Preliminary Study on Lander System and Scientific Investigation for Next Mars Exploration

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This paper presents Japanese Mars exploration plan. Firstly the outline of Mars exploration plan, scientific objectives and technological challenges.This paper presents Mars robotics exploration by landers in detail. This paper describes the system design of landers and science investigation. This paper also presents the technical challenges, especially accurate navigation and guidance, reliable landing scheme with obstacle avoidance, surface exploration technology.

Key Words: Mars Exploration, Lander System, Surface Exploration, Mars Science.

1. Introduction

Japan Aerospace Exploration Agency (JAXA) established a new Directorate, JAXA Space Exploration Center (JSPEC) in 2007. The mission of JSPEC is to consolidate activities related to space exploration having been conducted across JAXA's offices and sections, and to build a single scheme to address space exploration programs including coordination with external organizations. JSPEC has earnestly studied future lunar or planetary exploration missions in Japan[1)]. Those missions will follow up Nozomi[2)], a mars orbiter exploration mission launched in 1998, Hayabusa[3)], an asteroid sample return mission launched in 2003, SELENE (SELenoligical Engineering Explorer)[4)], a lunar global remote sensing mission launched in 2007. One of main missions for lunar robotics exploration in post SELENE missions[5)] is to demonstrate the technologies for lunar or planetary surface exploration and human activities on the moon in near future.

The working group for future Mars exploration has been established in September 2008. The ultimate goal of Mars exploration is to fully understand the evolution of Martian atmosphere, the water, and its climate as shown in Fig1. To significantly reduce uncertainties in the current models, this mission includes the following three science objectives. The first one is “Escaping Atmosphere”, which will study in detail controlling processes on removal of ions/neutrals from the upper atmosphere with special focus on the solar-wind interactions, and will complements 2013 Scout mission (TGE[6)] or MAVEN[7)]), with heritage from NOZOMI (launched in 1998). The second one is “Meteorology”, which is part of “comparative meteorology of 3 terrestrial planets (Earth, Venus and Mars)” with particular interests on water cycles and will complement 2018 Mars Science Orbiter, with heritage from Venus Climate Orbiter, Planet-C[8)] (launch in 2010). The third one is “Interior Structure”, where seismic study will improve knowledge on interior structure, contributing to understand evolution of Mars as a “solid” planet and its roles on climate history with possible network science with ESA's Mars NexT (2018) and technology developed for SELENE-2 and earth science studies.

The working group is studying the next Mars exploration missions including two orbiters and some landers. Cooperative exploration by orbiters and landers is expected for future mars exploration. This paper describes the outline of Mars exploration. Some technical challenges are required to achieve such advanced exploration. Especially this paper presents Mars robotics exploration by landers. This paper describes the system design of landers and science investigation. This paper also presents the technical challenges, especially accurate navigation and guidance, reliable landing scheme with obstacle avoidance, surface exploration technology.

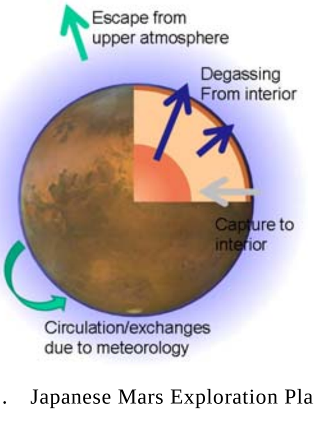


Fig. 1. Japanese Mars Exploration Plan

2. Japanese Mars Exploration Plan

The big question is “Did Mars really have a warm and wet environment in its early days ?”. To answer the above question, it is needed to fully understand the evolution of Martian atmosphere, the surface environment, and the interior structure. That is why the Japanese working group has earnestly studies MELOS (Mars Exploration with Lander-Orbiter Synergy) mission9), which challenges the following 3 science objectives.

