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SCIENTIFIC RESEARCH IN THE LUNAR ORBITING MISSION SELENE

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Abstract

SELENE(Selenological and Engineering Explorer) mission is planned in 2005 for lunar science and technology development. The launch was rescheduled last summer in the rearrangement of HII-A launch schedule. The main objective of the mission is to study the origin and evolution of the Moon. The spacecraft consists of a main orbiter at about 100 km altitude in the polar circular orbit and two subsatellites in the elliptical orbits with the apolune at 2400 km and 800 km. The main orbiter will carry instruments for scientific investigation including mapping of lunar topography and surface composition, measurement of the magnetic fields, and observation of lunar and solar terrestrial plasma environment. The mission period will be one year. If extra fuel is available, the mission will be extended.

1. Introduction

The primary objective of the SELENE mission is to study the origin and evolution of the Moon by global mapping from the polar orbit at 100 km altitude. The element abundances are measured by x-ray and gamma-ray spectrometers. Alpha particle spectrometer is used to detect the radiation from the radon gas and polonium. The mineralogical characterization is performed by a multiband-spectrum imager at a high spatial resolution. The mineralogical composition can be identified by a spectral profiler, a continuous spectral analyzer in visible and near infrared bands. The surface topographic data are obtained by high resolution stereo cameras and a laser altimeter. The subsurface structure is probed by an rf radar sounder experiment. Doppler tracking of the orbiter via the relay satellite when the orbiter is in the far side is planned for study of gravimetry and geodesy. A magnetometer and electron detectors will provide data on the lunar surface magnetic field. Radio sources on the two subsatellites are used to conduct the differential VLBI observation from ground stations.

Measurement of the lunar environment and observation of the solar-terrestrial plasma environment are also planned in the mission. The study of the lunar environment includes the measurement of high energy particles, electromagnetic field, and plasma. For the solar-terrestrial plasma observation, the orbiter carries imaging instruments to observe the dynamic structure of the earth plasma environment and the aurora. High-sensitivity wave receivers are used to detect the planetary radiation from the Jupiter and Saturn. For publicity and educational purposes, high-resolution cameras are onboard to observe the earth from the Moon orbit.

2. SELENE System

The performance of the SELENE spacecraft is summarized in Table 1. The configuration of the orbiter in the lunar orbit is shown in Fig. 1. The orbiter moves towards +x or -x direction in the figure. Since the solar paddle is deployed in the -y axis, the orbiter has to make yaw-maneuver and change the direction of the motion when the beta angle is 0° and 180°. Most of the sensors for the remote-sensing observation are installed on the z-plane which is controlled to face the lunar surface all the time by a three-axis attitude control system. The control accuracy is ±0.1°(3 σ). Two pairs of 15 m antenna for radar sounding are configured to cross perpendicularly to each

Table 1 SELENE mission summary

Launch	H-IIA Launch in 2005 from Tanegashima
System	Main orbiter (2.1 x 2.1 x 4.2 m), Relay satellite and VRAD satellite (1 mϕ x 0.65 m)
Orbit	Direct injection to the lunar transfer orbit 100 km circular, Inclination 90°(Main orbiter) 100 km x 2400 km elliptical, Inclination 90° (Relay satellite) 100 km x 800 km elliptical, Inclination 90° (VRAD satellite)
Mission Period	1 year nominal plus optional observation
Attitude Control System	Main orbiter: 3-axis control, 2 Star sensors, 2 IMUs, 4 Sun sensors 4 Reaction wheels(20 Nms), Pointing ±0.1°(3 σ), Determination ±0.025°(3 σ) Stability ±0.003°/s(3 σ) Relay/VRAD satellite: Spin stabilization(>10 rpm)
Thruster System	Main orbiter: 500 N x 1, 20 N x 12, 1 N x 8
Power System	Main orbiter: GaAs solar array paddle 3.5 kW, Battery NiCd, 35 AH x 4, 50 V Relay/VRAD satellite: High efficiency Si Solar Cell 70 W, NiMH 13 AH, 26 V
Communication System	Mian orbiter: S and X bands, High gain antenna(S, X), 4 Omni antennas (S), 10 Mbps(X downlink), 40 or 2 kbps(S downlink), 1 kbps(uplink) Relay/VRAD satellite:128 bps
Orbiter Data Recorder	Main orbiter: 10 GBytes
Weight	Launch 2885 kg Orbiter(Dry Weight) 1720 kg Science Payload 270 kg(approx) Relay Satellite 45 kg VRAD Satellite 45 kg

