Chapter 3
Exploration Tools

Stephan van Gasselt, Angelo Pio Rossi, Damien Loizeau, and Mario d'Amore

3.1 Introduction

The geological exploration of the Solar System beyond Earth started with telescopes, and the very first geological observations of extraterrestrial solid bodies were those performed on the Moon. Even the very first published lunar geological maps were obtained from ground-based astronomical observations and were crafted in the early 1960s.

As of today, planetary exploration has been robotic, or jointly human-robotic as for the unique case of the US-American Apollo program realised by the *National Aeronautics and Space Administration (NASA)* in the 1960s and early 1970s. The research field of *planetary geology* was born in such a human-robotic context, by applying Earth-bound principles (see Chap. 2), and matching them with remote-sensing measurements, and by returning their data to Earth for analysis. The main tool for observing and analysing extraterrestrial surfaces is *remote sensing* which uses a variety of platforms, in addition (Fig. 3.1) to Earth-based or astronomical

S. van Gasselt (✉)
National Chengchi University, No. 64, Sec 2, ZhiNan Rd., Wenshan District, Taipei 11605, Taiwan
e-mail: svg@nccu.edu.tw

A.P. Rossi
Jacobs University Bremen, Campus Ring 1, 29795 Bremen, Germany
e-mail: an.rossi@jacobs-university.de

D. Loizeau
Université Lyon 1, Lyon, France
e-mail: damien.loizeau@univ-lyon1.fr

M. d'Amore
German Aerospace Center (DLR), Berlin, Germany
e-mail: mario.damore@dlr.de

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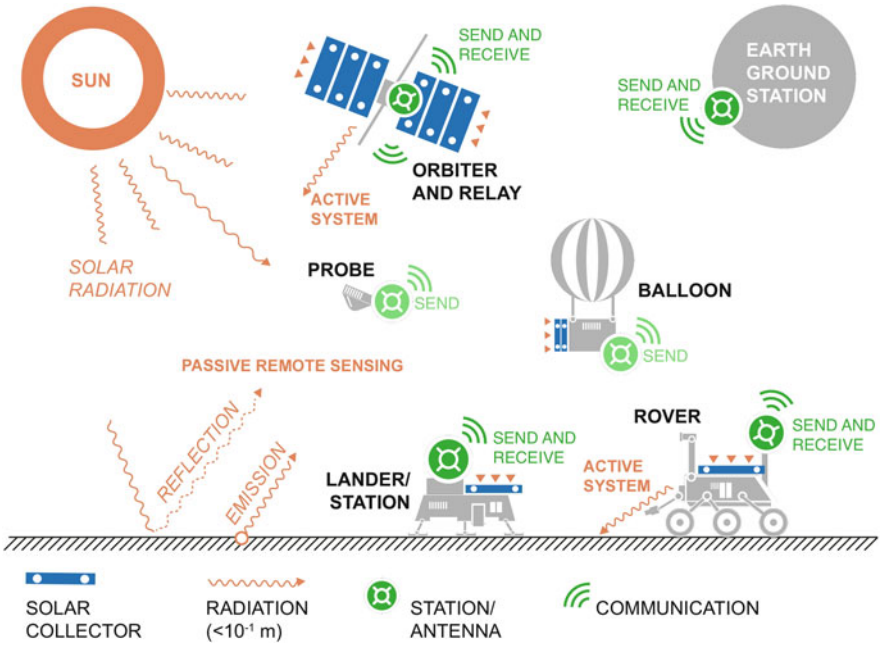

Fig. 3.1 Cartoon depicting main platforms involved in planetary exploration. On most platforms remote sensing experiments can be accommodated. On surface platforms (landers, rovers) also geological in-situ instruments and small laboratories for analysis can be hosted

observations. The basic principles and geological applications of remote sensing are introduced in Sect. 3.2.

Remote sensing is a methodology to gather qualitative or quantitative information of an object from distance and without physical contact, usually through information transported by electromagnetic radiation from instruments on orbiting platforms. Remote sensing data are usually characterized by the geometric and spectral resolution of the observation, the observation time and scientific contents (Sect. 3.2). Historically, remote sensing observations have been the first to be made to explore planetary objects and for most bodies in the Solar System such observations have remained the only ones. In few lucky cases—as for the Moon, Mars, few asteroids and comets—additional data came from samples recovered by robotic probes or humans, or they were delivered to Earth as meteorites (Sects. 6 and 7). With few notable exceptions, the latter usually miss contextual geological information, e.g. exact source location or provenance of a certain meteorite from within a large, geologically complex body.

The ultimate goal in the exploration of extraterrestrial environments is human, but the only attempt thus far was targeted at the Moon in the 1960s and early 1970s in the context of the Apollo program. A renewed geological exploration of the Moon might well start soon, while other targets, such as near-Earth asteroids (Chap. 13) or

Table 3.1 Platforms for planetary exploration and Solar System bodies visited

Type	Moon	Mars	Venus	Mercury	OSS	SSB
Flyby	6	5	10	1	3	2
Entry probe	0	0	5	0	1	0
Orbiter	27	14	7	1	2	3
Impactor	11	0	0	0	0	1
Lander	9	4	7	0	0	2
Rover	3	5	0	0	0	0
Sample return	8	0	0	0	0	1
Human	6	0	0	0	0	0

OSS Outer Solar System objects, *SSB* Small Solar System Bodies.
Source: NASA NSSDC

Mars (Chap. 11), require considerably more time. Table 3.1 summarizes the state of the art of planetary exploration through available platforms.

Robotic exploration has many assets: it can be carried out essentially in each environment by sending a spacecraft (or, in the case of Earth, an aircraft, drone, robot or alike), it can typically record, retain and send back data for analysis using a wide range of experiments once commands are implemented. However, remote sensing approaches when performed exclusively are often affected by considerable ambiguity in absence of ground truth. Local ground validation exists on the Moon with both landers/rovers and samples and on Mars with ander/rovers. Main limitations of in-situ measurements for planetary applications when compared to terrestrial ones are in terms of mass, power, sensibility, overall operating conditions, or data rates.

Remote sensing experiments can be classified in different ways. The most common one is based on where and how the electromagnetic radiation is generated to investigate the object from far. While *passive remote sensing* takes advantage of either radiation generated by the target body or by external sources such as the Sun (e.g., X-ray radiation, infrared radiation, microwaves, see Fig. 3.2) which interacts with the target body, *active remote sensing* is based on electromagnetic radiation generated by the spacecraft experiment, which then interacts with the target body (e.g. radar, laser).