2.1. Science Objectives

The first one of science objectives is “Escaping Atmosphere”: to understand how Mars atmosphere has evolved10). That will study in detail controlling processes on removal of ions/neutrals from the upper atmosphere with special focus on the solar-wind interactions, and will complements 2013 Scout mission. Observation in orbit during the solar maximum of the 25th solar cycle, around in 2022 is good for MELOS mission. Solar wind and radiation should be monitored on the companion orbiter. The study will be enhanced by the noble-gas isotopic measurements on the lander. This will be performed with heritage from NOZOMI launched in 1998.

The second one is “Meteorology”: to understand what is going on now11). This is a part of “comparative meteorology of 3 terrestrial planets (Earth, Venus and Mars)” with particular interests on water cycles (transportation and re-distribution). Global mapping of atmospheric motions will be performed with imaging cameras from an elongated orbit with its apocenter near the ecliptic. A sub-mm sounder will provide vertical information up to 150 km altitude, connecting meteorology to escaping atmosphere. This will form a network of ground stations with other missions, such as Mars NEXT etc. This will complement 2018 Mars Science Orbiter, with heritage from Venus Climate Orbiter, Planet-C.

The third one is “Interior Structure12) and Surface Environment13)”: to understand how solid body affects the atmosphere. Seismic study will improve knowledge on interior structure, contributing to understand evolution of Mars as a “solid” planet and its roles on climate history. Measurements of surface-material composition will be performed to study how surface environment developed. This will establish the crater chronology on Mars by measuring ratios of radio-active elements and will greatly benefit from network science with ESA's Mars NEXT (2018). The key technology will be developed for SELENE-2 and earth science studies.

2.2. Technical Challenges

The working group is studying the next Mars exploration mission, MELOS including two orbiters and some landers. Some technical challenges14) are required to achieve such advanced Mars exploration. Orbital control technology is required to control and separate orbiters and landers after MOI and change their orbits as desired by the science requirement. Table 1 shows the examples of required technology for MELOS plan. Technical challenge14) will cover heat shield technology, entry-descent technology15), navigation and guidance technology, pin-point landing technology, reliable landing scheme with obstacle avoidance, safe landing mechanism on rough terrain, surface or inner exploration technology, tele-science and tele-operation technology, planetary protection technology etc.

Table 1. Technological Challenges

Orbital Control	Orbit design Orbit change Separation technology
Orbit Insertion	Accurate orbit determination Aero-brake technology Aero-capture technology
Entry	Heat shield Aero-assist technology Parachute technology
Descent and landing	Pin-point soft landing Navigation and guidance Navigation sensors, Landers
Surface Exploration	Surface explorer Sub-surface explorer Airplane exploration
Others	Tele-communications Long lifetime Small, Light-weight, low power Planetary protection

3. MELOS Configuration

In MELOS plan, two orbiters and some landers are expected to explore Mars cooperatively as shown in Fig.2. This is one example and one of candidates of the MELOS configurations. The rocket vehicle is not decided yet, but HII-A is one of the candidates, which can launch more than 2 tons to the Mars orbit. In the current study, MELOS consists of a 3-axis-stabilized orbiter for comparative meteorology, a spin-stabilized orbiter for atmospheric escape studies, and landers for seismic measurements and heat flux for interior structure studies and in-situ surface observation for geological studies, environment investigation, etc.

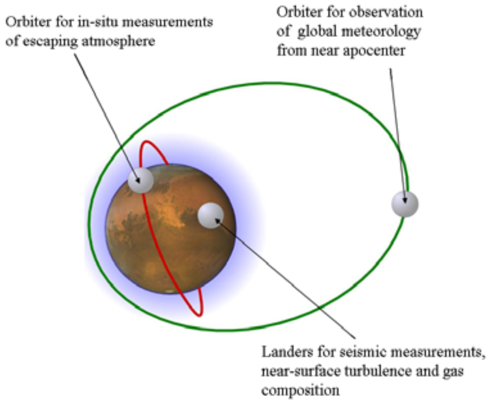


Fig. 2. MELOS Configuration

4. Scientific Exploration by Landers

This section focuses on surface exploration by landers. The MELOS working group is studying underway the next Mars mission using a landing or descending probe. Here the science objectives and the feasibility study are presented in detail[16) 17)].