other. The mast for the magnetometer is deployed 12 m in +x direction to avoid the magnetic interferences from the main body. The solar array paddle in the -y direction rotates along the y-axis to track the sun generating 3.5 kW power. The capabilities for mission data recording and downlink are 10 GBytes and 10 Mbps, respectively.

The phase-A study of SELENE started in 1996. The preliminary design of spacecraft was completed in March 2001. Environmental tests were just completed using a Mechanical Test Model(MTM) and the thermal vacuum test using a Thermal Test Model will start this autumn. The fabrication of the flight models will be completed in 2003 and the systems test is planned in 2004. The overall development schedule is shown in Fig.2.

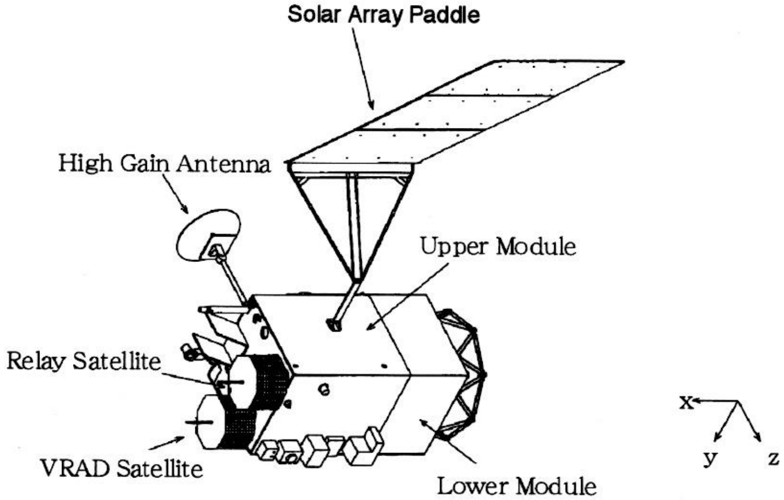

Fig.1 Configuration of the main orbiter.

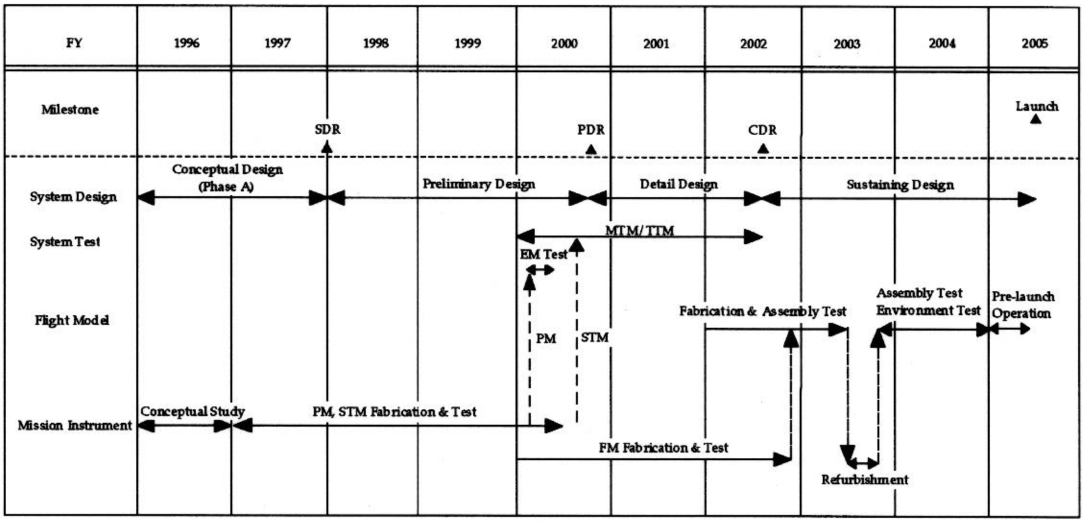

Fig.2 SELENE development schedule.

