Chapter 5
Ground Truth

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5.1 Introduction

The robotic exploration of the Solar System, similarly to remote-sensing observation and monitoring of our own planet, is key to capture the broad, large-scale perspective and reconstruct the evolution of bodies located millions or even billions kilometres away from the Earth. Such distances in space and time separating us from the geological objects of study are challenging. Interpretation of remotely-sensed data can be affected by large errors, like any measurement, but most importantly by interpretation bias.

The *present is key to the past* (Chap. 2) and the Earth is our key to interplanetary uniformitarianism, but *ground truth*, on Earth and even more on other planets and moons is the tool of choice to develop and understanding of planetary environments and processes. Fieldwork, in particular if robotic, does not necessarily provide final answers. Typically, extended fieldwork complementing remote sensing and well-contextualised sample return form the best combination for planetary geological exploration. Such combination, however, is rare, and has thus far only been achieved for the Moon while Mars might be the next candidate.

The terrestrial analogue field perspective (Chap. 2) is important, both for scientific and operational aspects, although there are limits in both cases. Conditions might be relatively close in terms of temperatures for certain analogues, but very far with respect to other parameters, such as gravity, or surface pressure.

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In the case of the terrestrial planets and the Moon similarities might be relatively close, e.g. lithologically, when one compares Venusian plains to terrestrial basalts. For small bodies such as asteroids and comets (Chap. 13) it is much more challenging to simulate surface (or subsurface) conditions on the Earth. Complications are further increased in the case of icy satellites hosting subsurface oceans (Chap. 12), where analogies, operationally and also geologically, are conceivable.

In all the cases outlined above remote sensing observations tend to be ambiguous, thus, the need for independent *ground truth* arises. Sample return from extraterrestrial objects (Chap. 3) is one of those cases where such field control, with in-situ measurements are of paramount importance. Going into the field is central in Earth geology (Chap. 2), but in planetary exploration it is mostly achieved with robotic platforms (Chap. 3) except for the thus far unique case of the Moon. Benefits of in-situ verification and sample acquisition for further lab analyses, impossible, difficult or overly expensive to be performed otherwise, are several: one can design and deploy exploration platforms lighter and relatively less complex and easier to operate. Autonomous robotic exploration for geological purposes, however, does not exist yet, and the only ‘platform’ able to do that is human, but in the forthcoming decades this might change.

Until today human-only geological exploration (Fig. 5.1a, b) has only been achieved on the Earth, and even terrestrial exploration begins to rely on robotic resources, such as drones. In addition, tools such as hand-held LIDAR and spectrometry of various kind support basic geological mapping and goes far beyond the classical use of topographic maps as a basis for surveying (Chaps. 2, 4).

The NASA Apollo Program constitutes to date—half a century from its beginning—an unparalleled coupling of effort and achievement that shaped Planetary Geology (Chap. 1) and sparkled the development of many disciplines within. Astronauts, either originally or specifically trained in the geosciences (Fig. 5.1c) allowed for the collection of data and samples of high-quality, with appropriate geological context. Its heritage is still being geologically exploited, its samples are still used for making new discoveries and any future planetary exploration, on the Moon itself, on asteroids or on Mars, will have to measure itself with the scale of success of the Apollo program.

5.2 Lander and Rover Exploration

Landers and mobile rovers are the most well-known and common platforms to collect field data on planets other than the Earth. They look back on more than half a century of developments and field experience, following—and often leading—the developments of robotics and autonomy, as well as the range of experiments available to characterise extraterrestrial surfaces (Fig. 5.1d).

The most direct and somehow violent way to perform ground truth is to trigger a surface or subsurface effect remotely with impactors which are potentially equipped with sensors. This has been done both in the early phases (also recently with

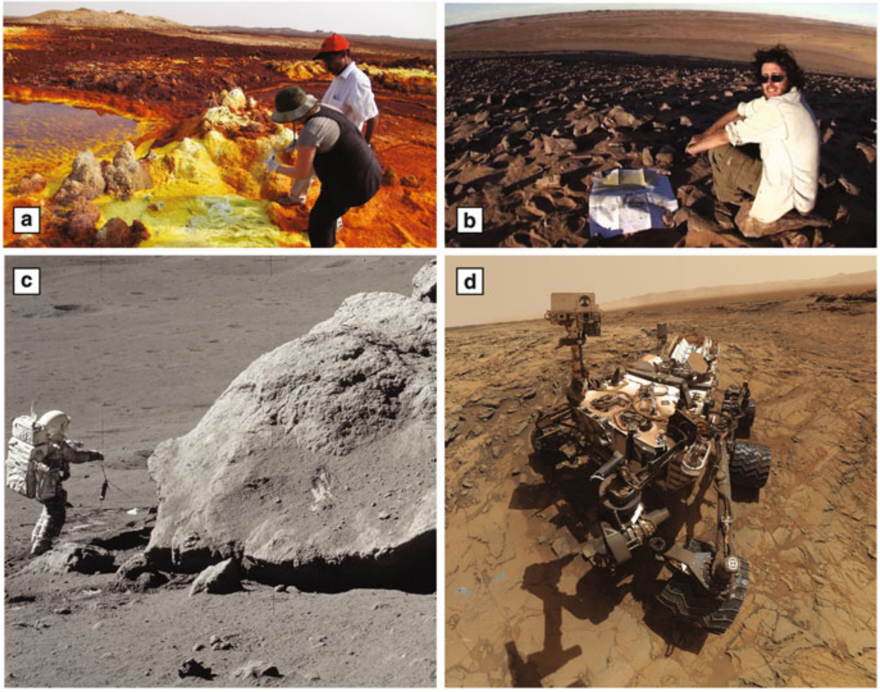

Fig. 5.1 Human vs. robotic ground truth: The level and amount of equipment is variable, from just hammer or simple sampling device to specialised tools and analytical facilities. The degree of autonomy is also highly variable: (**a**) B. Cavalazzi sampling hydrothermal hot springs in the Dallol crater (Afar, Ethiopia). (**b**) A.P. Rossi performing panoramic observations over the inner rings of the Richat structure (Mauritania). (**c**) Apollo 17 observations in the vicinity of a large ejected block. (**d**) MSL rover self-portrait mosaic of MastCam images: The dust cover is comparable with that shown in (**b**). Source: (**a**) B. Cavalazzi. (**b**) R. Sabbadini. (**c**) NASA Apollo photo as17-140-21496. (**d**) ASA Photojournal image PIA19920

LRCROSS) of Moon and cometary exploration (Deep Impact). Artificial impacts can expose subsurface material, as well as provide information on the target's material nature, composition and strength (Chap. 7). Some impacts or atmospheric plunges have been planned as end of a mission lifetime (SMART-1 on the Moon, Messenger on Mercury, Galileo on Jupiter and soon Cassini on Saturn), but the observations of their effects has been more problematic, since they were the only platform orbiting their target body, and thus not able to observe themselves while impacting the surface. A somewhat similar, low-speed end-of mission was planned and performed for ESA Rosetta. Specific cases of spacecraft impactors deliberately deployed and observed by the mother spacecraft were used e.g. with NASA Deep Impact.

The non-destructive deployment of static landers equipped with scientific experiments on the surface of a Solar System body is much more complex. The first body where this was achieved is the Moon for obvious reasons. After several ill-fated attempts in the late 1950s to get to the Moon with impactor and orbiter probes, the very first robotic impactor landing on another planetary object was the Soviet Luna 2 in 1959. Its science return was relatively limited but the pressure was raised on the US, in particular after the 1957 Sputnik event. A month later, the Soviet Luna 3 spacecraft was the first to send images of the lunar farside back to Earth. It was not until 1964 that the US successfully employed their Ranger program, 3 years after the Apollo program had been officially announced. The Ranger impactors, equipped with a set of vidicon cameras operating with different focal lengths, were also designed as impactor missions and targeted at the Moon. Despite malfunctions, Ranger 4 hit the farside surface but only the last 3 Ranger missions successfully impacted and returned sequences of descent images to Earth in late 1964 and early 1965. It was 1966 when Luna 9 made the very first soft touch down and returned first images from the surface of the Moon. Just a few months later, the US successfully targeted the seven Surveyor landers to the Moon which all succeeded and which paved the way for the successful Apollo program. During the six Apollo landings between 1969 and 1972, the Soviet Union sent several spacecraft for autonomous operation and sample return to the Moon. Finally, Luna 16, 20 and 24 succeeded to bring back rock samples. The successful Luna 17/Lunokhod 1 and Luna 21/Lunokhod 2 rovers ended that area of lunar exploration in 1973, 1 year after termination of the Apollo program. It took until 2013 when the Moon was visited again by spacecraft. At that time the Chinese Space Agency (CNSA) sent the Chang'e 3 lander mission to the Moon where it deployed the rover Yutu to perform surface operations.

Once a static lander is deployed on the surface and with enough power supply (either battery-, solar- or nuclear-powered), the lifetime of the lander itself and the data volume and length of the data time series collected strongly depend on the amount of energy and its replenishment, the degradation of the hardware and its intrinsic technical life span (e.g. maximum battery recharge cycles) as well as the harshness of the surface environment with respect to the lander life span itself (extreme temperatures, pressures, or alike). Attached to a static lander several types of experiments can be run, optimally (such as in the case of Viking 1, 2 and Phoenix landers) with a robotic arm to either deploy an experiment on the surface or collect surface or subsurface materials to be analysed on the lander itself. Simple tethered rovers can also be attached to a lander, providing energy and eventual communication to a small rover.

Wheeled rovers can range from very small, toy car-sized (e.g. Mars-2 rover with 4.5 kg mass) to large real car-sized objects (e.g. MSL Curiosity with 900 kg, and Mars 2020). Their capabilities, range and operational life are typically directly proportional to their size. Operations ranging from hours to years (even over a decade as in the case of MER) are possible. Mobility opens a much wider range of possibilities for observing diverse geology and terrain types. With increasing mass and volume available for experiments, the number, quality and possible complexity of ground truth-performing instruments increases. Sample acquisition can be more advanced (e.g. surface coating removal, shallow or deeper subsurface sample acquisition), allowing also sample preparation and processing complex enough to run small-scale laboratory procedures and analyses inside the chassis of the rover (e.g. X-Ray diffractometry, mass-spectrometry).

The accuracy level or type of measurements are nevertheless limited on a rover, even if as big as a small bus. The following step in terms of capability, where rover-based experiments cannot deliver, is to select using the experiments on board the rover itself, collect and cache samples for eventual return to Earth. In this case, ground truth literally brings samples back to ground. Robotic caching and return of sample from the Moon has been achieved decades ago (USSR LUNA), human-robotic one as well (so far the most effective both qualitatively and quantitatively). Mars is far more difficult in this respect. Further and farther than Mars, the effort is increasingly complicated.