Mars is the planet of interest in many fields of planetary science. Numerous missions to the planet have been carried out, are now performed, and are planned in the future. The purpose of Mars exploration is mainly focused on evidence of life or signs in geological and material features that shows habitability of past or current life. Thus the priority is put on probing the existence and amount of water that life needs as well as on searching for hydrate minerals that indicate the past environments on Mars.

On the other hand, Mars has a lot of large volcanic, erosion, or sedimentation features that show evidences of vast ancient surface processes. Since its intermediate size between the Earth where active processes undergo and the Moon where processes have been ceased, interior material and structure, mantle dynamics, and thermal history of Mars are crucial to understand not only the planet itself but terrestrial planets in general. Hydrothermal reactions of material with ground water and volcanic heat are characteristic of Martian surface processes. Furthermore, Martian surface processes are most important to be solved by precise mineral, chemical and isotopic analysis.

Japanese Mars mission is outdone by a lot of foreign ones, but should have originality and priority in scientific and technical aspects. Thus the authors believe the interior or surface processes of the planet will have top priority. Although synergy of observation ith orbiters aiming at Martian climate and atmosphere-loss processes is also taken into account, the science that is realized by landing and/or descending should be targeted. Some examples are shown below, which are currently studying their technical feasibilities.

(1) Martian interior probing by Mars Lander:

Martian interior structure is studied by seismometry detecting seismic waves induced by fluvial collision at volcanoes or meteoritic impacts or by fluvial induced free oscillation modes. These observations can be done alone but much improved by correlation analysis with another international station, and more precise investigation could be done by geophysical network with some internal stations. Martian thermal structure is probed by magneto-telluric method with a long-elongated antenna detecting the diurnal changes of response to solar wind magnetic field. Heat from interior is measured by heat flow probes to know thermal state of interior and amount of heat-generating nuclides there.

(2) Martian Geologic History Exploration:

Stratigraphy or geological layered structures are investigated by detailed observation from a helicopter or some flight robotics. Valles Marineris or other eroded structures are found to show layers representing history of Martian volcanism and sedimentation.

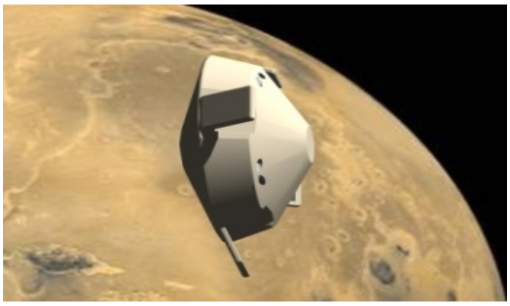
(3) Sample-return of Martian Dusts and Atmosphere:

Precise mineralogy and dating of Martian surface materials and atmospheric gasses are required by sample-return to investigate Martian surface processes and gaseous outflow. For that purpose, dust particles and atmosphere are sampled at 40km altitude during free-return trajectory, and returned back to the Earth.

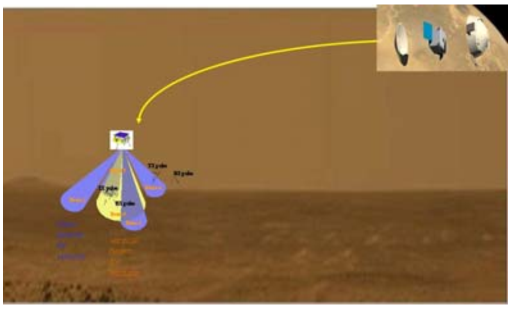
5. Lander System

The working group is studying the lander system and performing the feasibility study of the landing technology. Landing technology includes heat shield technology, accurate orbit determination technology, entry technology, entry-descent-landing technology, navigation and guidance technology, pin-point landing technology, reliable landing scheme with obstacle avoidance, safe landing mechanism on rough terrain, surface or inner exploration technology, tele-science and tele-operation technology, etc. Figure 3 shows the conceptual Mars exploration by lander, especially for EDL (Entry, Descent, Landing) technology and Surface Exploration.