3.2 Imaging

Imaging remote-sensing instruments, such as classical analog or modern digital camera systems employed on orbiting and roving platforms operate in the visible wavelength from about 390–700 nm (0.39–0.7 μm) to the near infrared with wavelength of up to 900 nm. Due to their close resemblance to what the human eyes perceives imaging data are the most accessible means to study planetary surfaces and their features. Classical photographs and digital images enable us to investigate

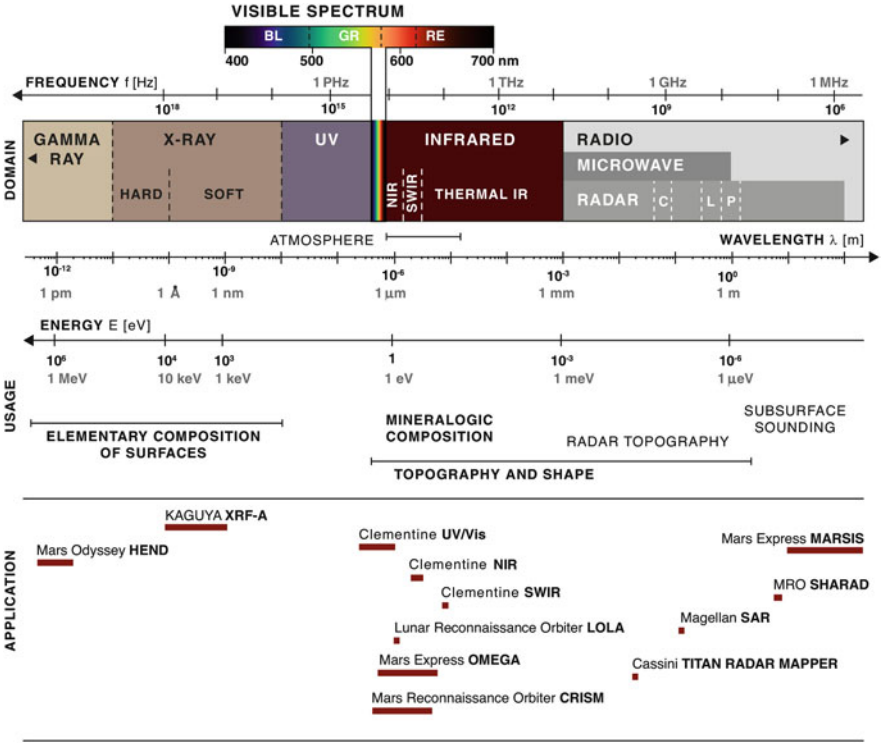

Fig. 3.2 Regions of the electromagnetic spectrum as used in planetary remote sensing and examples of applications on past and recent missions

morphologic characteristics such as relative positions, extents, sizes, structures, textures and colours of surface units and they allow us to eventually transfer these pieces of information into thematical maps. In order to study the actual composition of surface units, visual inspection of image data does not provide any direct clue and a variety of different spectrometers are employed which provide compositional details at wavelengths beyond the sensitivity of the human eye.

All imaging instruments consist of a radiation collecting and focusing unit, such as a telescope, and a unit which converts and stores the brightness pattern retrieved at the sensor on analog film or digital storage medium. Data, either digital or analog, are more than just pictures to look at if the instrument is properly calibrated and scientific data processing has been undertaken. Each grain on a photographic film and each pixel on a digital sensor carries physical information about the interaction between radiation and the surface. Due to calibration, we can directly measure the amount of light that falls onto the sensor at the spacecraft I_1 as so-called *radiance* L $[\mathrm{W} \cdot \mathrm{sr}^{-1} \cdot \mathrm{m}^{-2} \cdot \lambda^{-1}]$.

As we know how much light was sent to the surface it was reflected from and as we know the radiation source usually well, we can relate that quantity of incoming

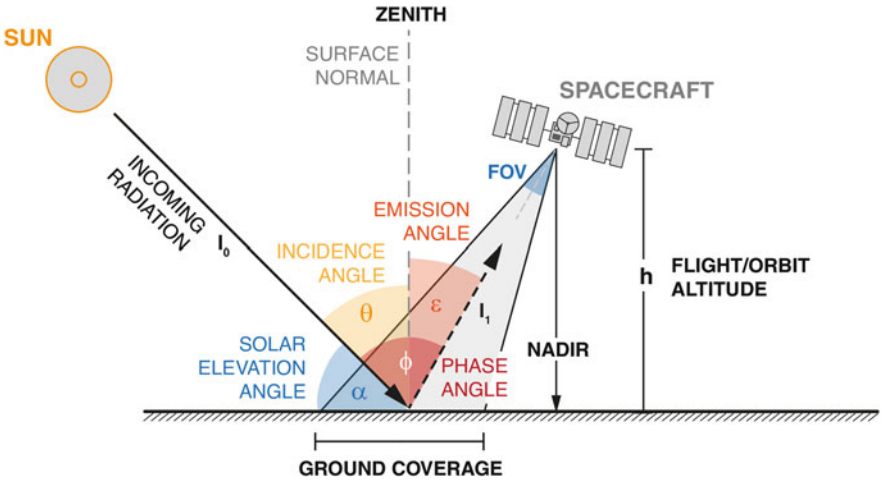

Fig. 3.3 Observation geometries and angles

radiation I_0 to the quantity collected at the sensor I_1 and derive the dimensionless so-called *reflectance* $\varrho = I_1/I_0$ [–].

$$\varrho = \frac{\pi \cdot \mathrm{L}_\lambda \cdot \mathrm{d}^2}{\mathrm{E} \cdot \cos\theta}[-] \tag{3.1}$$

Here, L_λ is the (wavelength-dependent) spectral radiance, d is the distance between radiating object and surface, E is the solar constant and θ is the solar zenith (or incidence) angle, i.e. the angle between the center of the Sun's disk and zenith. (see Fig. 3.3). The solar zenith angle is complementary to the solar elevation angle α. The emission angle ε describes the angle between outgoing (reflected or emitted) radiation and zenith, and the phase angle φ describes the angle between the Sun and the observer, i.e. the instrument.

These basic principles and geometric properties remain essentially the same for all imaging devices and spectrometers, however, the way information is collected and stored has significantly changed over the last 50 years of planetary remote sensing. Imaging cameras covering the visible wavelength range have always been playing a pivotal role for retrieving the first-ever impression of an unknown object, for flyby reconnaissance, or for systematic studying surfaces from orbiting platforms or from landers and rovers. On Earth, photographic film was widely used to image surfaces from spacecraft starting in the 1960s and 1970s during the US Keyhole program. While on Earth exposed film could be sent back by dropping it to the Earth's surface and catching it in-flight, the retrieval of analog film from platforms orbiting planets posed a major challenge. Early Soviet and US-American programs employed photographic cameras on lunar missions with great success by making use of an automatic film processing and scan unit. The

Soviet Yenisey-2 photo-television system operated on Luna 3 (1959) and took the first-ever image of the lunar farside, while the US Lunar Orbiter program (1966–1967) employed a similar system for systematic mapping and landing-site reconnaissance for the Apollo program. Both units operated essentially in a similar way by automatically photographing the lunar surface and by developing exposed film in a complex processing system onboard the spacecraft. After the developing and drying process, photos were automatically scanned and subsequently recorded on a television system which transmitted the modulated electromagnetic signal back to Earth where it was played back from a TV and recorded on film again.