Almost regardless the type of ground truth experiments and sample processing, analysis or caching capabilities, what largely makes the difference is how much diversity of geological units and materials can be accessed and how good it can be characterised. Beyond static landers and wheeled rovers, several other landing exploration options have been developed, particulary for low-gravity environments such as those on small bodies: hopping has been developed for JAXA Hayabusa and Hayabusa-2 missions, e.g. with the DLR MASCOT hopping lander. Further ahead, different types of locomotion are envisaged, e.g. for low-gravity bodies more or less rugged terrains hopping and rolling or, for higher-gravity targets, such as planets, legged robots: their terrestrial applications are relatively new and their planetary counterparts not common yet.

More recently, flying drones or UAVs have received considerable attention. They can be considered as semi-autonomous to autonomous robotic platforms complementing ground truth operations and have been rapidly spreading in Earth research. They are well-suited for planets and planetary satellites with an atmosphere such as Venus, Mars, and Titan.

The nature of ice and volatile-rich Outer Solar System bodies (Chap. 12) requires a special design of landers, also due to planetary protection aspects of bodies such as Icy Satellites (Chap. 14). For most of the categories above, the first and closest testing ground is the closest extraterrestrial object: the Moon.

Testing ground truth platforms and related experiments for low gravity environments (asteroids, comets) can be performed in condition of microgravity, e.g. using parabolic flights or drop tests). The choice of landing sites (Chap. 3) for ground truth is extremely important: although any field site on a previously unexplored planet or planetary satellite typically triggers a leap in geological understanding, the cost and effort involved in landing missions require a careful and well-designed selection process. When very little is known about the surface, more flexibility is needed: for example the Huygens probe was not known to land on solid or liquid (methane) surfaces on Titan, thus, it was designed to be able to float as well—a feature that was not needed in the end. The information available in order to select a meaningful landing site can vary substantially: from very limited data such as for the first set of lunar missions, to extensive multi-mission, multi-experiment datasets and models, such as in the case of later and near-future Mars rover missions.

The number of observations needed during ground truth for characterising aspects of the local geology (morphology structure, composition, age, state of activity etc.) is a key aspect: if the final aim is to collect only few tens of samples the number of ground-based remote sensing observations will be very high (10^2–10^3), the number of contact measurement in-situ is on the order of 10^2, as based on the MER Spirit experience: such order of magnitude is respected on similarly equipped missions, with comparable conditions (e.g. MSL).

5.3 The Moon

The Moon is the Solar System body with the overall best level of ground truth, performed through robotic and human in-situ exploration as well as sample return, carried both automatic probes and by astronauts. The number of landing sites on the Moon is higher than any other Solar System body (Fig. 5.2). It is a body with very limited large-scale geological heterogeneity and a limited number of terrains (anorthositic highlands vs. basaltic lowlands) with substantial regional and local complications due to both impact, volcanic/tectonic processes and solar forcing. Also, the absence of any sizeable atmosphere is both an asset, limiting complications dealing with time-varying atmospheric conditions such as those on Mars, and an issue, not providing any deceleration for eventual incoming probes.

The geological significance of the Moon has multiple facets: it is centered on its capacity to retain large portions of geological history of the early Inner Solar

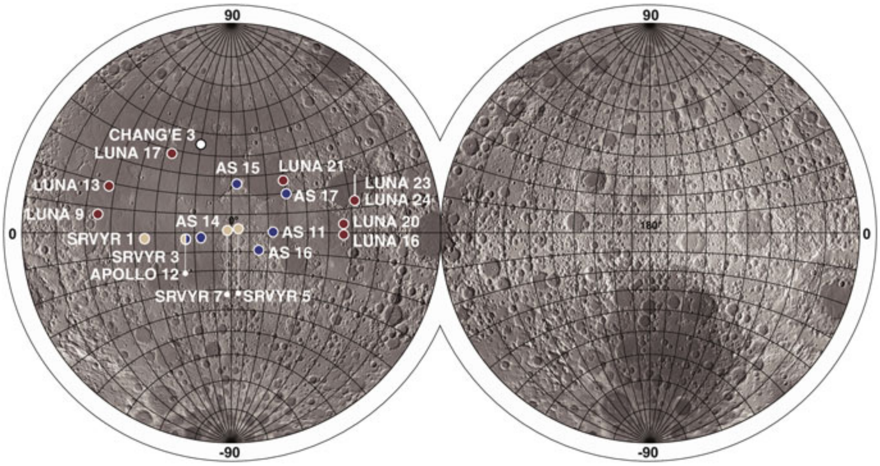

Fig. 5.2 Location of spacecraft landed on the Moon. Topography is color-coded (*dark* = low, *bright* = high) shaded relief in stereographic projection with central latitude and longitude at 0°N/0°E and 0°N/180°E. *Symbol colors* refer to mission program. Source: lander positions: NASA NSSDC, Wikipedia, on NASA LRO/LOLA hillshade

System that is either lost or unaccessible elsewhere. The Moon is also in the position to shed light on Earth's unique evolutionary path among all terrestrial planets. The only body in which absolute calibration of crater size-frequency dating has been directly performed is the Moon (Chap. 7). On more strictly exploration terms, the Moon can be the most proximal large-scale extraterrestrial outpost beyond Earth, as well as a possible remote, but still relatively close, source of resources valuable for further exploration (Chap. 15), as well as a possible base for it.

Several, if not most, of those key geological features were not well-known before the robotic exploration of the Moon started. Pre-spacecraft astronomic observations could highlight already large provinces and the features of impact basins and craters, including their inner morphology, ejecta and structural features. Key concepts and hyphotheses in planetary science such as the giant impact hypothesis and models such as the magma ocean developed from Moon-based data and samples, later applied elsewhere in the Solar System.

The scientific importance of the Moon for Earth's history and the Solar System as a whole has been understood thanks to the exploration itself. Moon exploration, both remote-sensing, in-situ and via sample return is what effectively kick-started Planetary Geology as a discipline (Chap. 2). It all began with the efforts culminating in the US Apollo and USSR Luna programs. With a pattern similar to that of Mars' exploration, but more pronounced, the Moon had a peak of ground truth and preparatory remote sensing missions in the 1970s, followed by a long gap until the mid 1990s and a renewed, multi-faceted exploration in recent years and upcoming future.

Only from the lunar nearside lander units can communicate directly with Earth without orbital relay. Consequently, lander missions have been place on the nearside but new approaches to send landers to the farside will follow in the upcoming years (Fig. 5.1).

The types of platforms used for ground truthing the Moon is extensive, from penetrators to static landers, particularly in the early phases, up to robotic rovers, such as USSR's six-wheeled Lunokhods. Ground truth platforms had to withstand lower gravity, no surface pressure and a harsh thermal environment with temperature ranges across illuminated and shadowed areas of about 300°K. The range of in-situ experiments deployed on the Moon is also the largest, although most of them date back to the 1970s, therefore they do not include the relatively recent technological advances available to Mars lander/rover exploration the last decade has brought up. In addition to lander-based remote sensing and photography aimed at characterising surface morphologies, experiments targeted at soil mechanics, chemical composition, mostly robotic, as well as passive and active geophysical experiments (Chap. 3). Most of them were deployed by astronauts and collected long time series of data, until even today. Sample collection and return was performed in both automated and manual ways (Figs. 5.3 and 5.4).

As outlined above, early robotic exploration by the US and USSR included fly-by attempts, orbiters and also employed hard and soft landers in the 1960s. After the initial success by the USSR to reach Earth orbit in 1957, to photograph the lunar farside for the first time, and to impact on the lunar surface in 1959 the

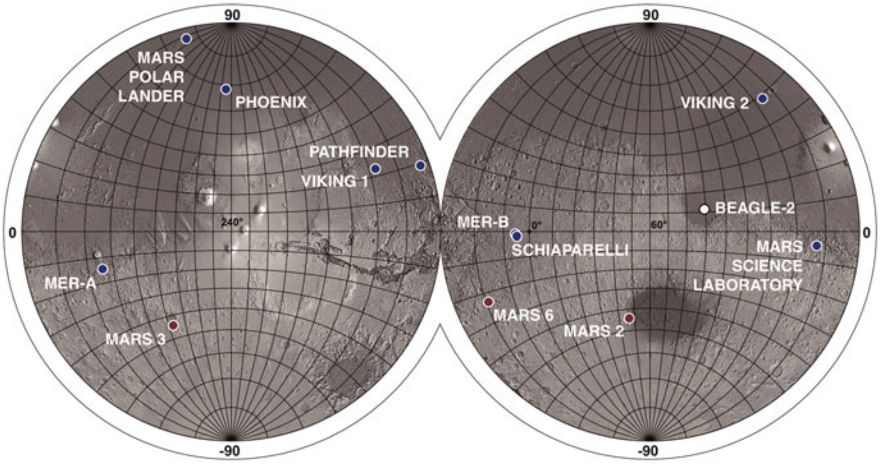

Fig. 5.3 Location of spacecraft landed on Mars. Topography is color-coded (*dark* = low, *bright* = high) shaded relief in stereographic projection with central latitude and longitude at 0°N/240°E and 0°N/60°E. *Symbol colors* refer to mission program. Source: lander positions: NASA NSSDC, Wikipedia, on NASA MGS/MOLA hillshade

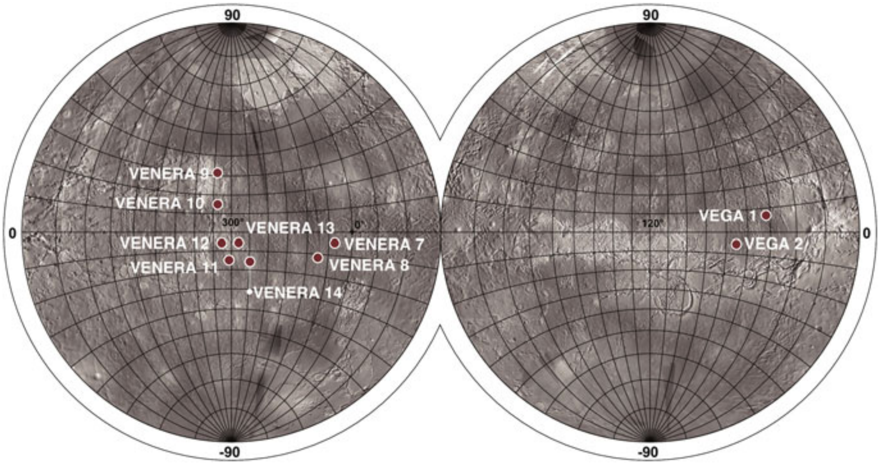

Fig. 5.4 Location of spacecraft landed on Venus. Topography is color-coded (*dark* = low, *bright* = high) shaded relief in stereographic projection with central latitude and longitude at 0°N/300°E and 0°N/120°E. *Symbol colors* refer to mission program. Source: lander positions: NASA NSSDC, Wikipedia, on NASA/Magellan hillshade

US followed with the Ranger and Surveyor program as precursor to the Apollo investigation. They were complemented by the short-lived but overwhelmingly successful Lunar Orbiter program between 1966 and 1977 during which the Moon was imaged at highest resolution. The spacecraft of Surveyor 3, landed in 1967, was revisited by the Apollo 12 astronauts in 1969 after a pinpoint landing in walking distance away from the landing site. Samples of the Surveyor spacecraft were returned to Earth for inspection and characterization of the lunar environment. The ranges of objectives during the early investigations were broad, largely linked to the characterisation of the lunar surface, imaging and the identification of potential landing sites and their suitability and safety for subsequent human-robotic landings. Besides imaging, the investigation of geophysical and astrophysical properties of the lunar environment were the main focus of Soviet missions during the 1960.