(a) Entry



(b) Entry, Descent, and Landing



(c) Exploration by Lander and Rover

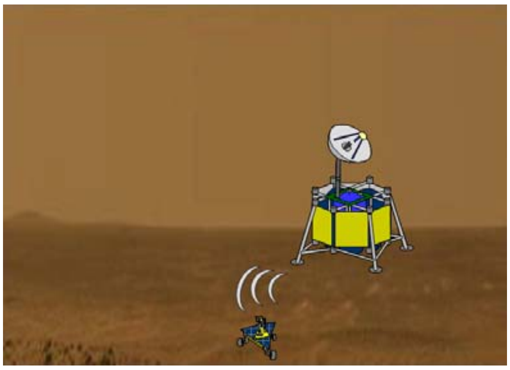


Fig. 3. MELOS Lander Exploration

5.1. Lander System

Table 2 shows the preliminary study on system configuration of landers. The configuration depends on the mission requirements and the system requirements. That is why this is just one example of the configurations.

Table 2. Mss Budget for Lander

Mass Budget	1 lander	2 landers	3 landers
AOCS	32.8	32.8	32.8
Power	59.2	59.2	59.2
Comm	18.8	18.8	18.8
DHU	6.9	6.9	6.9
EDL	80.0	80.0	80.0
Launch SS	0.0	0.0	0.0
Propulsion	40.9	40.9	40.9
Wire Harness	15.2	15.6	16.4
Structure	55.6	56.8	59.2
Thermal	7.6	7.8	8.2
CI	316.9	318.7	322.3
PI	13.1	21.3	37.7
Dry	330.0	340.0	360.0
Fuel	50.0	50.0	50.0
Wet	380.0	390.0	410.0
Margin	57.0	58.5	61.5
Total	437.0	448.5	471.5

5.2. EDL Sequence

Figure 4 shows the preliminary study on EDL sequence. The entry will be performed at the altitude 120[km] at the velocity 4.6[km/s]. The peak of heat flux will occur at the altitude 48[km]. At the altitude 10km, the velocity will be 200[m/s]. The parachute will be deployed to reduce the velocity at the altitude 10[km]. At the altitude 200[m], the velocity will be reduced to about 24[m/s] and then the parachute will be jettisoned. The powered descent will be performed by using main thruster. The velocity will be smaller than 1[m/s] at the touch down to the Martian surface. The leg system of the lander will reduce the shock at the landing.

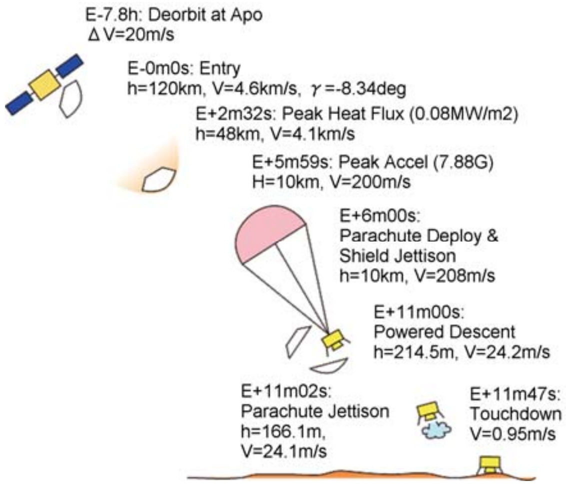


Fig. 4. EDL Sequence

5.3. Navigation Sensor

As shown in Fig.4, the landing sequence of the Mars mission consists of parachute descent phase and power descent phase. In the descent phase, the lander is navigated by an image navigation system, an inertial navigation system, and a laser altimeter. During the descent phase, the lander compensates any positioning errors and avoids collision with obstacles by means of navigation based on the inertia system, the image system and the landing radar. The landing radar is the main sensor which corrects any errors inherited from the inertial navigation system. Therefore, the most important requirement for the lander system is that the radar must be able to track the Martian surface even if the terrain is unknown and rough.

The radar[18)] should provide information about the altitude and the horizontal velocity during the decent phase. The requested minimum range of the radar is determined by the accuracy of the inertial navigation system, and is in the range of 0 - 50m/s.