Due to its complexity in implementation and error-proneness the automatic film-development system could not establish and the US as well as the USSR switched to the Vidicon system which was very successfully employed in particular during the Mariner and Viking missions to Mars. A phototube—basically a reversed TV-tube—lets incoming radiation pass through a vacuum tube and temporarily create an electric resistance pattern which is proportional to the amount of incoming light, i.e. brightness, on a sensitive surface. That pattern was scanned line-by-line, transmitted to Earth and wiped out again on the sensor to make room for the next recording. Vidicon tubes were often relatively heavy and prone to errors whenever the previous signal could not be completely erased, causing ghosts artifacts. Also, the tube design caused severe radial distortions of the image so that so-called *reseau marks* (small crosses covering the optics) were needed for later image rectification.

In the 1990s finally, digital camera technology was also applied in planetary exploration by making use of *Charged-Coupled Devices* (CCD) and *Complementary Metal Oxide Semiconductor* (CMOS) detectors which can be found today in basically all digital consumer-market cameras. These detectors allow for an improved handling of data and provided higher resolution, quality and integrity.

Along with the change of detectors and smaller sizes of CCD picture elements (pixels) (usually in the range of few μm), telescopes have been improved and allowed for higher geometric resolution that are determined by focal length and instrument aperture. In the late 1960s, the Mariner 4 camera system produced images at scales of 300–3000 m/px, in the late 1970s the Vidicon-based Viking Imaging System (VIS) allowed for ground-pixel sizes of up to <10 m although most image data were collected at spatial resolutions of several tens to hundreds meters per pixel. They were eventually transferred to the global *Mars Digital Image Mosaic* (MDIM) with a resolution of 231 m/px (or 1/128 px/degree). The Mars Orbiter Camera (MOC, 1996–2006) obtained resolutions of up to 3 m/px and in 2010 the Mars Reconnaissance Orbiter HiRISE camera could get down to 30 cm pixel sizes. The same picture is drawn in lunar exploration and translates to an increase in resolution of roughly one magnitude per decade.

The possibilities of improving spatial and also spectral resolution however come with a limitation regarding the amount of data that can be transferred from the sensor to onboard-storage and through interplanetary space back to Earth which is related to the spacecraft's power budget—and therefore performance—of telemetric systems. Also, the need for higher resolution imaging required more sophisticated approaches for the design of sensors. While imaging until the late 1990s was

characterised by *frame-camera* systems, allowing to take (mostly quadratic) fixed-size surface snapshots as a whole at a given instance of time, modern systems have been making use of *pushbroom* and *pushframe* technology. Here, the surface is imaged line-by-line, similar to a scanning device. With these new sensors, long image strips can be acquired while the spacecraft progresses in orbit over the surface. However, such an advantage comes at the cost of simplicity as data processing becomes more complex and observation and illumination geometries as well as time changes from one scanline to the next. It is noteworthy that the only so-called *whiskbroom* system (side-way scan) ever employed on a planetary orbiting spacecraft was the optomechanical scanner of the late Apollo 15–17 mapping cameras that imaged the lunar surface from orbit in a similar way the Earth observing Landsat satellite and its descendants have been operating since 1972.

3.3 Composition and Properties

The study of the composition of planetary surfaces requires different sensors that are sensitive to various types of radiation and wavelength ranges to record radiation from the surface of the body. This radiation can take different forms:

- solar electromagnetic radiation reflected from a surface (in the UV, visible domain or near IR),
- electromagnetic radiation emitted by the surface (in the thermal IR domain),
- electromagnetic radiation emitted by an instrument onboard and reflected by the surface (in the radio domain, or in the near IR),
- high energy radiation (gamma rays or neutrons) produced by the interaction of the surface or near subsurface with cosmic ray particles.

Radiation interacts with the bonds between atoms inside the crystals and absorbs radiation preferentially at given wavelengths. However, when the planetary body is surrounded by an atmosphere, radiation goes through it before reaching the orbiting instrument, and also interacts with the molecules in the atmosphere, and can eventually even be absorbed before reaching the ground.

The infrared (IR) portion of the EM spectrum is of particular interest in Geology as most rock-forming minerals have typical responses. Some instruments in the UV to IR work as single point spectrometers, others are spectral-imagers. Spectral imagers take images line by line or point by point and record portions of the radiation spectra for each pixel of the image. Thus, a single spatial location relates to spectral characteristics taken at different wavelengths.

Infrared wavelengths (Fig. 3.2) are suitable for remote identification of several important rock-forming minerals. Near-infrared (NIR, 0.75–1.4 μm) and short-wavelength infrared (SWIR, 1.4–3 μm), as well as mid infrared (MIR, 3–8 μm) record specific adsorption bands for many silicates. This applies also to hydrated minerals, including silicate hydrated ones (e.g. on Mars, and in Fig. 3.4). Some minerals though, notably quartz or feldspar, lack diagnostic features in these spectral