The Apollo program initiated in 1961 and lasting until 1972 was a large, complex and ambitious set of missions that enabled human exploration of multiple locations on the nearside of the Moon. It included both orbital and landing elements, the first of which did not reach the Moon but explored the space environment and tested systems and procedures in Earth orbit (Apollo 7, 9), orbited the Moon and returned to Earth (Apollo 8, 10, 13, the latter was planned to land originally) and 6 successfully orbited, landed and returned (Apollo 11, 12, 14, 15, 16, 17, in Fig. 5.2). Luna, roughly synchronous with Apollo, included several elements from basic penetrators to complex, autonomous sample return missions (Luna 16, 20, 24, in Fig. 5.2).

Experiments carried out or deployed by astronauts during the Apollo missions covered areas beyond geology, such as measuring in-situ the solar wind (SWC), but the majority of instruments and operations were focused on the geology. Equipment included: soil mechanics experiments, chemical and mineralogical experiments for in-situ characterisation of samples to eventually collect, geophysical experiments. Certain experiments were deployed and left to collect data, others were used to support fieldwork and sample collection.

Apollo samples and to a lesser extent in-situ data are still being exploited in these years. The preparations and planning of field activities for Apollo was thoroughly reviewed and procedures tested well in advance during the geologic training of astronauts on analog sites on Earth (Chap. 2).

Exploration was typically conducted in traverses, planned in advance and moderately adjusted based on local boundary conditions and geological variability at field scale. Field equipment included rock and regolith handling tools, such as hammers, chisels, scoops, rakes, as well as corers and drillerscapable of reaching several decimeters to few meters of the subsurface. Aids for photographic documentation was provided by scales and gnomon, recording local illumination conditions. Geophysical equipment used at discrete locations included magnetometers, seismometers and gravimeters, in addition to active seismic transmitting and receiving systems (Fig. 5.5).

A substantial focus on resources was related the renewed exploration of the Moon in the 1990s and later years, with both Clementine and Lunar Prospector missions, which paved the way for the recent multinational orbiters with high-resolution imaging from NASA (LRO), Japan (Kaguya/SELENE), China (Chang'e), as well as impacting elements (LCROSS), focusing on volatiles. All of those constitute a set of precursors, at different stages, of human exploration, thus characterising with increased resolution, globally or locally, the surface features, environment and

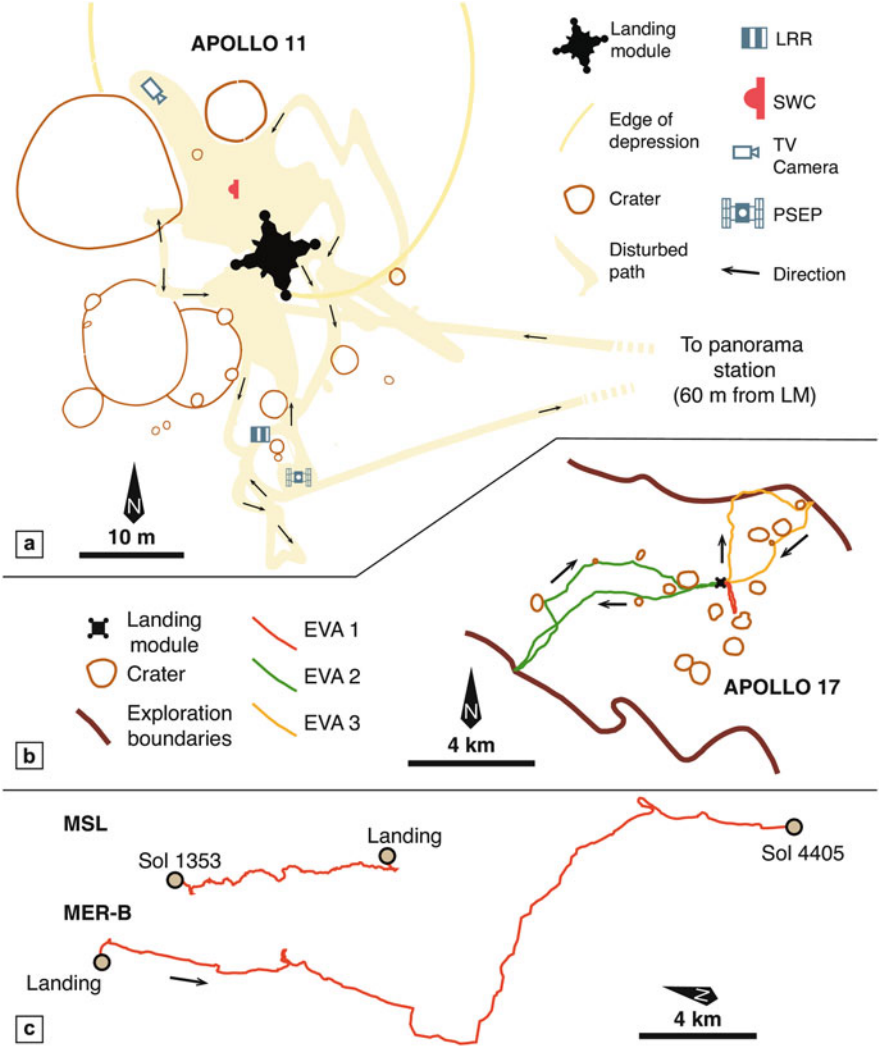

Fig. 5.5 Rover traverses on Moon and Mars, displaying the evolution of Apollo traverse during EVAs from Apollo 11 to 17. (**a**) Simplified traverse map from Apollo 11, with indication of main physiographic features, main direction of movement (on foot) of the astronauts and location of selected experiments, such as LRR, SWC, PSEP. (**b**) Apollo 17 traverse map with a much larger area explored; (**c**) scale of MSL Curiosity first 1353 Sols of exploration in comparison to the distance traveled by MER-B Opportunity after 4405 Sols of primary and several extended missions. Source: (**a**)–(**c**) NASA

potential resources at the surface or in the near subsurface of the Moon (Chap. 15). The first rover that returned to the Moon after Apollo and Luna was China's Chang'e-3 rover Yutu in 2013 (Fig. 5.2).

5.4 Venus

Venus as a target for geological exploration is naturally suited, being so similar in overall size to Earth, relatively close and relatively difficult to observe in detail due to its dense atmosphere and cloud cover, and yet, so visible in the night sky and familiar to most ancient civilisations in Latin. Also, Venus was the first Solar System body beyond the Moon to be reached by a spacecraft fly-by, with NASA Mariner 2 in 1962. Its robotic study turned out to be complex and with its own odds to the planetary exploration *superpowers* (US and USSR): Unlike for Mars, Soviet spacecrafts, entry probes and landers scored better mission success rates than American ones. In addition to orbital missions (Chap. 3) capable of penetrating the thick cloud cover, e.g. with SAR, the most relevant geological platforms on the ground were the Venera landers.

The specific requirements for ground truth on Venus are related mostly to the challenges it creates to optical Remote Sensing, essentially with an atmosphere opaque at visible wavelengths and at most optical ones (Chap. 3), as well as the extremely harsh surface conditions (more than 90 bar pressure, temperatures of around 450°K). Those challenges were both technical regarding the design of spacecrafts able to withstand such conditions (Fig. 5.6), as well as scientific, regarding the characterisation of the surface composition and age with limited remote sensing options. As it is often the case in Planetary Science, what is a limit or handicap in one domain turns out to be an asset in another: the atmosphere opacity and the visibility of Venus' cloud top rather than surface provides observational opportunities for studying its atmospheric dynamics. Environmental constraints to deal with on Venus are essentially its very high surface pressure and temperature, the optical opacity of its atmosphere, the very strong winds characterising its atmosphere (*superrotation*). The barren surface imaged by the Venera landers is dominated by volcanic materials with variable degrees of weathering and alteration (Fig. 5.7). Robotic ground truth on Venus has been achieved with atmospheric probes and static landers. Soviet Venera landers were limited in number (Fig. 5.7) and lifetime, limited by few hours based on battery power and, mostly, environmental harshness, as well as loss of contact with the relay orbiter for communications to Earth. Venera landers evolved through the years in their design, but shared some basic features, such as the quasi-spherical geometry of the pressure vessel (Fig. 5.7a), hosting most experiments and analytical facilities, as well the impact ring at their base (Fig. 5.6), in order to soften the impact on the solid surface. In general, Venera landers were rugged, nevertheless short-lived: their operational lifetime did not exceed a couple of hours. Experiments hosted on Venera (Fig. 5.6b, c), in addition to surface imaging (Fig. 5.7) include investigations on the chemical and isotopic composition with mass spectrometers, gamma-ray spectrometers, as well as gas chromatographs. Measurements of the mechanical properties of the soil were also present, although not always successfully completed.