The lander may be tilted at ±15deg by the main thruster for the purpose of avoiding collision with obstacles. Therefore, the radar should be able to perform tracking and measuring even when tilted at an angle of 15deg. The required error of the altimeter and the velocity meter is less than 5%. In particular, the accuracy of the velocity measurements in the low velocity region just before landing is extremely important for avoiding falling. The required accuracy depends on the structure of the landing gears and the barycentric position of the lander, although it should be about 10cm/s. On the other hand, there is always the problem of saving weight, since the weight of the fuel in the lander needs to be several times greater than the weight of the payload.

Table 3 shows the functions and the characteristics of the landing radar. The beam shapes of the radar antenna are illustrated in Fig.4. The landing radar employs a pulse-type radar using 4.3GHz C-band microwave radiation. As shown in Fig.5, it has a wide beam for measuring the altitude in vertical direction, as well as four narrow beams for measuring the Doppler effect. The wide beam of the altimeter allows the lander to be tilted at an angle of ±15deg. Similarly to a typical airborne Doppler navigator, a classical Janus system is employed for the measurement of the Doppler effect. Although many airborne Doppler navigators use pencil beams whose width is several degrees, the landing radar uses relatively wide (15deg) beams in order to obtain sufficient robustness with respect to unknown terrains on the Martian surface. The nominal pulse width is 50ns, which is changed to 15ns for short-range measurements. For long-range measurements, the landing radar uses code modulation by means of MSL (Minimum Side Lobe) code. The operation of those three kinds of pulses should be considered during the engineering model design phase. When measuring the altitude, the landing radar detects the leading edge of a pulse reflected from a surface. Before the detection of the leading edge, random noise is suppressed by an averaging procedure.

Table 3. Landing Radar

Radar Type	Pulse radar
Function	Altimeter Velocity meter
Frequency	4.3 GHz
Range	10m-3.5km
Accuracy	5%
Pulse Width	15ns for short range 50ns for middle and long range

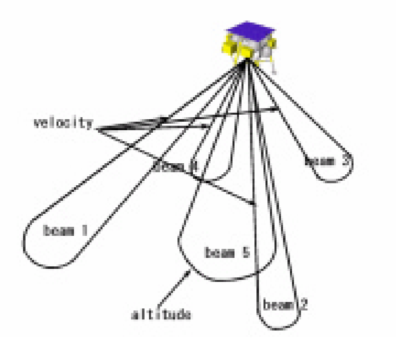


Fig. 5. Schematics of Radar Beams

6. Surface Explorers

The working group is studying the detailed surface exploration around the lander, wide area exploration by balloons or airplanes, subsurface exploration by mole type robots.

6.1. Rover Exploration

The authors have designed a small rover for Mars robotic exploration requiring detailed investigation around the lander. The picture and the specification of the developed micro rover are shown in Fig.6 and Table 4 respectively. The weight of the designed rover is about 5[kg]. The rover measures about 0.53[m] wide, 0.55[m] long and 0.25[m] high. The wheel diameter is 0.1[m].

The designed rover is driven by five wheels controlled independently. The steering is controlled by the differential of left and right wheels. Those wheels are actuated by small DC motors. The velocity of the rover is about 1.5[cm/s]. The designed rover has the new suspension system called "PEntad Grade Assist SUSpension" (PEGASUS)[19]. The proposed suspension system PEGASUS consists of a conventional four-wheel drive system and a fifth active wheel connected by a link. The fifth wheel, which is attached to the end of the link, and the other end of the link, is attached to the body with a passive rotary joint. This joint has restriction from neither spring nor actuator, can move freely. The proposed system is designed to distribute the load of weight equally to all five wheels whenever the rover climb up or down. That means that the fifth wheel supports the load taken to the front wheels when the front wheels climb up rocks, and it also supports that taken to the rear wheels when the rear wheels climb up the rocks.

