4: Planetary Interiors

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Investigating the composition, structure, and processes of the interior of planets is fundamental to understanding the origin, evolution, and present state of the solar system. Interior measurements provide the basic information about what planets are made of and how they "work." In virtually every science strategy report for exploring the solar system or a single planet, one of the major stated objectives has been to determine interior structure and dynamics of the terrestrial planets. In broadest terms this includes characterization of the core/mantle/crust divisions in terms of depth of boundaries, composition, and mineralogy; the study of mantle/core motions (i.e., convection and magnetism); and determination of the thermal history and state, as well as the closely associated tectonic and volcanic history of a planet.

For example, these objectives have been explicitly enumerated in the latest report of the Committee on Planetary and Lunar Exploration of the National Research Council (*COMPLEX*, 1994). This report identified two main themes to guide planetary science in the next two decades: understanding planetary origins and understanding the constitution and fundamental processes of the planets themselves. Within this latter theme, planetary surfaces and interiors comprised one of the four major components. It proposed four specific goals related to interior measurements for addressing this theme:

1. Understand the internal structure and dynamics of at least one solid body, other than the Earth or the Moon, that is actively convecting.
2. Determine the characteristics of the magnetic fields of Mercury and the outer planets to provide insight into the generation of planetary magnetic fields.
3. Specify the nature and sources of stress that are responsible for the global tectonics of Mars, Venus, and several icy satellites of the outer planets.
4. Advance significantly our understanding of crust-mantle structure . . . for all the solid planets.

These goals can all be addressed to some extent, and in many cases almost exclusively, by measurements made on the surfaces of planetary bodies.

However, this enterprise has unique difficulties, in that even with *in situ* instruments on the surface one is still essentially confined to remote sensing of the region of interest. There are basically four types of measurements that can be made at the surface that are directly relevant to the deep interior: seismic, magnetic, heat flow, and geodetic. We will discuss each of these in turn.

4.1. SEISMOLOGY

The importance of seismology in understanding the interior structure and tectonics of a planet cannot be overstated. It is the only tool available that can furnish detailed global and regional information on the compositional structure and physical state of a planetary interior. Whereas gravity, dynamics, and magnetic measurements can supply key information on some aspects of interior structure, they cannot provide a substitute for the precise radial (and, to a lesser extent, lateral) structure information that can be derived from seismic data. Some of the salient questions that could be addressed are described below.

4.1.1. Thickness of the Crust

Gravity studies can offer tantalizing suggestions as to the crust's structure, but are essentially ambiguous without additional constraint. The mean crustal thickness has fundamental implication for the degree of differentiation of a planet and for the nature of its magmatic evolution. Crustal thickness also bears directly on the thermal evolution of the planet because of the tendency of incompatible radioactive elements to segregate into the crust. Lateral thickness variations are intimately related to the isostatic state of topography and thus the mode of support of topographic features.

4.1.2. Layering Within the Mantle

The accumulation of teleseismic travel-time data, together with normal mode (free oscillation) measurements, will allow the resolution of the radial density structure of the mantle. This structure may be due to chemical stratification or to pressure-induced polymorphic phase transitions. Any such layering would have important implications for the evolution and dynamics of the interior. In addition, the different pressure-temperature conditions of the interior can allow an independent test of models that have been developed to explain the interior structure of the Earth.

4.1.3. Size and Nature of the Core

Information derived from relatively large, distant seismic events can be used to unambiguously establish the existence and radius of an iron-rich core, its density (which is determined by the ratio of Fe to lighter alloying elements such as S), and its phase (solid or liquid). Both the nature of the solar nebula from which a planet formed and the subsequent thermal evolution of the planet can be constrained by this single vital measurement.

4.1.4. Transmission Properties of the Interior

One of the remarkable contrasts between the Earth and the Moon discovered by the Apollo seismic experiment was the difference in the seismic signal characteristics for the two bodies. Compared to events with similar size and range on the Earth, lunar signals are prolonged, with little coherence between the three components of ground motion. For example, an event that would generate a signal with a length of one minute on the Earth might last for up to several hours on the Moon. This is attributed primarily to the very high Q (low seismic attenuation properties) of the outer shell of the Moon and a sharp increase in seismic velocity with depth in the regolith (*Dainty et al.*, 1974). Whereas the outer layers of the Earth have a Q of about 200–300, the Q of the Moon has been estimated to be about 4000–6000 (*Nakamura and Koyama*, 1982). This contrast has been ascribed to the difference between the Earth and Moon in volatile content, primarily water, with reduced water content resulting in higher Q. Seismic attenuation is also sensitive to the temperature of a material relative to its melting point. The Q of a planet can thus tell us a great deal about the bulk properties of its interior.

4.1.5. Level and Distribution of Seismicity

The level and distribution of seismicity on a planet reveals a great deal about how geologically active it is today and about the state of stress due to tectonic processes and other sources. It can also provide information about the meteoroid flux in the planet's vicinity and the efficiency of its atmosphere (if any) in shielding it from impacts.

An in-depth discussion of the goals and requirements for a particular seismic investigation, that of Mars, is contained in a report by *Solomon et al.* (1991).