3. Mission Scenario

The mission profile is shown in Fig.3. The spacecraft will be launched by the H-IIA rocket and directly injected into the lunar transfer trajectory. It takes about five days to reach the lunar orbit. The mid-course maneuver is planned twice on its way to the Moon. The spacecraft is captured by the Moon into an elliptical polar orbit with apolune at 11,300 km and perilune at 100 km. The apolune is lowered by 6 orbit-transfer maneuvers and finally the orbiter reaches the mission orbit at about 100 km altitude. During the orbit transition, the relay satellite and the VRAD satellite are released in the elliptical orbit with an apolune at 2,400 km and 800 km, respectively. Upon arriving at the mission orbit, the main orbiter extends 4 antennas for the radar sounder experiment and a mast for the magnetometer. Remote-sensing observation of the lunar surface and observation of the lunar and solar-terrestrial plasma environment will be performed for about one year. The altitude of the main orbiter will be kept at 100±30 km by orbit maintenance operation. If the fuel to control and keep the orbit is available, the observation mission will be extended. One option is to lower the orbiter to 40-70 km altitude for precise measurement of the lunar magnetic and gravity fields. The two subsatellites have no fuel to keep their orbits, but will survive more than one year.

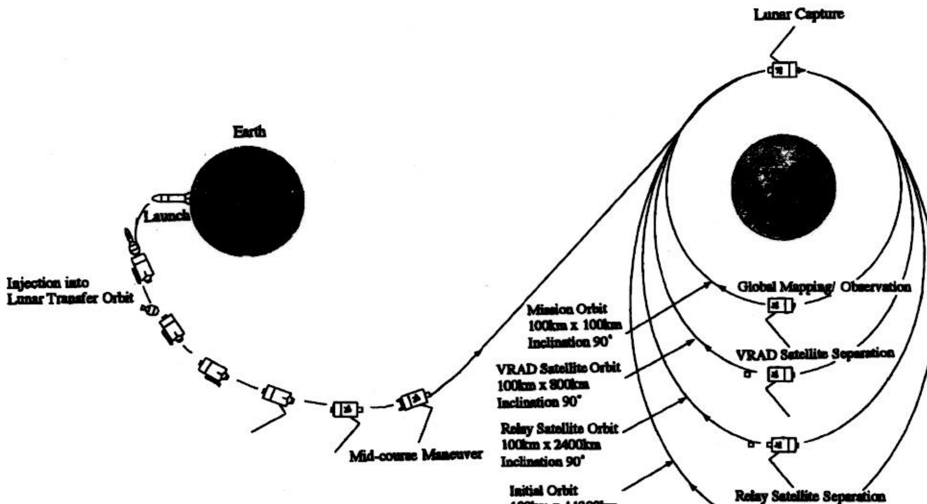

Fig.3 SELENE mission profile.

Especially the VRAD satellite is expected to survive much longer.

The orbital period is about 2 hours. The distance of the adjacent orbit is about 35 km at the equator. The orbiter returns the initial orbit every month if the orbital perturbation is negligible. By adjusting the orbital latitude, global mapping with a high-latitude resolution less than 35 km at the equator is possible. Totally four maneuvers to keep the altitude are planned during one year.

Figure 4 shows commanding and telemetry system for SELENE. Commands are up-linked to the three satellites through the NASDA ground stations. S-band telemetry data of the main orbiter are down-linked to the NASDA ground stations. X-band mission data(10 Mbps) are down-linked to the ISAS Usuda Deep Space Center(UDSC). Telemetries from the subsatellites are down-linked to UDSC. In the initial phase before injection to the mission orbit, JPL/DSN stations will be used to support the critical operation for the orbit maneuvering.