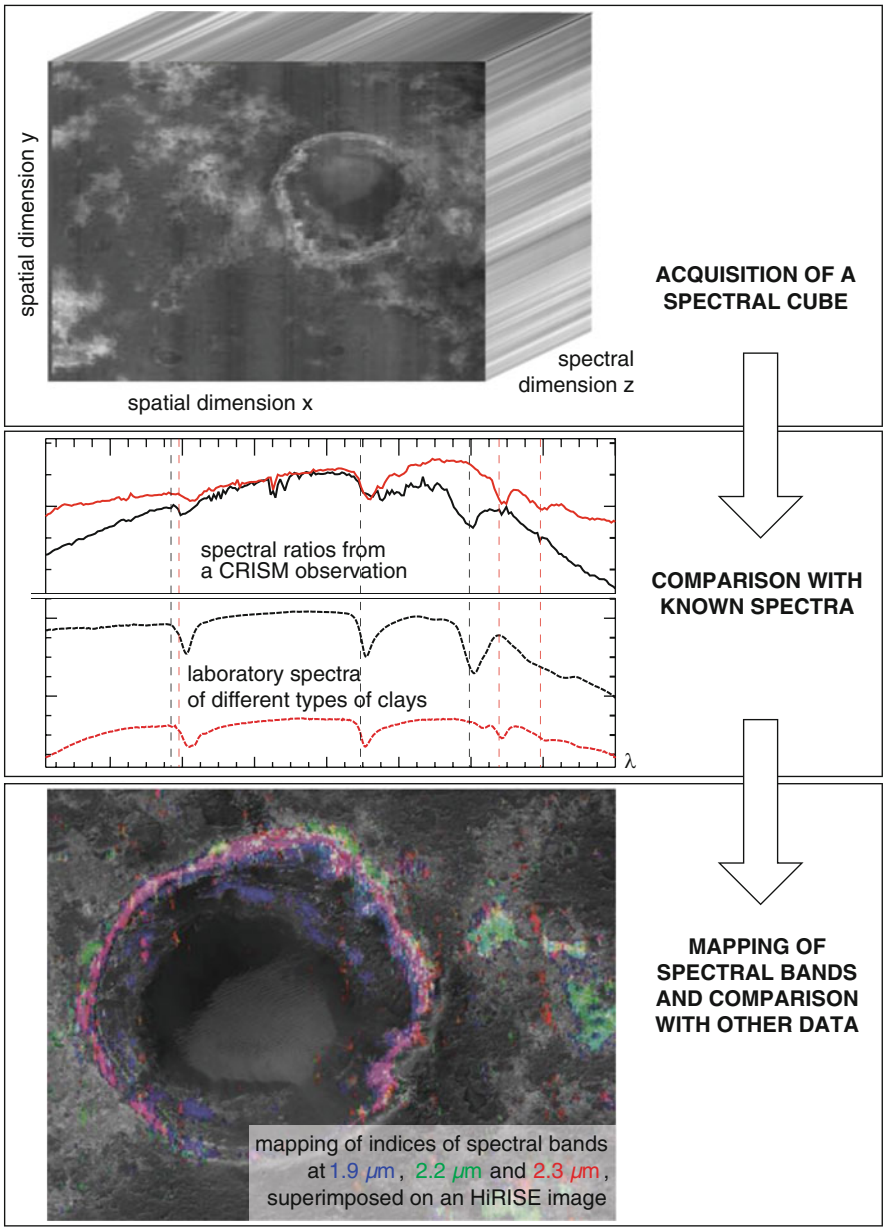

Fig. 3.4 A spectral cube and the main steps of its analysis. Source: Images NASA/JPL/University of Arizona; Laboratory spectra extracted from the RELAB Spectral Database; Copyright 2014, Brown University, Providence, RI

ranges. Thermal infrared (8–15 μm) spectral ranges can help identifying some of those minerals not properly addressed by VNIR/SWIR. Non-imaging spectrometers in TIR range were used successfully on Mars respectively on orbiter and rover platforms: TES, miniTES; other imaging TIR experiments are going to observe (in the 2020s) Mercury (MERTIS).

Geological infrared imaging can also benefit from experiments designed for atmospheric measurements mainly, such as VEX VIRTIS, taking advantage of few *atmospheric windows* where signals from the surface can be detected, such as anomalously hot portions of the surface, possibly also matched by visible brightness increase (Chap. 8), e.g. linked to possible recent or present volcanism.

The final data product created by hyperspectral imagers are spectral cubes (see Fig. 3.4), i.e. stacks of images, each corresponding to a different wavelength.

Ultraviolet (UV) spectral wavelengths (Fig. 3.2) are not very used in geological remote sensing, but they have been used for observing planetary atmospheres for typical gas adsorptions in such spectral range. Indirect geological applications could be, so far only Earth-bound, on volcanic gas emissions, for example. There are several specialized techniques, relying on different portions of the electromagnetic spectrum, that are not mentioned in this chapter (see Fig. 3.2).

Gamma and X-ray wavelengths (Fig. 3.2) in planetary remote sensing applications are used for identifying elemental composition of the uppermost layers of a planetary surface. Due to atmospheric absorptions they can only be used on planetary objects lacking an atmosphere or on the ground when in close or direct contact with a sample. Orbital applications rely on the interaction of solar radiation with the surface while surface application usually require active remote-sensing approaches. The case of high-energy radiation involves detectors that are poorly collimated, the detection is made for the whole area under the spacecraft (or within a solid angle below the spacecraft, intersecting the planetary surface), which depends on its elevation. Hence, mapping of hydrogen and other atoms is performed at different scale when compared to previous methods. Refinements of mapping can be made after many orbits, and methods of collimation are developed for the new instruments. In general, data derived from such experiments are of relatively low spatial resolution, compared to imaging experiments, due to the need of long integration times over multiple passes of the spacecraft over the same region. Therefore large-scale or global elemental maps from Gamma and X-Ray spectroscopy may take several years of observations to be produced by orbiters. Examples of such experiments are the Gamma-Ray Spectrometer (GRS) suites on board Mars Odyssey and LEND on board Lunar Reconnaissance Orbiter.

After recording a spectroscopic signal from the surface, one needs to compare it to known spectra, recorded in a laboratory for example, with well characterized materials. This will enable detecting, mapping and possibly quantifying the presence of atoms or minerals at the surface (Fig. 3.4). In the case of IR spectroscopy this reference is usually contributed by laboratory spectra. In the case of high-energy spectroscopy in the X-ray domain the reference is usually established by carrying sample material of known composition which is exposed to the Sun during mapping.

At the scales we observe (from few tens of meters per pixel to few hundreds of kilometers), surfaces are heterogeneous with different rocks and different types of regolith, and even at microscopic scale, rocks are heterogeneous, so a single spectra, unless taken in a laboratory using a controlled sample, is always a mixture of different minerals and different autochthonous and allochthonous components, such as bedrock and dust.

Here are some recent examples of instruments that mapped the composition (atomic composition or mineralogy) of bodies of the solar system, the list is not comprehensive but tries to cover instruments with major contributions on a diversity of bodies:

- Mars
  - Thermal Emission Spectrometer (TES) on Mars Global Surveyor (MGS),
  - Observatoire pour la Minéralogie, l'Eau, les Glaces et l'Activite [Visible and Infrared Mineralogical Mapping Spectrometer (OMEGA)] on Mars Express,
  - Compact Reconnaissance Imaging Spectrometer for Mars (CRISM) on Mars Reconnaissance Orbiter (MRO),
  - Gamma-Ray Spectrometer (GRS) on Mars Odyssey (MO),
- the Moon
  - Moon Mineralogy Mapper (M^3) on Chandrayaan-1,
  - Lunar Exploration Neutron Detector (LEND) on Lunar Reconnaissance Orbiter (LRO)
- Vesta and Ceres
  - Visible and Infrared Spectrometer (VIR) on DAWN,
  - Gamma Ray and Neutron Detector (GRaND) on DAWN
- P67/Churyumov-Gerasimenko
  - Visible and Infrared Thermal Imaging Spectrometer (VIRTIS) on Rosetta

3.4 Topography and Structure

Deriving information about topography, together with imaging, is one of the key tools used to remotely study the geology of Earth or any solid extraterrestrial body. There are several ways to construct or extract topographic models of a planetary surface:

- stereo-photogrammetry using passive optical sensors and data (e.g. taking advantage of Solar radiation or emission from target bodies),
- laser scanning using active optical sensors by measuring return times of light signals sent to the planet's surface,

- radar imaging using active sensors in the microwave/radar domain allowing to make observation through thick atmospheres such as present on Venus or Saturn's moon Titan.