When the rear wheel climbs up a step, forward force is generated by the traction of the fifth wheel backward. These forces produce nose-dive moment, and then the moment turns to a vertical force of the front wheel to support traction. By this mechanism, when the rover moves forward, this mechanism works at maximum performance. When the rover moves backward, the mechanism works as a conventional four-wheel drive system. Most of all times during the mission, the rover moves forward. Therefore, the unidirectional characteristic is not a problem. This system can be realized to be simple and light in weight, because the design is based upon a simple four-wheel drive system.

The climbable step of the rover is about 0.15[m] and the climbable slope is about 30[deg]. Power is supplied by solar panel. The rover is also driven by on-board batteries.

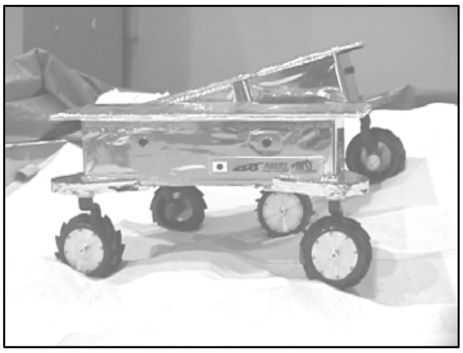


Fig. 6. Developed Micro5 Rover

Table 4. Specification of Micro5

Size	0.53[m](W) 0.55[m] (L) 0.25[m] (H)
Wheel diameter	0.1[m]
Weight	About 5[kg]
Mobility System	PEGASUS,
Mobility Performance	Velocity : 1.5[cm/s] Climable step : 0.15[m] Climbable slope : 30[deg] on hard surface 20[deg] on soft surface
Power Supply	Solar Panel : max 27[W] Battery : Lithium
Power Consumption	Actuator : max 5[W] Computer : max 4[W]
Payload	4 stereo cameras

6.2. Airplane Exploration

Technology advances in unmanned aerial vehicles and space flight systems have enabled a viable mission concept for the first flight of a powered airplane above the unexplored landscape of another planet. From its unique vantage point, a few kilometers above the Mars surface, an autonomous airplane can return unique science measurements over regional-scale distances for immediate scientific review and public dissemination. Such exploration by airplane would give the following merits.

1) to return fundamental scientific knowledge about the planet's atmosphere, surface, and interior;
2) to inspire the next generation of explorers
3) to demonstrate the synergies possible through integration of nation's aeronautics and space enterprises.

As shown in Fig.7, planetary airplanes with potential application to Mars, Venus, or Titan have been studied as a means to bridge the scale and resolution measurement gaps between orbiters (global-scale, limited spatial resolution) and landers (local-scale, high spatial resolution). When regional-scale distances are traversed at near-surface altitude, planetary airplane observations complement and extend orbital and landed measurements while providing a fresh perspective for scientific discovery. Planetary aircraft can also survey scientifically interesting terrain that is inaccessible

An optimum airfoil design20) for future airplane for Mars exploration is pursued by the evolutionary computation coupled with a two-dimensional Reynolds-averaged Navier-Stokes solver. The optimized airfoil at this flow condition is also compared with the airfoils optimized at different Reynolds number or at different Mach number for the discussion of Reynolds number and Mach number effects on the airfoil design. These results indicated that as the Mach number or Reynolds number increases, the maximum lift-to-drag ratio airfoil has lower camber and thicker airfoil thickness.

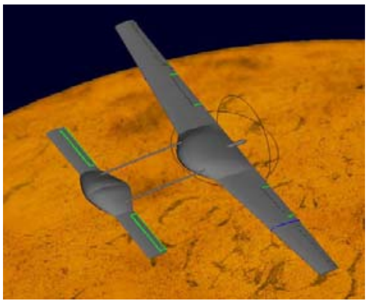


Fig. 7. Airplane for Mars Exploration20)

6.3. Subsurface Exploration

It is very significant to investigate the subsurface of Mars. The authors have studied and developed a mole type robot to explore the subsurface. Figure 8 shows the developed mole type robot21).

Fig. 8. Mole type of digging robot

7. Conclusions

This paper has presented Japanese Mars exploration plan, MELOS, scientific objectives and technological challenges. This paper described the system design of landers the technical challenges, especially accurate navigation and guidance, navigation sensor, surface exploration technology.

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