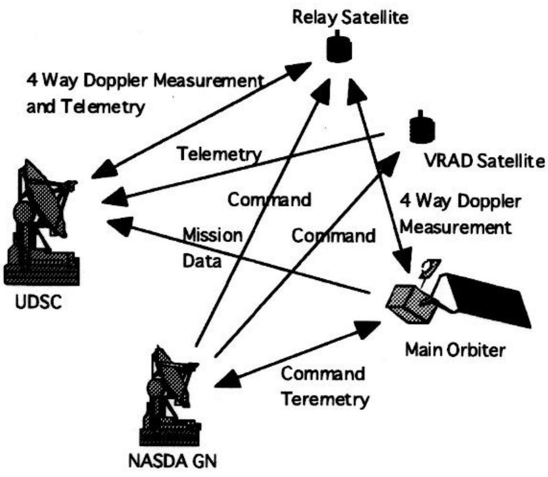

Fig.4 Commanding and telemetry system.

4. Scientific Research

The global characterization of the lunar surface and investigations of the interior in this mission are categorized into 5 fields of observation; element abundance, mineralogical composition, geological features, global gravity, and magnetic field. Totally 15 mission instruments including those for observation of the lunar and solar-terrestrial environments are under development. The major characteristics of the instruments are listed in Table 2. The configuration of the sensors is illustrated in Fig.5. Figure 6 shows how the SELENE measurements are used and integrated to study the origin and evolution of the Moon.

4.1 Global Mapping of Element Abundances

Global mapping of the lunar element abundances and mineralogical composition will make it possible to estimate the entire lunar chemical composition, which gives

Table 2 SELENE scientific instruments

Observation	Instrument	Characteristics
Element Abundance	X-ray Spectrometer	CCD 100cm^2, Energy range 0.7~8 keV, Resolution 90 eV, 5μm Be film, Solar x-ray monitor, Calibrator with sample, Global mapping of Al, Si, Mg, Fe distribution, Spatial resolution 20 km
	Gamma-ray Spectrometer	High pure Ge crystal 250 cm3, Energy range 0.1~10 MeV, Resolution 2~3 keV, Stirling refrigerator 80°K, Global mapping of U, Th, K, O, Al, Ca, Fe, Mg, etc., Spatial resolution 160 km
Mineral Composition	Multi-band Imager	UV-VIS IR imager, Si-CCD and InGaAs, 9 bands in 0.4-1.6μm(Si: 415,750,900,950,1000; InGaAs: 1000,1050,1250,1550 nm), Band width 20~50 nm, Spatial resolution 20-60 m
	Spectral Profiler	Spectrometer, Si pin photo-diode and InGaAs, Band 0.5 to 2.6μm. Spectrum Sampling 6~8 nm, Spatial resolution 500 m, Calibration by halogen lamp, Observation of standard lunar site
Topography, Geological Structure	Terrain Camera	High resolution stereo camera(±15°), Si-CCD, Spatial resolution 10 m
	Lunar Radar Sounder	Mapping of subsurface structure, Frequency 5 MHz(4~6 MHz swept in 200μs every 50 ms), four-15 m antennas, 5 km depth with 100 m resolution, Observation of natural waves (10 k~30 MHz)
	Laser Altimeter	Nd:YAG laser altimeter (1064 nm, 100 mJ, 15 ns), Si-APD, Beam divergence 3 mrad(30 m spot) Height resolution 5 m, Spatial resolution 1600 m (pulse rate 1 Hz)
Gravity Field	Differential VLBI Radio Source	Radio sources on Relay Satellite and VRAD Satellite(3 S-bands, 1 X-band), Several tens of mW, Differential VLBI observation from ground (3 stations or more)
	Relay Satellite	Far-side gravimetry using 4 way Doppler measurement, S uplink, S spacelink, X downlink, Perilune 100 km and Apolune 2400 km at orbit injection, Doppler accuracy 1 mm/s(10 sec)
Magnetic Field	Lunar Magnetometer	3-axis flux gate magnetometer, Accuracy 0.5 nT, 32 Hz sampling, Mast 12 m, Alignment monitor
Lunar Environment	Charged Particle Spectrometer	Measurement of high energy particles, Si-detectors, Wide energy range 1.8~28(p), 4~113 MeV(Fe), High energy range 50~430 MeV(Fe), Alpha particle detector 4~6.5 MeV, 400 cm2
	Plasma Analyzer	Plasma energy and composition measurement, 5 eV/q~28 keV/q(ion), 5 eV~17 keV(e)
	Radio Science	Detection of tenuous lunar ionosphere using S and X band coherent carriers
Earth Ionosphere	Plasma Imager	Observation of plasmasphere and aurora, XUV(304 Å) and visible(5 bands)
Earth	High Density TV	Observation of the earth in super-high resolution, for publicity and educational purposes