The result of any technique might be a local, regional or global topographic model (Chap. 11).

Information about topography itself is of importance not only to describe and understand the geomorphology but also to reconstruct the geology of any planet or satellite. The combination with imaging, compositional and contextual information are synergistic for geological interpretation as topography allows to reconstruct the relative and absolute position of geologic units and their extent. In each snapshot the topographic signature of present or past impacts (Chap. 7), endogenic (Chap. 8) and surface (Chap. 9) processes and overall geodynamics (Chap. 10) are recorded. The hypsography, i.e., the cumulative histogram of the topography of a planetary body, summarizes at a glance the overall distribution of heights, highlighting, for example, the large amount of volcanic plains on Venus, the oceanic vs. continental lithosphere on Earth, Mars' dichotomy or the primary and secondary crusts of the Moon, respectively anorthosite highlands and basaltic maria (Chap. 11).

Photogrammetric restitution of the surface topography is based on the calculation of viewing geometry, typically imaging the same portion of a planetary surface under different angles (Fig. 3.3). It is based on the basic principles introduced in Sect. 3.2 and it takes advantage of the parallax between two or more cameras pointing at the same area/object in order to derive the distance and, with some additional or a-priori knowledge, the absolute height/topography. Essential to its application are detailed knowledge about the interior information of a camera system and the observation geometry. Photogrammetry is the oldest technique for topographic creation, after trigonometric land-based surveying.

Alternatively, coherent laser light pulses are used for deriving information about surface topography. Once a laser pule is sent off from an altimeter system, its time to return is used to calculate the distance to the surface and back to the detector. In the case of Mars Global Suveyor's Mars Orbiter Laser Altimeter (MOLA) during 1996 and 2006 the surface footprint of a single laser shot was about 160 m in size due a *laser beam divergence* of 420 μrad and an orbit altitude of roughly 378 km. For the Lunar Reconnaissance Orbiter (LRO) Lunar Orbiter Laser Altimeter (LOLA), the beam divergence was reduced to 100 μrad and orbit altitude was significantly lowered to 50 km resulting in footprints of 5 m diameter. Also, the frequency with which laser pulses have been sent to the planet's surface were improved from 10 Hz for the MOLA instrument to 28 Hz for LOLA resulting in a finer along-track spacing of measurements. Orbital laser altimeters and scanners sample the surface along tracks with a dense point spacing *along track* and considerable point spacing *across track* depending on the exact orbit geometry. Naturally, in a polar orbit point densities are higher near polar areas when compared to equatorial areas. To overcome this, point data need to be interpolated to be able to provide gridded maps with continuous data coverage.

The behaviour of most geological materials at radar wavelengths (Fig. 3.2) provide ways of distinguishing them, although usually with less detail compared

to optical remote sensing depending largely on the combined effect of surface dielectric constant and surface roughness scaled to radar wavelength. Radar imaging has been used extensively in studying the surface of Solar System bodies with thick atmospheres, such as Venus (Magellan) and Titan (Cassini-Huygens). Atmospheres can be partially or totally opaque at visible wavelengths as well as in other portion of the visible spectrum. However, the potential of radar imaging and mapping has not been exploited yet for planetary exploration and they are mainly used for either imaging purposes or for the reconstruction of topography using single radar pulses in a somewhat simpler process compared to radar image reconstruction.

Single footprints of radar echoes sent to the surface of a planet or satellite are typically relatively large as they are defined by the size of the antenna. In order to improve spatial resolution the antenna's size is *synthetically* increased by making use of the spacecraft's motion in orbit and by processing the signal returns with respect to their specific time. This method, termed *Synthetic Aperture Radar (SAR)*, allows for much higher spatial resolutions without physically creating larger antennas. In the case of NASA's Magellan mission to Venus, radar altimeter footprints typically ranged between 10 and 30 km (e.g. for a spacecraft orbiting down to ~300 km of altitude). Very high resolution topography can be obtained from SAR data using radar interferometry, e.g. SRTM is a notable example from the 90s when the Space Shuttle, equipped with radar antennas, collected SAR data that were later processed to produce quasi-global topography. SAR interferometric measurements have not been performed on planets other than Earth so far.

3.5 Geophysical Tools

Geophysical probing of Earth's near and deep subsurface relies on a variety of methods, using several parts of the electromagnetic spectrum, either remotely, in-situ or in close contact. A very wide range of geophysical exploration techniques have been developed through time on Earth, driven by resources (oil and gas, minerals) in most cases. Among those available and used for terrestrial applications, a fraction is used for planetary geological exploration. Similarly to what applies to imaging remote sensing, some geophysical techniques rely on passive observations, other on active ones, the latter being much less used, due to their inherent higher operational complexity on extraterrestrial settings.

3.5.1 Potential Fields

Gravity and magnetic field measurements are most used for investigating the physical state and subsurface structure of planets and moons, as well as typically the first and most affordable large-scale surveying options for terrestrial oil and mineral exploration (e.g. from satellite or aircraft platforms). Gravity variations, or

anomalies (which tend to be the most used in geology, more than absolute values) are sensitive to the mass distribution inside a planet, this can have close correlation with surface and subsurface geology, particularly in its topmost layers.

The detail and spatial resolution at which gravity data can be directly measured is strongly dependent on the distance between measurement and the size/scale of the source, thus the orbit altitude of the platform. Apart from direct measurements in-situ with gravimeters, one could use combined topography, spacecraft orbit data, and spacecraft tracking information (radio science). Global gravity data are often used in conjunction with topography in order to construct models of the subsurface, such as crustal or lithospheric thickness (see Chap. 8).

Magnetic field measurements, especially if carried out far from planet or moon surfaces can carry variable information on the subsurface. Magnetic field values can be measured using specific experiments (magnetometers) or can also, in some limited cases, derived from other types of measurements (e.g. ionosphere-sounding radars, such as MARSIS). Magnetic measurements allow for detecting not only currently present global magnetic fields (e.g. on Earth), but also ancient ones, whose record is preserved as remnant magnetization in minerals within the crust, still measurable from orbit, like in the case of Mars. In any case, the presence of a global interior magnetic field is strongly linked to the interior state of any planet or moon (Chap. 10).