Future platforms on Venus' surface suitable for geological exploration can be classical static landers or orbiters, as well as balloons. Several concept studies have

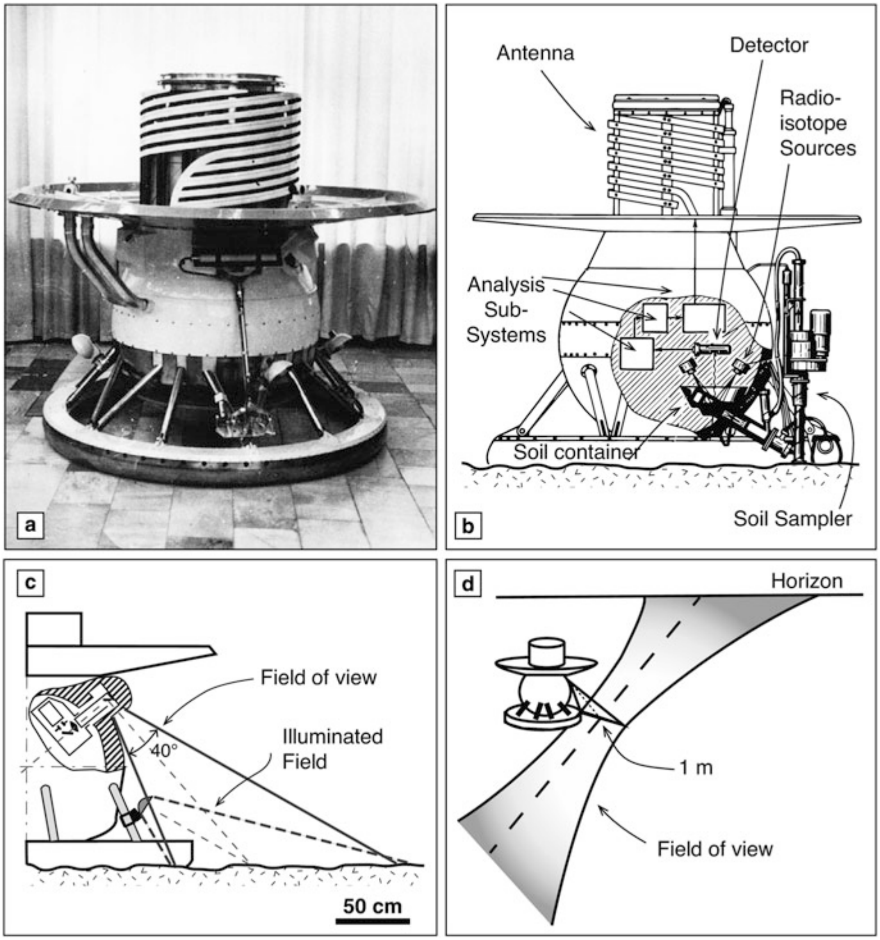

Fig. 5.6 Sample of Soviet VENERA landers with their typical impact ring at their base of round-shaped spacecrafts: (**a**) Venera 9 model. (**b**) Venera 13 simplified scheme and partial cut-out, including the sample acquisition mechanism. Not all subsystems are indicated (**c**) Imaging geometry of Venera TV cameras. (**d**) Ground range of the field of view of Venera TV cameras, as in Fig. 5.7. Source: (**a**) NASA NSSDC. (**b**) Adapted from Surkov et al. (1984). (**c**) Adapted from Florensky et al. (1977)

been carried on balloon explorations and more audacious sailing rover concepts. Regardless the exploration strategies and technologies, the geology of Venus, especially its elusive past, would deserve another close look (Chap. 11), as much of its past is completely unknown. More capable, durable landers with increased mobility and life span would certainly improve our knowledge of Venus' geology. In addition, geophysical measurements would shed light on the interior structure and state of activity of the planet (Chap. 11). Surface nominal lifetime of several tens

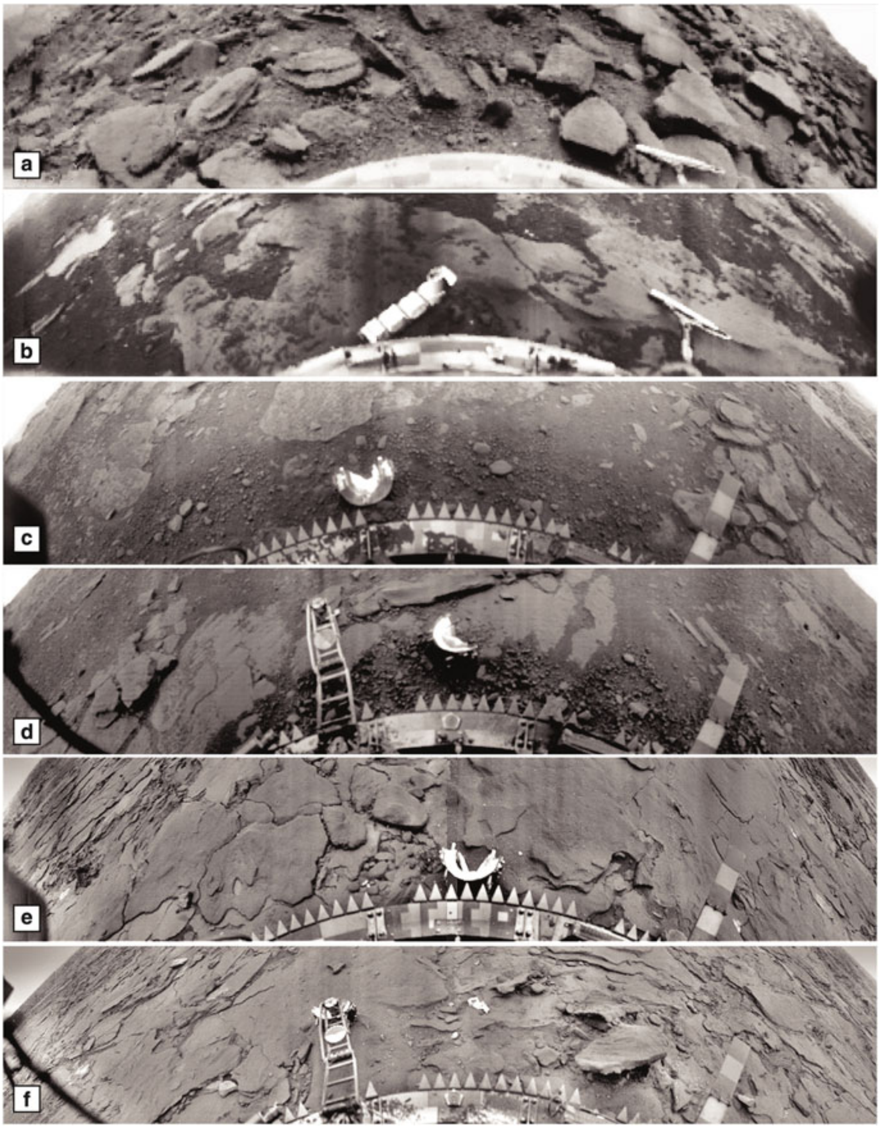

Fig. 5.7 Compilation of surface views on Venus as observed by the USSR Venera landers: (**a**) Venera 9. (**b**) Venera 10. (**c**) Venera 13A, panorama. (**d**) Venera 13B, panorama. (**e**) Venera 14A, panorama. (**f**) Venera 14B, panorama. Source: (**a**)–(**f**) Courtesy of Russian Academy of Science, Sasha Basilevsky

of days and several hundred meters of range would be comparable to the original nominal mission duration of the Mars Exploration Rovers, exceeded by more than one order of magnitude in the case of MER, a case most likely not repeatable on Venus.

5.5 Mars

Due to its geological and environmental relative closeness to Earth, Mars is the most suitable Solar System target for exploration with landers and rovers. Its gravity is in between that of the Earth and the Moon, and the design of some of the landers (e.g. landing gear) is somewhat similar to that of the Moon (Fig. 5.8a–c). The scientific drivers for such exploration are very diverse, ranging from reconstructing the geological evolution of Mars vs. other terrestrial planets, the search for fossil or extant life, as well as the study of resources and risks related of human temporary or permanent settlements (Chap. 15), in perspective. Search for water occurrences and Mars' past and present habitability as a whole (Chap. 14) are both independent drivers as well as topics closely linked to those mentioned above.

In all those cases, ground truth is a key requirement as well as an important validation tool for the extensive remote sensing coverage on Mars. Sample return would crown ground truth activities on Mars as it did for the Moon. The natural next step for obtaining ground truth would be human exploration, but the complexity, cost and risks are much higher, although recent developments in commercial space exploration might help bridging this gap in the near future.

Mars' surface environment is by far less extreme than that of Venus (high pressure and temperature), the Moon (virtually no atmosphere, extreme temperature range) or Mercury (extremely challenging thermal environment), but it does have its own difficulties regarding exploration. Unlike in the case of the Moon, the travel time of information of 12 min on average between Earth and Mars makes real-time commanding unfeasible, thus autonomous or semi-autonomous operations are performed by all lander missions. Landing in the first place is complicated by a dynamic atmosphere, with time-variable characteristics (e.g. dust contents, physical parameters, optical properties and related trajectory and communication problems). Several missions have been lost, even after successful orbit insertion and deployment. Once landed, missions powered by solar panels need to deal—again—with dust deposition from the atmosphere. Fortunately in the mid 2000s NASA's Mars Exploration Rovers (MER) demonstrated that natural dust lifting events linked to the passage of dust devils (Chap. 9) serve as a natural dust removal process, increasing eventual lost efficiency of dusty solar panels. Temperatures on the surface can reach and cross 0°C but they typically vary around several tens centigrades below zero. At medium to high latitudes seasonal frost sublimation and condensation occurs and low areas where surface pressure is higher (e.g. Valles Marineris, Hellas) are often affected by substantial cloud or dust cover. Landing is typically too complicated for highly elevated areas on Mars, such as the large volcanoes located on the Tharsis bulge (Chap. 8) due to the reduced atmospheric braking effect on entry probes, and active braking would require too much fuel.