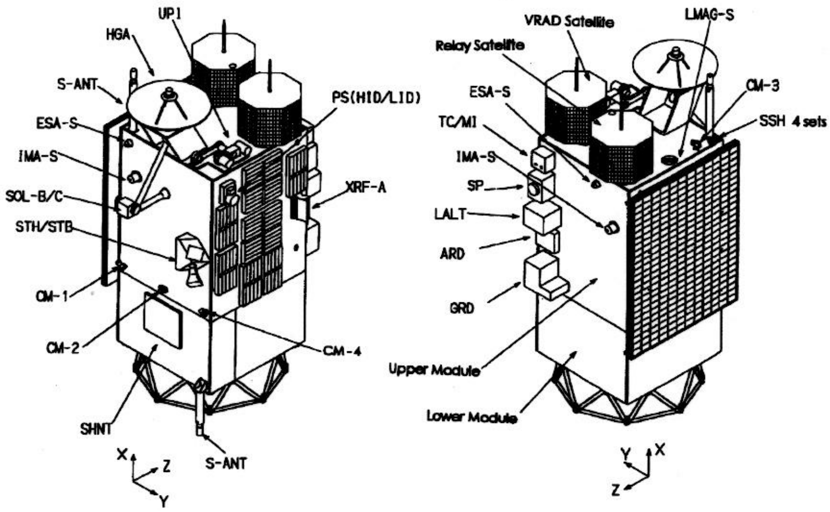

Fig.5 Configuration of instruments. UPI:Plasma Imager, HGA:High Gain Antenna, S-ANT:S-band Antenna, ESA-S:Plasma Analyzer(Electron), IMA-S:Plasma Analyzer(Ion), SOL-B/C:X-ray Spectrometer(Solar X-ray Monitor and Calibrator), ST:Star Sensor, CM:Monitor Camera, SHNT:Shunt Dissipator, XRF-A:X-ray Spectrometer, PS:Charged Particle Spectrometer, LMAG-S:Lunar Magnetometer, VSTAR:VRADSatellite, RSTAR:Relay Satellite, TC/MI:Terrain Camera/Multi-band Imager, SP:Spectral Profiler, LALT:Laser Altimeter, ARD:Alpha Particle Detector, GRD:Gamma-ray Spectrometer, SSH:Sun Sensor.

constraints to the origin of the Moon. The element abundances are measured by the x-ray and gamma-ray spectrometers. The x-ray fluorescent spectrometer up to 10 keV with a large aperture CCD totally 100 cm^2 will be capable of measuring the major elements such as Mg, Al and Si with a spatial resolution of 10 km. The gamma-ray spectrometer up to 10 MeV using a high-purity germanium crystal of 250 cm^3 will measure the natural radioactive elements, such as U, Th, and K, and major chemical constituents of some 10 kinds. The spatial resolution is 160 km. A Stirling refrigerator is used to achieve the operational temperature about 80° K for the crystal. The high-energy resolution(~3 keV) enables us to identify the hydrogen of the water ice which is expected to exist in the polar region. The ground trace for the x-ray and gamma-ray observation along the orbit is illustrated in Fig.7. One-year observation provides complete global mapping. Alpha particle spectrometer with a wide detection area typically 400 cm^2 with anti-coincidence will be used to detect alpha particles from the radon gas and polonium. The

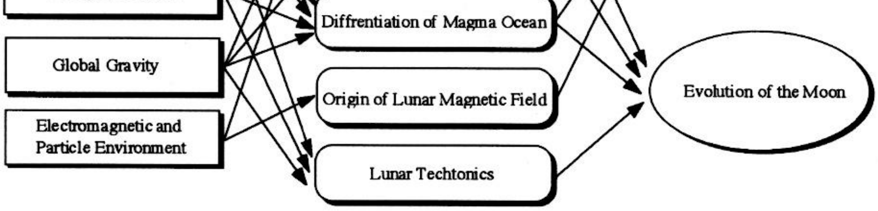

Fig.6 Scientific approach towatds the origin and evolution of the Moon.