3.5.2 Seismics and Subsurface Sounding

Both active and passive acoustic probing of the subsurface are well-established techniques on Earth used since many decades and with a large variety of applications. They make use of generation, transmission, reflection and refraction of seismic waves through Earth's crust in order to derive information on the physical characteristics and—indirectly—of its geological nature, such as composition, lithology, state of fracturation. In such cases this is achieved through *ground truth*, which for the subsurface typically consists of drilling or coring. Also, the combined use of independent geophysical techniques (e.g. acoustics and electromagnetics) allows for better constraining the in-principle unknown or poorly known subsurface geology. In the planetary case, the subsurface is largely unknown in absence of a subsurface sounding experiment and very often contextual or *ground truth* information is missing. Seismics on solid bodies other than Earth have been successfully performed only on the Moon (see Fig. 3.5). Active seismic investigations on the Moon were performed in later Apollo missions.

Seismic waves can be produced actively through percussion (such as hammering) or explosions (such as by mortars used during Apollo), while passive seismics could make use of earthquakes (moonquakes) or possible energization due to small asteroid impacts, particularly on atmosphere-less bodies such as the Moon, but also on planets with a relatively thin atmosphere, such as Mars.

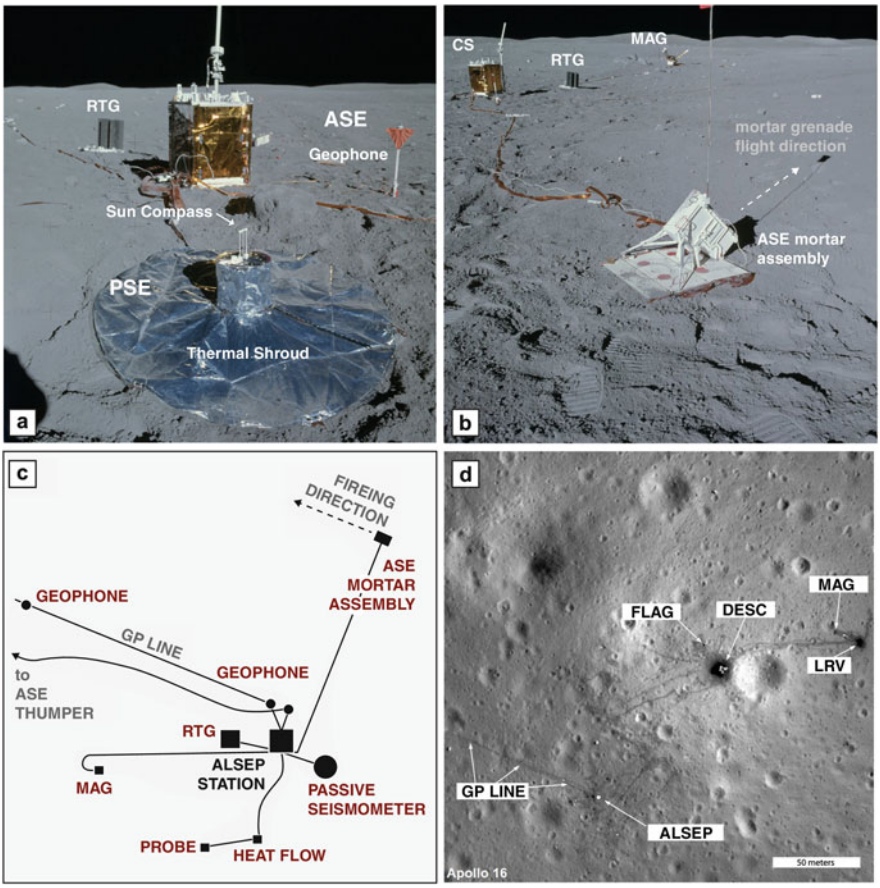

Fig. 3.5 Seismic experiments on the Moon. (**a**) The Apollo 16 Passive Seismic Experiment, PSE; (**b**) the Apollo 16 mortar package of the Active Seismic Experiment, ASE; (**c**) overview of the ALSEP surroundings with ASE and PSE equipment, cf. (**a**) for reference; (**d**) high-resolution image of the AS 16 landing site with ALSEP location and larger context. Label ALSEP refers to the Apollo Lunar Surface Experiment Package, ASE and PSE refer to the Active and Passive Seismic Experiment, respectively. RTG refers to the radioisotope generator, MAG is the surface magnetometer, CS is the ALSEP Central Station. GP labels a Geophone and DESC refers to the Apollo Descent stage. Source: (**a**), (**b**) AS16-113-18347. (**d**) from NASA/LRO landing site montage, 23 Nov 2015

Alternatively once more radar wavelengths can be utilized to investigate the subsurface of planetary bodies. Subsurface sounding radars were so far employed only on the Moon (ALSE) during Apollo times, and later by JAXA's Selene/Kaguya (LRS) on Mars twice, with MARSIS and SHARAD on board ESA's Mars Express and NASA's Mars Reconnaissance Orbiter (MRO), respectively. The fact that water ice is transparent to a wide range of radar wavelengths (Fig. 3.2) makes radar sounding ideal to investigate the subsurface of icy or ice-rich bodies (glaciers,

planetary polar caps, permafrost or ice-rich regolith). On the other hand liquid water, due to its very high dielectric constant, is preventing radar signals from crossing water-saturated levels.

Future subsurface exploration of icy satellites in Jupiter and Saturn systems will also rely on orbital radar sounders able to penetrate the icy crust (see Chap. 12). Ground-based radar sounding is very common on Earth (GPR) and are also bound to planetary targets (Mars) on board upcoming rover missions (ExoMars). A more detailed treatment on planetary interiors, investigated through measurements and models, is provided in Chap. 10.

3.6 Landing Sites and In-Situ Tools

Going beyond remote sensing on any planetary surface requires landing somewhere in order to perform experiments. The selection of an adequate landing sites is extremely important for both in-situ exploration and, even more, for sample return. Landing sites are literally the locations for *ground truth* for extraterrestrial bodies (Chap. 5).