Thus, in addition to scientific constraints and requirements, engineering constraints for landing mission include among others topographic height, surface roughness at multiple scales, as well as dust cover, or illumination conditions for both thermal and energy availability (e.g. through photovoltaic panels) for the

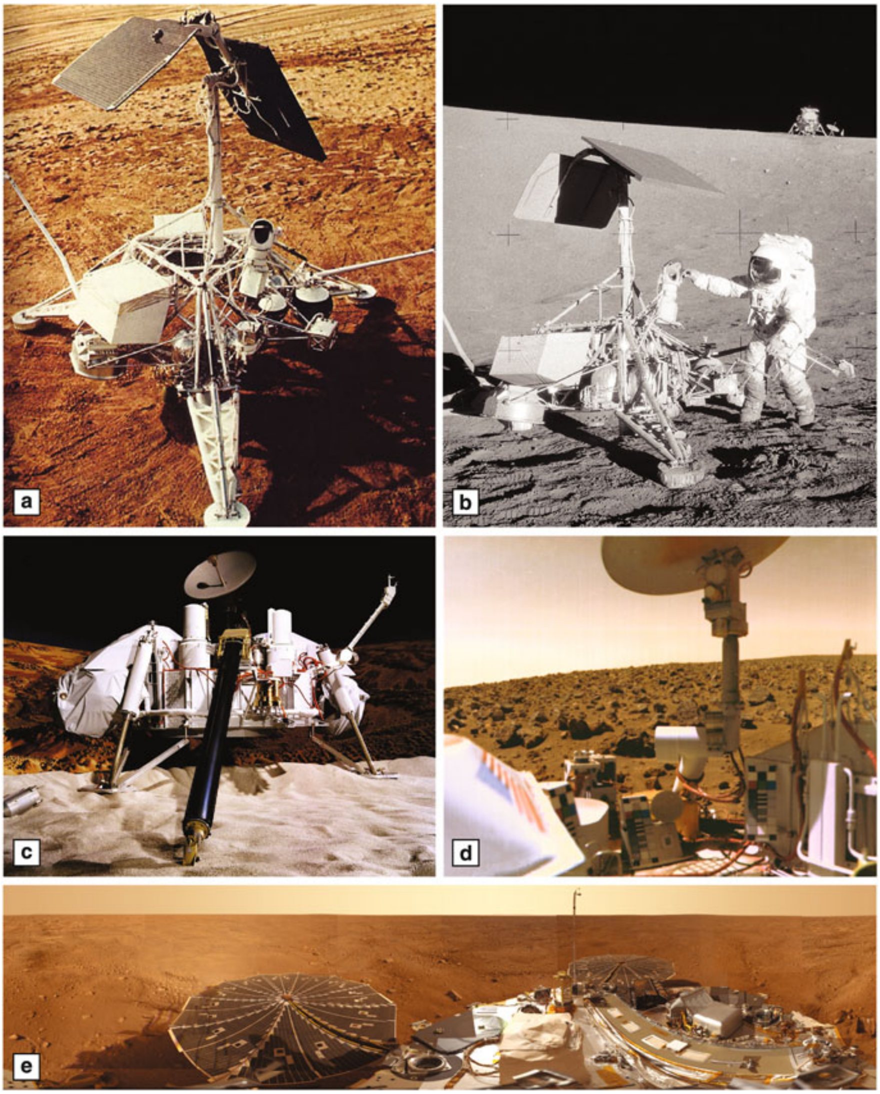

Fig. 5.8 Comparison between Lunar Surveyor lander and Viking and following Mars landers. (**a**) Model of Surveyor-III on a terrestrial beach; (**b**) actual Surveyor-III lander visited by Apollo 12 astronauts; (**c**) model of a Viking lander with sampling arm in the foreground; (**d**) view from the Viking 1 lander-mounted cameras; (**e**) self-portrait of the Phoenix Mars lander from the mast, see also Fig. 5.9. Source: (**a**, **b**) NASA NSSDC. (**c**, **d**) NASA. (**e**) NASA Planetary Photojournal image PIA13804

lander/rover. Depending on the exact scientific mission specifications and spacecraft layout parameters their values vary considerably.

Ground truth on Mars so far used static landers (Viking 1 & 2 landers) as well as rover with an egress platform as a base (Mars 3, Sojourner, MER) and lately a more complex rocket-powered so-called *sky crane* delivering a massive rover (MSL), shared also with Mars 2020. The range of lander types used on Mars, compared with the unmanned spacecraft sent to the Moon a decade earlier is depicted in Fig. 5.5. One can roughly compare the range of distances covered by rovers on Mars and the Moon. Mars 3 probably moved only for an extremely short distance before malfunctioning, Sojourner moved around a hundred meters, MER-A (Spirit) some 8 km, MER-B (Opportunity) around 50 km over more than a decade, and MSL has been travelling tens of km. Moon rovers, both robotic ones (Lunokhod) and human-driven ones (Apollo) covered distances of several tens of kilometres (Fig. 5.5). The scientific value of such range capabilities is substantial, as it allows to reconstruct the space-space or space-time (Chap. 2) local and regional geological variations, as well as the large-scale to global effects or stratigraphic markers (Chap. 11). This my be accomplished partially by high-resolution orbital data (Chap. 3) or by surface-based information (gradient of certain compositional parameters as measured in-situ, or the geometry of geological bodies).

In the decades to come, human exploration, if actually achieved, will most likely start on a temporary, relatively short-term, basis, although far longer than what has been done initially on the Moon due to obvious differences in distance, required travel time, higher complexity of life-support systems, and overall challenges of interplanetary transfer. Human ground truth operations will necessarily rely heavily on robotic aid for transportation, communication and logistical aspects, as well as for scientific and resource-related measurements (Chap. 15). They might get equipped with hardware probably not too different from that of advanced rovers with powerful analytical capabilities (such as MSL Curiosity), with a variable need for autonomy.

Experiments conducted on the surface and strictly related to ground truth of orbital observations are mainly those constraining elemental or mineralogical composition (e.g. remote-sensing spectroscopy on both orbiters and rovers vs. mineralogical or compositional data from in-situ observations, see Chap. 3). In that respect ground-truth experiments on Mars are therefore not different from those that would be carried out on the Moon.

Early rover-based exploration of Mars involved relatively small robots of fractions of a meter in length. On the other hand supporting landers allowing rover egress, were much larger, with footprints of up to few meters.

The very first lander deployed on Mars was the Soviet Mars 3 (location in Fig. 5.3), also featuring a miniature tethered rover which could not be deployed itself due to an early malfunction of the mother lander, which collected and transmitted data only for fractions of minutes before ceasing to work. The Viking landers (Fig. 5.8c–d) were delivered to the surface from Mars orbit by the Viking 1 and 2 orbiters, respectively. The landing-site selection was carried out based on the analysis of data collected by the orbiter themselves, during a period of about 1 month before landing. Operation of the RTG-powered Viking landers lasted few years which was even longer than the operation time of the Viking orbiters themselves. The Viking landers had a comprehensive payload aimed at characterising the surface and—as a prominent objective—to seek for signs of extant life. The payload included seismometers, imaging cameras, biology experiments and chemical analytical instruments such as gas chromatographs and mass spectrometers, as well as experiments for determining soil properties.

After almost two decades of relatively unsuccessful exploration attempts on and around Mars, the Mars Pathfinder mission succeeded to deploy a small rover on the floor of an ancient large-scale outflow channel (Chap. 9). The small rover Sojourner had a very limited payload, initially just APXS as contact instrument for determining in-situ elemental composition as well as a body-mounted camera. The main camera was hosted on the fixed lander and egress platform, monitoring the progress of the untethered rover in the vicinity of the landing site. The overall operation radius of Sojourner was several meters around the lander, providing communication from the rover to Earth.

Static landers with a very similar design and different fate (Mars Polar Lander and Phoenix) were developed with specific targets on the high latitude of Mars (Fig. 5.8e).

In 2003, NASA's Mars Exploration Rovers were launched and made a substantial technological and scientific step in exploring the geology of two locations on Mars: Gusev Crater and Meridiani Planum (Fig. 5.3). The two sites were rather different. Meridiani Planum is dominated by sedimentary rocks of mainly eolian to evaporitic nature while Gusev Crater consists mostly of volcanic materials with a wide range of water alteration of those. Gusev crater is largely covered by basalts, overlying most likely former paleolake sediments. The lack of enough detail at the time of landing-site selection and geomorphic indicators for a palaeolake in Gusev resulted in a relative surprise when volcanic material was found on the surface. This highlights the importance of landing-site selection and the challenges of the process, due to both data availability at the moment of investigation as well as limited knowledge of extraterrestrial local geology. Endurance, mobility and time are also of importance. Well after the nominal mission, MER rover Spirit reached the foothills of more ancient terrains at Gusev (Columbia Hills) that were not covered by later volcanics.

The payload of MER rovers allowed for morphological as well as chemical and mineralogical characterisation of surfaces and very shallow subsurface materials (Figs. 5.9, 5.10). It included panoramic to microscopic imagers (Fig. 5.9a), contact experiments (Fig. 5.10a), as well as chemical and compositional instruments.

Unlike larger static landers such as Phoenix, MER rovers did not host an internal analytical laboratory for processing and analysing collected samples, nor tools suitable for drilling or excavating beyond rind (Fig. 5.10c). Access to unaltered material is granted thanks to rock surface coating removal devices, both for MER (RAT) and MSL (DRT, Fig. 5.10d). Later rovers (MSL and the Mars 2020 rover) share some of the capabilities but largely exceed them in both number and variety of experiments (Fig. 5.10).

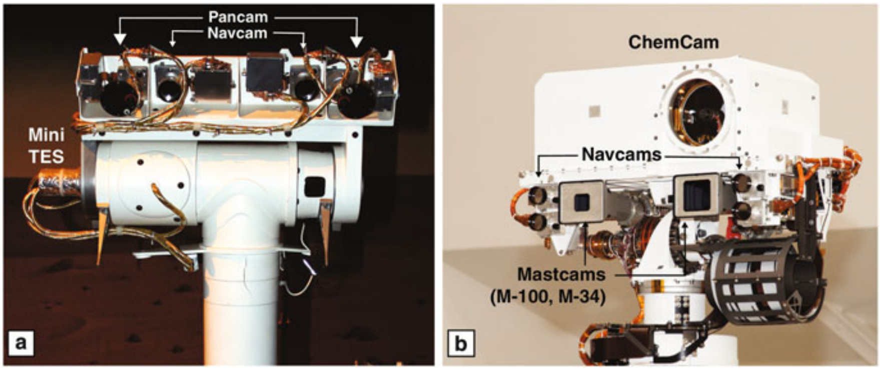

Fig. 5.9 Examples of instruments mounted on robotic masts for Mars surface landers and rovers: (**a**) MER mast with both panoramic and navigation cameras; (**b**) MSL mast-mounted experiments, including the LIBS experiment ChemCam, navigation and panoramic cameras. Source: NASA

The integration of different rover-based remote sensing and in-situ and contact experiments allowed for an appropriate geological characterisation of encountered outcrops and terrains. The multiply extended mission also permitted to cover large distances and comparably broad geologic traverses (Figs. 5.3, 5.5). Such range of observation scales, from microscopic scales to outcrop sizes and towards even larger extends, is ideal to investigate using high-resolution orbital imagery and local rover observations. This will ultimately allow for correlations and transfer of knowledge to other locations (Chap. 2, 3).