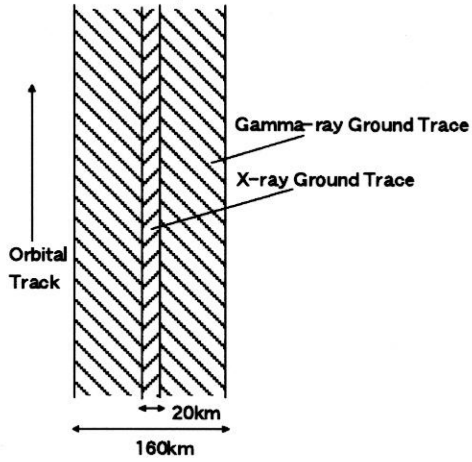

Fig.7 Ground trace of x-ray and gamma-ray observation.

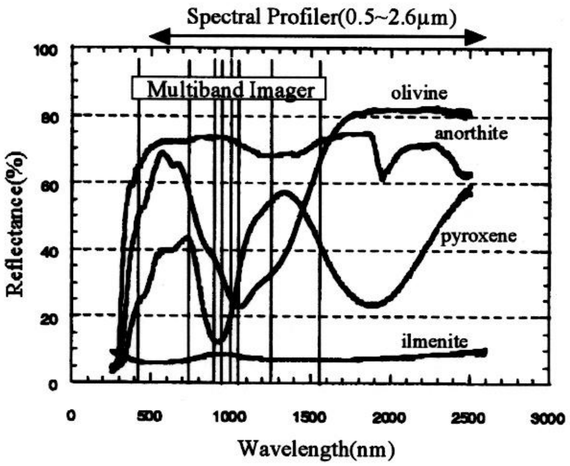

Fig.8 Mineralogical characterization and identification by Multiband Imager and Spectral Profiler[1].

observation of the gas ejection will contribute to understanding the lunar tectonic activity.

4.2 Global Mapping of Mineralogical Composition

The mineralogical characterization is performed by a multiband imager with 9 spectral bands ranging from 0.4 to 1.6 μm at a high spatial resolution typically 20 m. The bandwidth is 20~50 nm. The spatial resolution is nearly 10 times higher than that of the Clementine. The identification of mineralogical composition, such as pyroxene, olivine, and anorthite, is performed by the spectral profiler with a continuous spectrophotometry from 0.5 to 2.6 μ m. The spatial resolution is 500 m. The spectrum is sampled every 6~8 nm. Electric cooler is used for the IR sensor. Mineralogical characterization and identification by the two instruments are shown in Fig.8. The comprehensive data from the multiband imager and the spectral profiler are combined to map the mineralogical composition globally. The data inversion from the multispectral data to the mineralogical composition requires a data base which will be generated by laboratory simulation experiments in the mission preparation phase. The data of the spectral profiler are also used to identify the mineralogical composition of the deep crust material which is possibly exposed at the lunar surface, such as the inside of the large-scale impact craters.

4.3 Global Mapping of Lunar Surface

The surface topographic data are obtained by the high resolution stereo cameras and the laser altimeter. The stereo camera has a field view of 35 km with a spatial resolution of 10 m to provide images in three dimensions. The angle between the lines of sight for the two cameras is 30 degrees. The laser altimeter measures the altitude every 1,600 m along the orbit with a vertical resolution of 5 m and a spot size of 30 m diameter[2]. These data are used to produce global topographical maps with a higher accuracy than before. Combining topographic data with the spectral data from the multiband imager and spectral profiler, the mineralogical composition will be identified for individual geologic units which would make it possible to identify the origin of the geologic structure. The structure below the surface regolith, such as dislocation, volcano and lava flow, can be probed by the radar sounder using a 5 MHz transmitter[3]. The concept of the subsurface sounding is shown in Fig.9. The sounder experiment will reveal the inside structure up to 5 km below the surface with a vertical resolution of 100 m. The survey of the high land will provide important information on the hypothesis of "magma ocean". The observation of lunar surface enables us to understand the history of impact cratering, volcanism and tectonism. The topographic data can be used to investigate construction of the scientific facilities on the Moon such as the astronomical observatories in the future.