Any landing site has to satisfy scientific and engineering requirements, including safety, which can vary substantially depending on the mission scenario and the knowledge of the target planetary body: the selection of landing sites is a complex process and constrained by available data and information. In the case of very remote and complex landings, such as Huygens on Titan, the choice of an exact landing site is limited, therefore spacecraft need to be designed for broad range of survivability options. Early Soviet probes to Venus but also the modern Huygens lander had floating capabilities as it was not known whether the landing sites were liquid or solid surface. In most recent cases for Mars landing sites have been selected based on an increasingly large base of data used to take both engineering and scientific decisions. In some cases, exact landing sites are being selected with the help of instruments on associated orbital platforms and direct observations. In that way, the landing sites for the Viking 1 and 2 landers were selected and characterized as much as possible from orbit by the Viking Orbiter instrument suite before the landers were actually deployed. Details on how planetary *ground truth* is achieved are provided in Chap. 5.

Planetary surfaces visited by landers or rovers can be imaged through close-range remote sensing, but a wide set of in-situ analytical capabilities exist, ranging from small contact experiments to relatively large (but typically very small for Earth standards) in-situ analytical laboratories.

3.6.1 Contact Experiments

Remote sensing-based analyses can provide data on mineralogical or chemical composition, but more detailed local studies require in-situ approaches through

different techniques and experiments. Those can be mounted on robotic arms for easy access to the spot of investigation (Chap. 5) or hosted elsewhere on landers and rovers and fed by robotic appendices (arms, scoops, etc.).

Rover-based in-situ analytics for the determination of compositions can include some of the following instruments.

- Alpha Particle X-ray Spectrometry (APXS) generates x-ray excitation irradiating sounded materials with α particles produced by radioactive decay. Collected spectra are diagnostic of the chemical composition of the analysed rock.
- X-Ray diffractometry, widely used in geology and mineralogy for terrestrial applications was also used on Mars (CheMin on MSL): through irradiation of samples with X-Ray that are diffracted by the mineral structure, producing indicative spectra.
- Mössbauer spectrometry uses γ-Ray in order to provide mineralogical compositional information as well. It requires materials to bear Iron.
- Laser is used to investigate materials with Raman spectrometry: it can be used to identify both minerals and organic materials, thus, it is of interest for exobiology research (Chap. 14).
- LIBS experiments measure spectra indicative of elemental composition by collecting spectra of surface materials vaporized by laser pulses. A LIBS experiment, ChemCam, is currently operated by Curiosity (MSL) on Mars

Several variations of the above mentioned analytical techniques exist and they have either already been used on past lander or rover missions or they are going to be developed for upcoming ones.

3.6.2 In-Situ Laboratories

Automated acquisition, processing and analysis of extraterrestrial samples taken from the surface or sub-surface can be carried out with instruments and handling subsystems onboard landers or rovers. Such automated sample analyses have been achieved thus far on Mars, their advantage is in the much more time- and cost-effective handling of samples without the need of returning them to the Earth. Compared to other in-situ instruments presented in the previous section, the advantage is to better control the conditions of observation: light, temperature, air, solvents, liquid or gas reagents, size and state of the sample. The instruments can also be larger than those mounted at the tip of a robotic arm. This allows for more precise and complete studies of samples than with contact instruments as one can take microscopic images, test the physical or biological behaviour of the sample, identify minor compounds, differentiate isotopes, or identify organic molecules, and quantify these species. On the other hand, one needs to take the samples from the studied body, process them, and bring them to the instrument, which adds significant complexity to the mission.

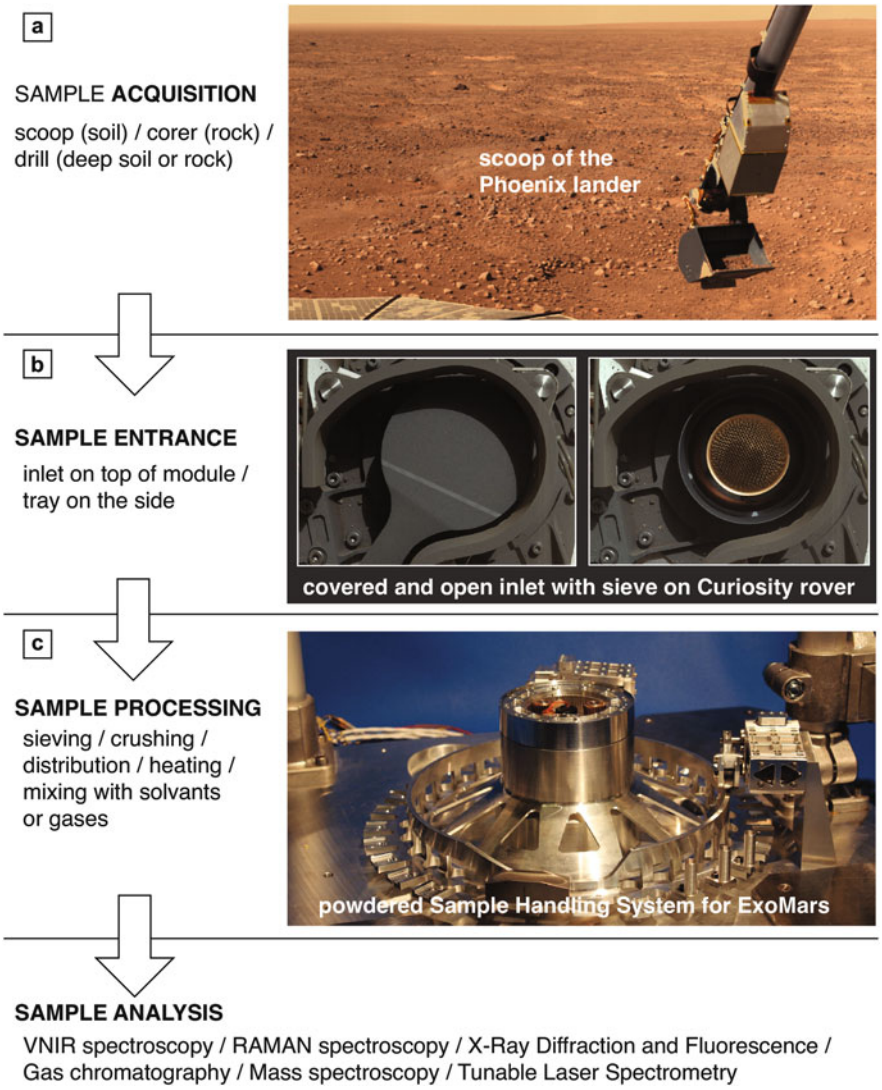

Fig. 3.6 Series of steps needed for sample analyses by in-situ laboratories. Source: (**a**) NASA/JPL-Caltech/university of Arizona. (**b**) NASA/JPL-Caltech/MSSS. (**c**) OHBSystem AG, 2016, courtesy of the ExoMars Project

For sampling, a variety of devices have been used, depending on the target and the type of lander or rover (Fig. 3.6). For atmospheric sampling, pumps such as for the Huygens lander during its descent through Titan's atmosphere have been used. Alternatively, atmospheric gas can be sampled by filling a collector passively through valves. First surface sampling techniques involved a scoop at the end of

an arm, taking samples of soil or regolith and bringing them to the laboratories on-board the probe. The technique works only with loose material, and was used on Mars on the Viking and Phoenix landers. Scoops were also employed on the autonomous Surveyor landers to the Moon in the 1960s. The main purpose here was to image the material and assess its physical properties using photographs. For harder material like rocks, drilling is needed. It also allows to obtain samples from greater depths. Drills of different lengths have been used or are planned on the Venera 13 and 14 landers on Venus, on the Curiosity and ExoMars rovers on Mars, and on the Philae lander on comet 67P.