In 2011 NASA's Mars Science Laboratory (MSL) Curiosity was launched to Mars to land in Gale Crater. It is the largest rover to date with a scale significantly larger than that of MER (Fig. 5.11). MSL operates irrespectively of daytime illumination, unlike MER, due to its nuclear-powered RTG. This increases productivity in data collection when sunlight is not needed, e.g. while drilling or performing operations without the need of visible imaging of outcrops or panoramic views.

The amount and quality of data used to select and characterise MSL's landing site is superior to any previous lander on Mars. This is also thanks to the favorable string of successful, long-lasting orbital mission providing a plethora of data as well as relay possibilities from global and targeted landing-site observations. Not all future missions to Mars might enjoy the same data coverage and diversity for sites not covered by archived data.

The scientific payload of MSL is both evolutionary and revolutionary compared to that of MER. It includes imaging experiments of different kind, both mast-mounted (Fig. 5.9b) and arm-mounted (Fig. 5.10e,f), as well as a suite of support tools for removing dust cover/rind, drilling, collecting sample and delivering to the internal analytical laboratory with powerful capabilities (Chap. 3), including several experiments carrying out chemical and mineralogical measurements. It also includes

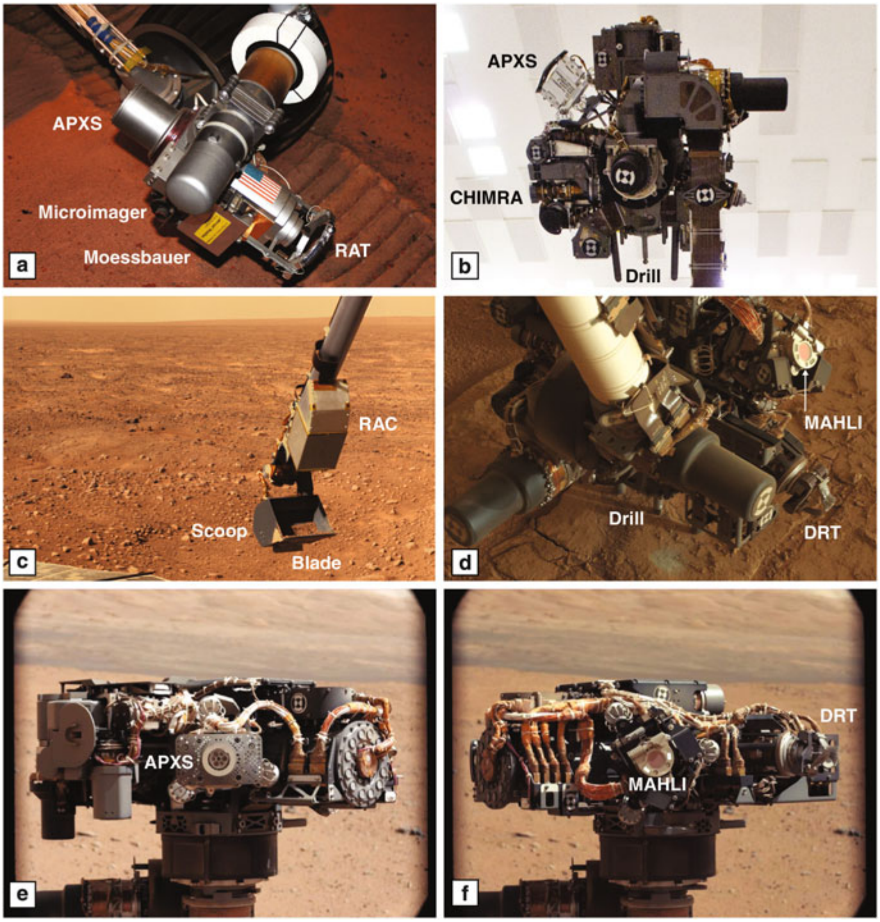

Fig. 5.10 Examples of instruments mounted on robotic arms for Mars surface landers and rovers: (**a**) model of MER robotic arm with contact experiments and surface preparation/abrasion tool; (**b**) view of the partially integrated MSL robotic arm with few experiments and support tools for surface processing and sample acquisition indicated; (**c**) Phoenix lander's robotic arm with scoop and arm-mounted camera, provided by LED, for imaging samples collected and later sent to the lander analytical laboratory; (**d**) MSL robotic arm flight model on Mars with the driller positioned on the surface; (**e**) picture of one side of the robotic arm of MSL with APXS imaged by Mastcam; (**f**) rotated view of MSL robotic arm with dust removal tool and hand lens-like imager (MAHLI) covered by its protection lid

LIBS paired with a camera (ChemCam) capable of both imaging targets analysed through laser ablation as well as long-range imaging, somewhat similar to binocular observations in the field.

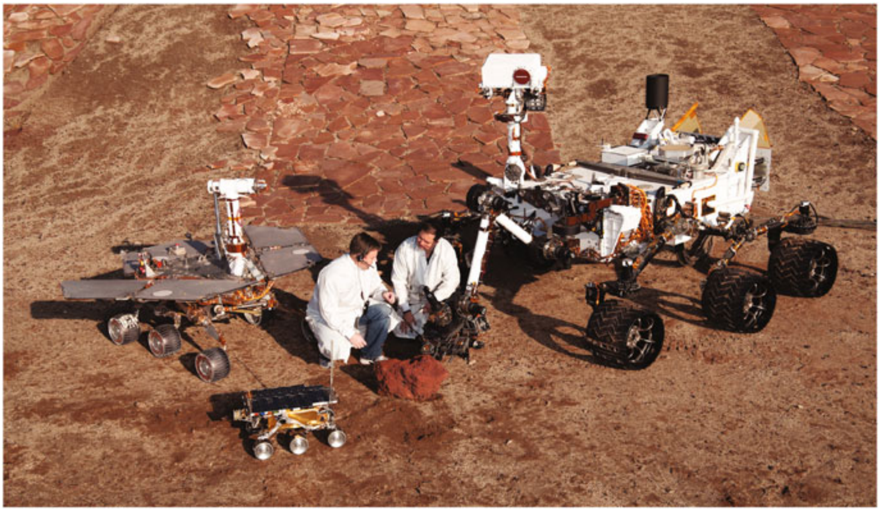

Fig. 5.11 Comparison of the last two decades of Mars rover models to scale: *from left to right* Mars Exploration Rover (2003+), Mars Sojourner (1997), Mars Science Laboratory (2011+). Source: NASA

The geological exploration of Gale and the traverse from its floor towards its central mound Mount Sharp is a multi-kilometer, multi-year endeavour and it makes use of orbital assets in addition to large-scale panoramic information and local in-situ data. Facies analysis and palaeoenvironmental reconstructions are possible, with both geometrical and compositional/geochemical data. Even absolute dating of collected materials has been performed using mass spectrometers on board the rover. A simple example of the very many panoramic views of outcrops collected during the long traverse so far in Gale crater is provided in Fig. 5.12, where images as well as in-situ measurements were collected. Those panoramas are obviously not the sole tool for interpreting local geology and its position in the overall evolutionary scenario of Mars (Chap. 11), but as demonstrated with MER and perfected with MSL, integrated use of independent datasets allows for more reliable geological interpretations, such as the nature of sedimentary rocks and their attribution to a certain sedimentary environment or system.

The capabilities of upcoming rovers, such as Mars 2020, share some overall design with MSL and will allow for sample caching and hosting of a local analytical laboratory. The presence of a complex analytical laboratory is also shared by biosignature-seeking rovers such as ESA ExoMars 2020. Caching of samples on a large, well-equipped rover requires a suitable choice which is strongly dependent on available information at multiple scales, as well as sufficient time for analysing data and selecting, choosing and eventually discarding a sample. This is contrary

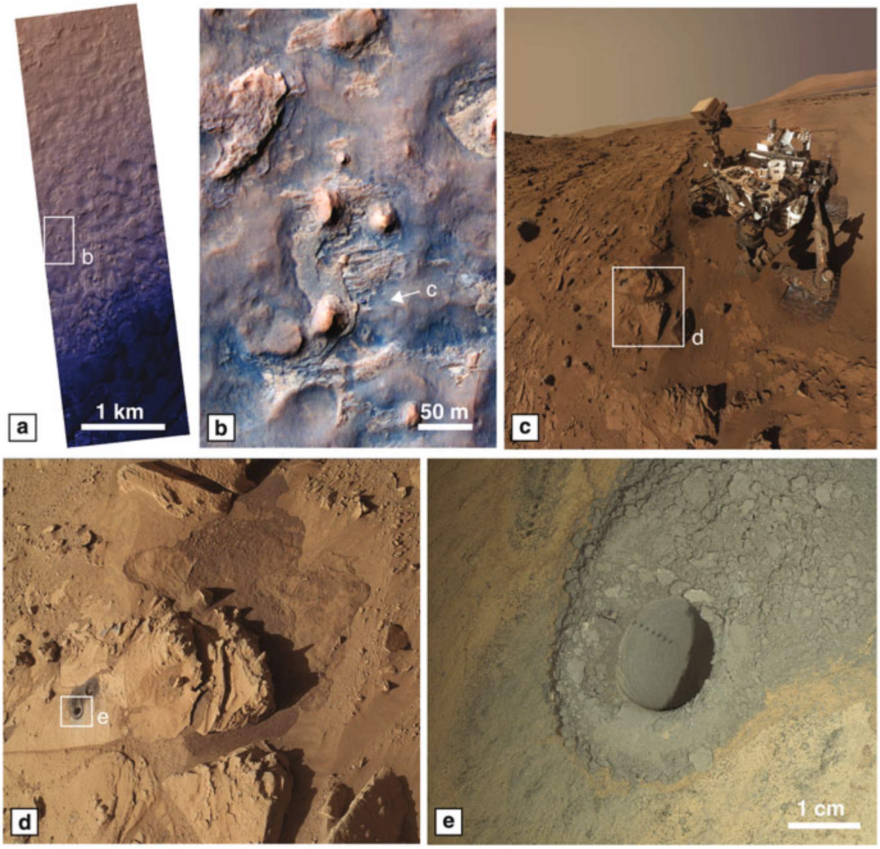

Fig. 5.12 Multiple scales of observations are available at selected landing site locations: nested examples from the Kimberley outgroup and Windjanadrill site on Gale Crater. The Kimberley rocks include several meters thick sedimentary rocks ranging from fine sandstone to conglomerate, interpreted to record an ancient fluvio-deltaic depositional system; (**a**) subset of HiRISE orbital acquired during rover operations; (**b**) close-up of the rover location; (**c**) self-portrait of MSL from MAHLI imagery collected between April 27 and May 12, 2014; (**d**) MAHLI image showing both the Windjana and a small preparatory drill hole, later filled in with cuttings from the main one; (**e**) Windjana drill hole showing aligned markings of ChemCam LIBS analyses along the inner wall of the drill hole itself. Field-based panoramic photos, matched with additional remote sensing and in-situ experiments are the base for geological interpretation. Similar outcrop mapping/line-drawing or context imagery is available from human platforms such as with NASA Apollo or robotic moon landers, until the recent Chang'e 3 rover Yutu. Source: info from Le Deit et al. (2016). (**a**, **b**) NASA/JPL/University of Arizona. (**c**)–(**e**) NASA/Caltech/JPL/MSSS

to the alternative *grab-and-go* approach that is partially blind and poorly contextualised and which is more suited for short-lived fast-paced sample return missions (Chap. 3).