4.4 Gravity Field Measurement

The radio sources on the relay satellite and the VRAD satellite are used to conduct differential VLBI observation from the ground[2]. Waves at 4 frequencies in the S and X bands are radiated from each satellite. At least three stations are used for the observation. The VLBI observation enables us to determine the location of the radio source

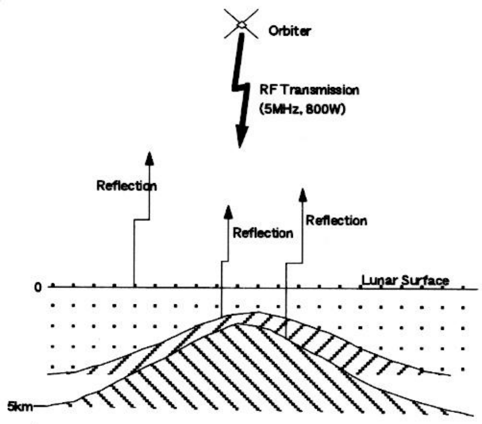

Fig.9 Concept of the subsurface sounding.

with a high accuracy. This will provide accurate information of the low-order gravity field and the moment of inertia of the Moon, typically 10 times better than before. With information of size of the core if any to be obtained by the Lunar-A mission, the composition of the core can be determined accurately. This will give a definite constraint to the origin and evolution of the Moon. On the other hand, the Doppler measurement of the orbiter via the relay satellite when the orbiter is in the far side is used to determine the local gravity field of the far side[2]. The configuration of this experiment is shown in Fig.10. The relay satellite is tracked by the 64 m dish at Usuda station and the accuracy is expected to be 1 mm/sec for 10 sec integration. The gravity anomalies typically less than 100 km will be determined for geodesy. The global gravity modeling will provide detailed information on the global crustal asymmetry as well as the internal lunar structure.

4.5 Magnetic Field Measurement

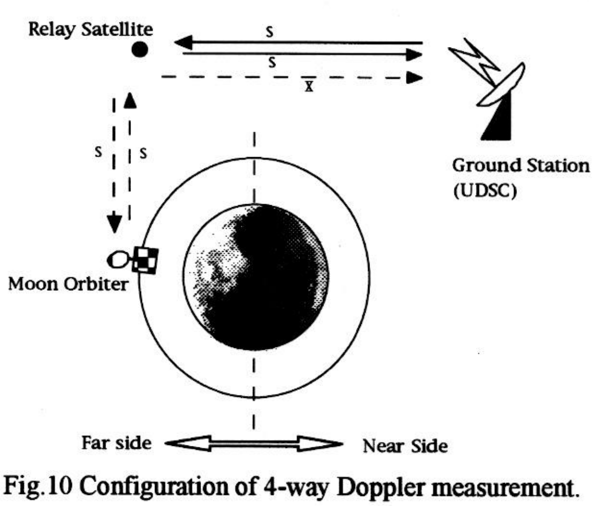

Fig.10 Configuration of 4-way Doppler measurement.

The magnetometer of 0.5 nT accuracy will provide global data on the lunar surface magnetic field and the lunar induced magnetic dipole. In order to estimate the lunar magnetic field separating from the magnetic field of the solar wind, the solar wind plasma is simultaneously measured by the plasma analyzer. The electron energy analyzer which is capable of detecting the solar wind electrons reflected by the surface magnetic field will show the distribution of the surface magnetic field. The data of the lunar magnetic field will provide an understanding of the origin of lunar paleomagnetism and paleomagnetism induced by impacts. The measurement of the electromagnetic response to the change of the solar wind magnetic field will allow us to estimate the internal conductivity and temperature profile, which give constraints to the size and composition of the lunar core.