Sample processing can involve sieving in the case of soils and regolith, or crushing it in the case of rock drills, and then dosing the samples for delivery to a display unit for the instruments. The display unit varies with the number of samples to be analysed and the instrument. In the case of Martian rovers, with several samples to be analysed, the sample handling an distribution device can be a carousel with cups or cells which delivers the sample to the various instruments, or ovens when heating is needed. Some systems have a limited number of uses (the number of heated samples will correspond to the number of ovens), while others can be used multiple times on different samples.

One can distinguish two broad groups of instruments: those which analyse samples without destroying them, i.e. *non-destructive* analysis (e.g. IR spectroscopy, Raman spectroscopy, X-ray diffraction and fluorescence), and those who need to modify the sample, by mixing the sample with reagents, or separating the different molecules by heating the sample or shooting laser pulses at it. This is as partially or totally *destructive* analysis. Gases expelled when heating can be analysed using tunable laser spectrometry or gas chromatography and/or mass spectrometry, and ions created by laser desorption are analysed through mass spectrometry. In some cases, before heating, the sample can be mixed with chemical solvents to help extracting eventual molecules of interest. Reference standards are also present for calibrating the instruments once on the surface of the planetary body. This is also the case for close-range remote sensing instruments, where colour chips or three-dimensional shapes are present as calibration targets.

In-situ laboratories that studied or attempted to study samples of soils and rocks include:

- Viking 1 and 2, two NASA landers on Mars (Biology and GC/MS experiments)
- Venera 11 to 14, 4 USSR landers on Venus (GC, MS and XRF)
- Phoenix, a NASA lander on Mars (TEGA, MECA)
- Curiosity, a NASA rover on Mars (CheMin, SAM)
- Philae, an ESA lander on comet 67P (Ptolemy, COSAC, Civa)

The ESA ExoMars rover—planned for launch to Mars in 2020—will also carry a suite of internal instruments (MicrOmega, Raman, MOMA). A MicrOmega instrument is also present on the lander MASCOT of the JAXA Hayabusa 2 mission, on its way to the asteroid 1999 JU3, but there it will analyse the samples directly on the ground, without any crushing or processing. NASA's Mars 2020 rover will study

soil and rocks with its mast and arm instruments and then take samples (*caching*) for potential return to Earth years later but will not analyse samples in situ.

3.7 Sample Return

The ultimate step in the mainly robotic scientific exploration of the Solar System is constituted by sample return. Returning samples form extraterrestrial bodies allows to use advanced analytical techniques and sample processing and preparation far beyond what is feasible on any spacecraft. Returning extraterrestrial samples is effort-intensive and costly, though. Therefore the choice of which samples to return is extremely important, but it is not always possible to achieve.

There are different ways to collect samples, depending on the planetary target, its distance to Earth, a priori knowledge and mission duration and profile, as well mass constraints for sample collection and sample return capsule. End members are:

- *Grab-and-go*: i.e. getting all what is possible to get given constraints, as fast as possible, or by
- collecting a well-constrained, carefully selected sample or sample suite.

Examples of grab-and-go for missions to small bodies are JAXA Hayabusa or NASA Startdust to an asteroid and a comet, respectively (Chaps. 6 and 13). Typically, the first steps of selecting and choosing samples is addressed by other exploration platforms and techniques, i.e. either by remote sensing for the selection of landing sites or other instruments providing in-situ measurements.

Even grab-and-go sample return for very short-duration operation (e.g. from an asteroid with quick touch-down like in the case of Hayabusa) requires careful selection of landing/sampling sites, for both safety/engineering and scientific reasons. Well-constrained sampling requires much more complex, multi-scale information both for scientific and engineering purposes, thus much more laborious preparations.

Existing sample return missions have been focused on the Moon mainly (Table 3.1). The other very large source of naturally returned samples is constituted by meteorites (Chap. 6). Moon samples are reasonably well-constrained, although parts of them are ejected material from very large distances (Chap. 7). Asteroid sample return missions have been successfully carried out (e.g., Hayabusa) or are in preparation for launch at the time of writing (e.g., OSIRIS-REx, Hayabusa-2).

Sampling variety (in terms of rock types, scientific objectives addressed) vs. affordable mission execution time and returnable mass always require trade-offs which have to be matched as well with safety constraints. Landing on a very safe spot might be far away from desired target materials, or the safe landing spot might be in geologically homogeneous terrain but the mission requirements include heterogeneous material. There would be a need for roving larger distances, collecting samples and returning them all in a repository (cache) for later retrieval. Both *grab-and-go* and selected, diverse samples share the same problem on planets

with relatively high gravity and an atmosphere such as Mars, where a single mission cannot perform collection, caching and return of samples.

Automated sampling on the Moon (e.g. the Soviet Luna program) followed largely a *grab-and-go* approach. Human robotic-assisted sampling on Apollo missions had more contextual information and mobility, plus geologically trained astronaut judgement that guaranteed sample diversity and—within limits—statistical representativity.

Although most planetary bodies are hostile to life as we know (Chap. 14), both missions and eventual samples recovered from extraterrestrial sources need to be evaluated for *planetary protection*, i.e. the need to prevent forward or backward biological contamination between planetary bodies, missions, samples and the Earth (see Chap. 14). Even astronauts onboard the first few Apollo missions on the Moon had to undergo quarantine, which was eventually lifted for later missions.

Take-Home Messages

Solar System geological exploration uses a variety of techniques and except for the Moon investigations were mostly based on remote sensing covering the full range of the electromagnetic spectrum.

Imaging and topographic reconstructions provide the first basic set of data for qualitative and quantitative geological and stratigraphic analyses

Multi- and hyper-spectral remote sensing combined with imaging and topography/morphology adds valuable and often unique compositional information

Ground truth on planets and satellites is provided typically by robotic landers and rovers, for the Moon it has also been performed by trained humans

Sample return, associated with geological contextual information and careful sample selection, when and where possible, is the ultimate robotic exploration tool for extraterrestrial bodies. Sampling and sample analysis on Earth is unrenounceable

Further Readings

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