Excursion 5.1 (Choosing the Right Place and Samples)
The choice of suitable landing sites is a challenge in itself given the costs and complexity of landing missions. It involves a more or less democratic selection process, with spacecraft and mission safety being the first priority, since a site with high scientific value but without a surviving spacecraft would lead to zero science return. Site are typically selected after a series of community-driven workshops that help to shortlist a limited number of landing sites based on scientific merit and safety constraints. The final landing site is typically chosen buy the space agency though for private missions the overall process might be slightly different (Fig. 5.13).

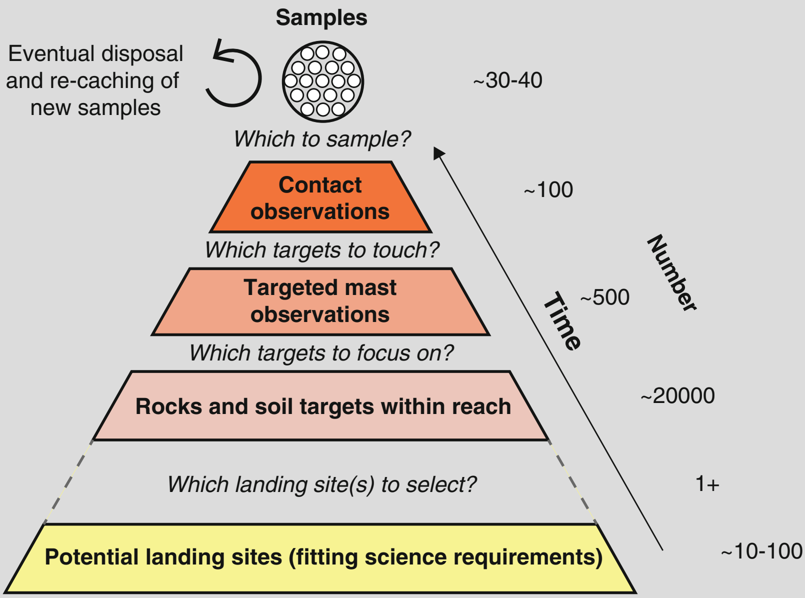

Fig. 5.13 Schematic process of sample selection, given a certain landing sites fitting scientific requirements, based on progressively more detailed observations leading to final selection. Samples, e.g. for sample return, such as MSR, are progressively characterised, collected and possibly discarded in favour of new ones. Source: modified from McLennan et al. (2012)

(continued)

Excursion 5.1 (continued)

Leaving aside *grab-and-go* sample return, very ambitious and complex tasks such as those of Mars Sample Return (MSR) are based on careful and informed selection of landing site(s). Once one or more potential landing sites are selected, the selection of outcrops to be imaged can be guided by existing knowledge (e.g. from orbital data), as well from long-range observations on the ground. Observations accumulate through time and are—based on the judgement of experiment and mission teams—used to *zoom in* to outcrops, beds, individual rocks or smaller-scale subdivisions with increased spatial resolution, contact experiments and extractions of samples for laboratory measurements to be carried out inside the rover. The capability of caching samples is for example embedded in NASA's Mars 2020 rover. The actual number of samples needed to address a given scientific question might vary depending on the type of objective as well as the needed details.

The number of observation leading to the collection of such a number of samples would need to follow a pyramidal approach, based on a very wide range of possible rocks/samples/specimens at reach (tens of thousands), remotely imaging hundreds to thousands, performing contact measurements on tens to hundreds, selecting then the most representative, yet keeping an option to discard some of them later if more compelling samples are to be found.

5.6 Ground Truth of Small and Remote Objects

Relatively small, often irregular solid bodies are scattered across the Solar System. Few of them are satellites, such as Mars' moons Phobos and Deimos, and most of them are either located in the Asteroid Belt or, further away, in the Kuiper Belt and the Oort Cloud, beyond Pluto. Pluto itself is classified as a dwarf planet and visited for the very fist time by a fly-by of NASA New Horizons (Chap. 13). The most accessible ones are the one close to Earth, so-called *Near Earth Asteroids (NEA)*, relevant for both their potential hazard (Chap. 7) and even more for their importance as (near) future source for economically important materials (Chap. 15). Exploring them geologically with landers poses largely different challenges and drives radically different requirements.

5.6.1 Small Bodies: Asteroids and Comets

The exploration of Asteroids and comets, often very irregular in shape, is a challenge for orbiters and even more for landers, having to manouver on a very low gravity environment and with surfaces that can be extremely heterogeneous at small spatial scale, as demonstrated by missions such as JAXA Hayabusa and ESA Rosetta to asteroids Itokawa and comet 67P/Churyumov-Gerasimenko, respectively.

Regardless of the exact purpose of the lander, the timescale of landing and landing operation has a higher pace than in the case of Moon or Mars and it can be counted in minutes to hours, rather than weeks to years. Hayabusa delivered few miniaturised hopping landers (Minerva) that missed the small target asteroid, and the mother spacecraft itself, as designed, performed sample return during a planned quick touchdown, which turned out to last longer than expected, before lifting off again. The sampling operation on missions to Phobos would last slightly longer, but most of the characterisation of the site in all those cases would have to be done by the orbiter mission and not before, since most small bodies are not imaged with high resolution before an actual spacecraft visits them.

Also the size of landers tends to be smaller, as well as the number and complexity of their payload. In the case of a cornerstone mission such as Rosetta with a rather large and complex lander such as Phylae, the number of experiments can be large, although the time of operation might be limited. This limitations might also be because of the difficulty of operations and unexpected characteristics of the target comet, e.g. with long-range relocation and bouncing (Fig. 5.14a) of the Philae lander itself (Fig. 5.14b).

Bouncing or hopping are sometime not seeked actively (Philae), but in some cases they are a handy way to relocate on a low-gravity body with opportunity for more than one observation point, thus increasing the scientific return. Such approach is shared by micro-landers such as Minerva (Hayabusa, Hayabusa 2) and MASCOT (Fig. 5.14c), where mobility is achieved with moving masses inside the spacecrafts.

The range of geometrical complexity can be exemplified in Fig. 5.14a and Fig. 5.14e: Philae hosted a very wide range of experiments, some similar to those on planetary landers, some different: e.g. APXS, soil properties, mass spectrometry, a magnetometer, an imaging experiment, some of which performed together with the orbiter (e.g. radio sounding, CONSERT). MASCOT, sensibly smaller, hosts imaging camera and spectrometers and a radiometer, as well as a magnetometer (Fig. 5.14e).

5.6.2 Outer Solar System and Water Worlds

Outer Solar System Satellites in the Jupiter and Saturn Systems display an extremely wide range of surface characteristics (Chap. 12). Some are characterised by icy crusts, with or without an atmosphere, some with liquid bodies (Titan), some with subsurface oceans (Europa, Enceladus, Titan, etc.). So far the only ground truth achieved is by the Huygens probe carried from the NASA-ESA Cassini-Huygens mission (Fig. 5.15a), which, back in 2004, returned data from both the atmosphere and surface of Titan. While the spacecraft slowed in Titan's atmosphere, its descent imager (DISR) covered the gap in resolution and scale between fly-by observations by Cassini orbiting in the Saturn system and close-range lander observations.

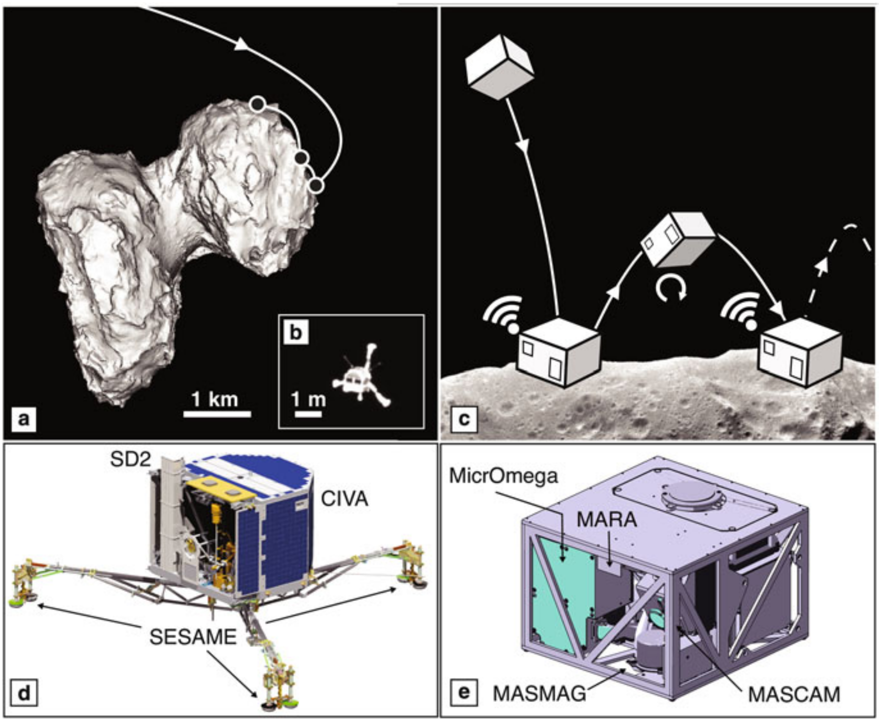

Fig. 5.14 Examples of landers on small bodies, characterised by low gravity: (**a**) cartoon (not to scale) depicting the landing and bouncing process of Rosetta's lander Philae on comet 67P/Churyumov–Gerasimenko on the side view of an artificially illuminated shape model; (**b**) Philae en route to the comet pictured by Rosetta OSIRIS; (**c**) cartoon (not to scale) describing the operations of an asteroid hopping lander such as DLR MASCOT: upon landing, phases of data collection are separated by phases of relocation; (**d**) Philae lander with partial indication of experiments and tools, such as the driller (SD2), the imaging experiment (CIVA) and a set of instruments (SESAME). The entire lander is about 2 m wide; (**e**) MASCOT asteroid lander, on board JAXA Hayabusa-2, capable of re-orienting itself and hopping, in order to collect data at different locations. Source: (**a**) ESA/Matthias Malmer. (**b**) ESA/Rosetta/MPS for OSIRIS Team MPS/UPD/LAM/IAA/SSO/INTA/UPM/DASP/IDA. (**d**) DLR, courtesy Stephan Ulamec. (**e**) DLR, courtesy Tra Mi Ho

Huygens itself was designed to withstand a landing on both liquid and solid surfaces. Its payload included several atmospheric experiments as well as imaging and surface instruments for addressing acoustic sounding or soil properties. The combination of remote sensing and contact experiments with descent imaging and orbital data provided a consistent view of the only other planetary object beyond Earth with a global, large-scale hydrological cycle and erosional as well as depositional features (Chap. 9) on a non-rocky substrate.