4.6 Lunar Environment

The study of the lunar environment, such as the high energy particles, electromagnetic field and plasma, is required for the future manned and unmanned utilization of the Moon. It also has a valuable scientific aspect. The observation of the energetic particles including heavy cosmic particles will contribute to studying the composition of solar and interstellar matter and their evolution. The plasma analyzer containing ion mass/energy analyzer plus electron energy analyzer and electromagnetic wave receivers will be used to study the solar wind and the geomagnetic tail, as well as the interaction of the solar wind with the Moon. The radio science using coherent X and S band carriers from the orbiter and the relay satellite will make it possible to detect the tenuous lunar ionosphere which was reportedly detected by Luna19 but has not been confirmed yet.

4.7 Observation from the Moon

SELENE plans to observe the solar-terrestrial plasma environment from the lunar orbit. The earth ionosphere is observed by an imaging instrument in the wavelength in extreme ultraviolet(304Å) and visible radiations(4278, 5577, 5893, 6300Å, and longer than 7300Å), which will clarify the global dynamics of the terrestrial plasma environment and auroral activities as shown in Fig.11. The planetary radiations up to 30 MHz from Jupiter and Saturn are observed under the extremely low noise environment in which the dominant radiations from the sun and

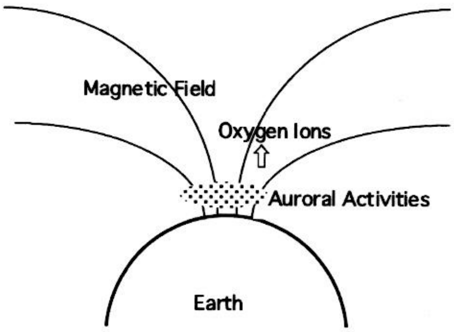

Fig.11 Observation of the earth ionosphere in the wavelength in extreme ultraviolet and visible radiation.

earth are shielded by the Moon itself. For the observation of the planetary radiations, the 15 m dipole antennas are shared with the radar sounder experiment.

5. Mission Operation and Analysis Center

A mission operation center for SELENE is to be established at ISAS in Sagamihara. The center will have four major functions as shown in Fig.12; satellite control, acquisition of science data, data analysis, and data distribution. The data are displayed in real time for satellite control and quick evaluation of the observation results. All data are stored and some of them are transmitted to the PI team members outside the center for operation monitor and data analysis. The total data will amount to several tens of terabytes. The center has the capability to generate the observation plan based on the requests from the PI team members. The observation plan is up-linked to the main satellite typically twice a week. All scientific data will be open to the public one year after completion of the nominal mission operation(1 year) and are distributed from this center upon request.

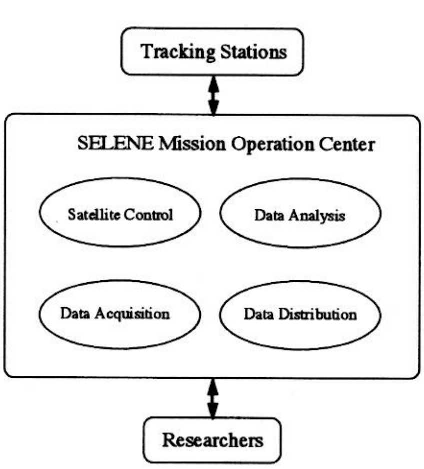

Fig.12 Concept of SELENE Mission Operation Center.

6. Summary

Current status of SELENE mission and onboard instruments are described. SELENE will carry 15 mission instruments on the main orbiter, the relay satellite, and the VRAD satellite. It is the largest-scale mission since the Apollo Project. The mission will provide systematic data of lunar topography and surface composition, the gravity field, and magnetic field, which will be integrated to study the origin and evolution of the Moon. The variety of the scientific data will provide a database which could be used for 15 to 20 years after the mission. More detailed information on SELENE science is given in [1]. The data will also provide crucial information to the landing and human activities on the Moon in the future. Qualification tests for critical parts and components have been completed. The design and fabrication of the flight hardware are now under way for the launch in 2005.

References

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