyngvi, A., P. Falkner, A. Atzei, D. Renton, M. v.d. Berg and A. Peacock, *Technology Reference Studies,* proceedings of International Astronautical Congress, Vancouver 2004

2. Gaffey, M., J. Bell and D. Cruikshank, *Reflectance Spectroscopy and Asteroid Surface Mineralogy*, **Asteroids II**, R. Binzel, T. Gehrels, M. Matthews (editors), The University of Arizona Press, 1989, pg 98-127

3. Tholen, D. and M. A. Barucci, *Asteroid Taxonomy*, **Asteroids II**, R. Binzel, T. Gehrels, M. Matthews (editors), The University of Arizona Press, 1989, pg 298-315

4. Molster, F., *Scientific Reasoning for A Deimos Sample Return Mission*, Internal Report, Science Payloads and Advanced Concepts Office, Directorate of Science, ESA, 2003

5. S. Kraft, J. Moorhouse, A.L. Mieremet, M. Collon, J. Montella, M. Beijersbergen , J. Harris, M.L. van den Berg, A. Atzei, A. Lyngvi, D. Renton, C. Erd, P. Falkner, *On the Study of Highly Integrated Payload Architectures for Future Planetary Missions,* proceedings of SPIE Europe International Symposium - Remote Sensing, Spain, Sept. 2004

6. Schulz R., *Ground-Based Support for Landing and/or Sample Return Missions to Small Bodies*, Advances in Space Research, Vol. 25, Issue 2, 2000, pg 257-268

7. Kemble, S., M. Taylor, C. Warren and S. Eckersly, *TRM to the Inner Planets: Payload in Orbit Optimization*, Technical Note 3, ESA Contract 17241/03/NL/HB, EADS Astrium Limited. (Stevenage), 2003

8. Race, M. and J. Rummel, *Bring Em Back Alive—Or At Least Carefully*, Ad Astra Astrobiology Issue Expanded Edition, http://wwww.astrobiology.com/adastra/bring.em.back.html

9. Task Group on Sample Return from Small Solar System Bodies, Space Studies Board (SSB), National Research Council, Washington D.C., *Sample Return from Small Solar System Bodies*, Advances in Space Research, Vol. 25, Issue 2, 2000, pg 239-248

10. Fujiwara, A., T. Mukai, J. Kawaguchi, and K.T. Uesugi, *Sample Return Mission to NEA: MUSES-C*, Advances in Space Research*,* Vol. 25, No. 2, 2000