Future missions with increased mobility are desirable. For the Moon and Mars such mobility is achieved with rovers, in the case of Titan, with such a vast amount of hydrocarbon seas, a floating and/or submersible vehicle could achieve

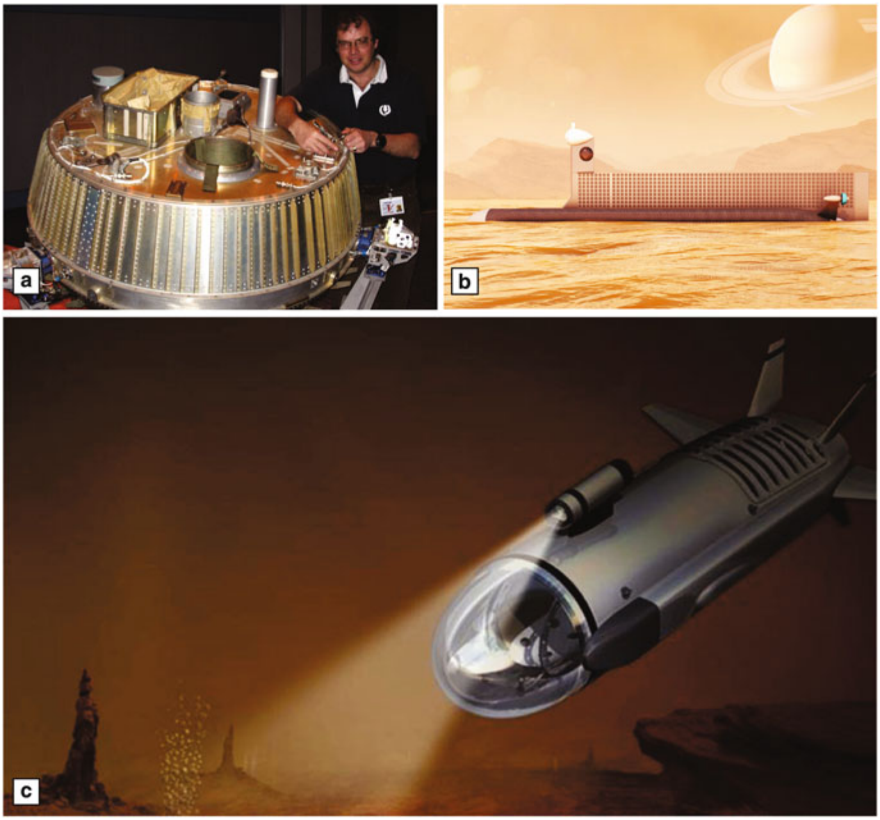

Fig. 5.15 Ground truth platforms for ocean world exploration: (**a**) ESA-NASA Huygens, delivered by Cassini on Titan. The lander, capable of floating, collected data both during atmospheric entry and on the surface; (**b**) concept of a floating-submersible vehicle exploring hydrocarbon seas on Titan; (**c**) artistic view of a submersible in Titan's seas, similar to ocean exploration ROVs, potentially similar to a subsurface ocean explorer in the outer Solar System. Source: (**a**) Courtesy Ralph Lorenz. (**b**)–(**c**) NASA

that (Fig. 5.15b, c). Much larger water bodies are most likely present in several other moons orbiting Jupiter (e.g. Europa) and Saturn (Enceladus). Landing on their surface or accessing their subsurface are very different challenges, both qualitatively and quantitatively. Reaching subsurface oceans covered by a considerably thick icy crusts is still beyond reach, but it would possibly share something with current Earth ocean exploration as well as Titan mare exploration platform designs (Fig. 5.15c). Beyond Saturn, no ground truth exists and only flybys were performed until today. One of them is NASA's New Horizons mission to Pluto (Chap. 13), which is also set to explore more Kuiper Belt objects. Spacecraft designed to land in such remote worlds are still far ahead.

5.7 The Future of Ground Truth

Ground truth operations have evolved enormously in terms of technology in the last several decades, although the range of explored distance of modern robotic platforms still scales similarly to that of Apollo 11–17 (Fig. 5.5). Sample collection and caching capabilities during Apollo and Luna times were quantitatively very large with over 300 kg of material collected over 6 Apollo missions.

Some drivers for exploration include the search for ancient and present life as in the case of Mars or the icy satellites (Chap. 14). Others are related to the evaluation and exploitation of extraterrestrial resources (Chap. 15). In particular the exploitation of planetary resources becomes increasingly important and endeavors develop beyond the fence of space agencies towards commercial actors. The actual success of those endeavours is obviously still to be seen.

The additional ground truth aspect for Mars and the Moon in particular is related to long-term human permanence, which poses challenges beyond resources alone. The geological relevance of such long-term options is the unique Earth-like, geologic mapping and data collection set of task that would naturally come. Crafting a geologic mapping on Earth is an exercise involving a large number of people, a consistent number of collected samples, diverse analytical facilities as well as time, measured between months and years for large projects. Lander and rovers have increasingly powerful capabilities relevant to geology, but the perspective of a long-term, human-robotic exploration on a terrestrial planet such as Mars would have a much larger and scientific return.

As it has been the case for the Moon since early Apollo times there is a trend towards further integration of human and robotic exploration capabilities, in terms of autonomous mapping and geological characterisation of surface and subsurface materials. In recent years Earth's geologic mapping is embedding the use of robotic platforms such as drones, UAV, in planning and executing geological and geospatial mapping tasks. This can be envisaged to develop further on Earth and to be applied, possibly expanded, also to Mars human-robotic geological mapping activities. The stricter constraints on mobility of astronauts related to accessibility and safety a well as life support limitation on Mars would benefit even more than on Earth from reconnaissance and robotic-aided fieldwork. Several analogue operational or geologic mapping campaigns, locally or remotely operated, have been carried out by either space agencies, scientific, industrial or private entities.

Some radically different platforms, either robotic or supporting human exploration are likely to emerge and to be used in actual missions, from terrestrial planet hoppers over large-scale slopes, to tethered robots in very steep areas, up to zoomorphic legged robots, the variety of possibilities to carry out geological observation is extremely large. The same goes for *water worlds*, where on the other hand platforms might resemble more those of marine geologic exploration. In the case of very remote targets miniaturisation of experiments and subsystems will be on the instrument side, while in the case of human exploration larger-scale geological analysis instruments might be more common. On the long run unexpected technological developments will change this, too.

Ground truth even on relatively close objects such as the Moon is increasingly a collaborative effort with the need of several teams. Permanent settlements on the Moon (*Moon village*) will offer unique occasions for detailed geological mapping sharing the cost and effort among several national or international partners producing a cumulative results in terms of samples, data and overall geological understanding. Those data, archived, curated and made available to the scientific community and the public at large might typically be used for decades after their collection, as Apollo has shown.

The next few decades might see a renewed impulse towards manned exploration of the Moon and Mars, likely preceded by sample return campaigns, to a variable extent. As much as Apollo made the difference in understanding the geologic evolution of the Inner Solar System as a whole, human-robotic exploration and even long-term permanence on Mars would be extremely valuable. Human ground truth on Mars, more than on earlier Moon exploration, would need to deal with planetary protection issues (Chap. 14), whose severity is not yet fully definite.

The additional physical long-term heritage of ground truth in the Solar System consists of the landed hardware itself: robotic geological explorers left on the surface of most visited planetary bodies can in fact last relatively intact for almost geological time scales, although planets with more reactive or corrosive atmospheres as well as with an active volcanism or hydrological cycle (e.g. Venus, Io, Titan) would not preserve as much landed robotic artifacts.

Starting from Apollo, the study of such heritage is the subject of Space Archaeology. Thanks to very high-resolution imaging (MRO HiRISE, LRO LROC), a large part of both successful and failed landers on Mars and the Moon were identified on orbital imagery. So far, a visit of landed hardware by human explorers has been achieved only in the case of Apollo 12 landing in the vicinity of Surveyor III (Fig. 5.8).

Take-Home Messages

The age of planetary exploration started in the late 1950s immediately after the success of the USSR's Sputnik launch into orbit in 1957. The Moon was the first target and the USSR succeeded to hard-land the first spacecraft, to image the farside for the first time and to soft-land a spacecraft on the Moon until the mid 1960s in the course of the Luna program.

The 1960 were marked by a number of very successful mission to the Moon: The Luna program, Ranger, Surveyor, Lunar Orbiter and, finally, Apollo which lasted from 1961 to 1972 culminating in 6 missions to land on the Moon. After 1972, planetary exploration a caesura with only little activity for a decade. Lunar exploration was revived in 1994 with the Clementine and Lunar Prospector programs. It took until the first decade of the twenty-first century that not only the US, but also Japan, China and India successful sent spacecraft to the Moon.

Venus was visited many times by the Venera program in the early years of planetary exploration. The spacecraft and probe design had to cope with the extraordinary challenging atmospheric conditions on Venus.

Mars has been studied in much detail since the 1970s. The Viking mission, Pathfinder as well as Mars Global Surveyor can be considered milestone missions until the late twentieth century. Europe succeeded to send the Mars Express orbiter to Mars and new high performance rovers (MER, MSL Curiosity) investigated the planet and changing the picture of Mars.

Resource extraction will be a major driver in upcoming decades and apart from the Moon and Mars, small bodies such as asteroids and comets will be a major target. New robotic instrumentation will need to be developed to perform autonomous operations to accomplish investigations.

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