4.1.6. Instrument Sensitivity

The physical quantity we measure with seismic instruments is normally the displacement of the ground with respect to time (time series) resulting from propagation of seismic waves through the planetary interior. Other quantities associated with seismic wave propagation, such as strain and rotation, may sometimes provide useful information, but are not likely to be the main objects of the measurement in the initial phase of planetary exploration unless specific scientific objectives arise that require these quantities to be measured.

The choice of planetary body and specific measurement objectives dictate to some extent the required response characteristics of a seismometer, e.g., its frequency range, sensitivity, and dynamic range. While instrument sensitivity as high as possible is desired for a planetary body of unknown seismic activity in order to be prepared for a very low level of activity, the local level of ground noise generally limits the usable instrumental sensitivity.

Figure 4.1 shows approximate frequency bands of ground motion observed on the Earth, ranging from solid Earth tides to local body waves, together with the typical level of ground noise that limits terrestrial seismic observations. Also shown on the figure is the largest seismic ground motion ever recorded on the Earth. An ideal seismometer for the Earth would respond to the entire dynamic range between the noise and the largest observed ground motion levels for the entire frequency band. However, this is not achieved even for instruments used on the Earth, and all terrestrial instruments are limited in both frequency and dynamic range to meet a particular objective.

For a planetary body other than the Earth, the appropriate ranges of instrumental response depend on several factors, including size of the planet, expected seismic activity, and expected sources of background noise. For small bodies, such as asteroids, the lowest frequency of interest for certain types

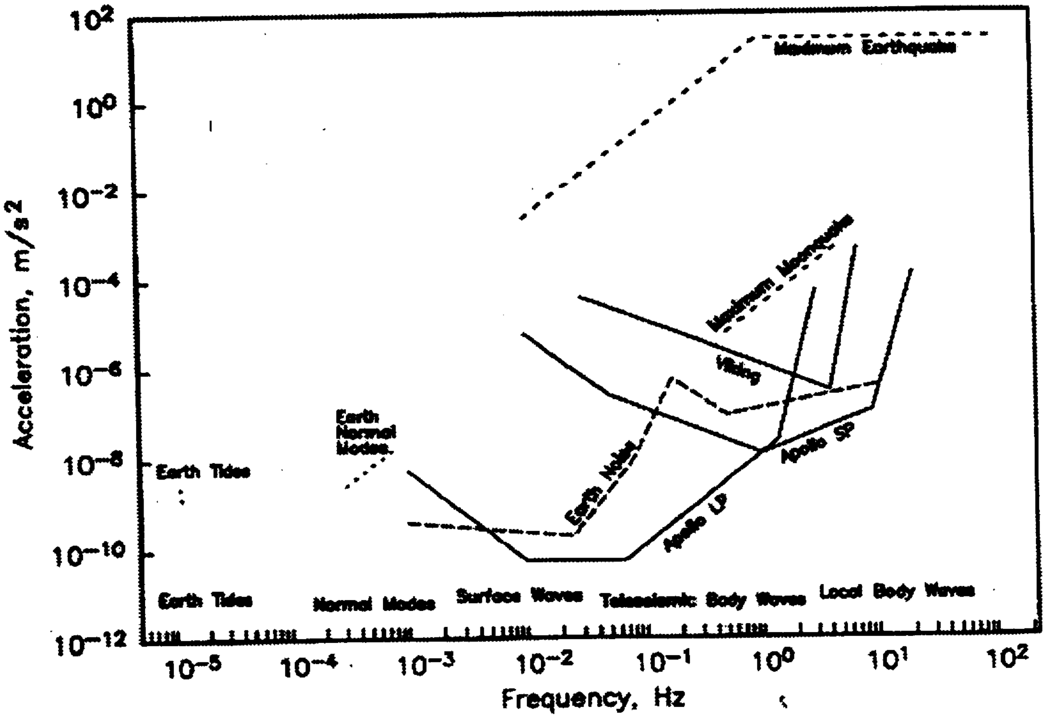

Fig. 4.1. Approximate frequency ranges of various types of seismic signals, along with seismic noise levels and sensitivities of previous planetary seismometers.

of seismic waves, such as normal modes and surface waves, will obviously be higher than on Earth. The expected level of seismic activity of a given planetary body is largely unknown until we have some data, and estimates are unreliable at best. Therefore, it is best to try for the highest achievable instrumental sensitivity until at least some real data are acquired to indicate the level of seismic activity on the planetary surface. Another reason why one should aim for the highest sensitivity possible for the initial observation is that the number of seismic events generally increases in proportion to an inverse power of the event size, thus dramatically increasing the number of detected events as one increases the detection sensitivity. Since the background seismic noise on most other planets is expected to be significantly lower than on the Earth, higher sensitivity than is useful on the Earth is desirable.

Also shown on Fig. 4.1 are the sensitivity of the Apollo lunar seismometer and the Viking martian seismometer. Many of the detected seismic events on the Moon were barely above the sensitivity threshold of the Apollo instrument. The background noise level on the Moon was below the instrumental sensitivity except at the times of sunrise and sunset, when thermal disturbances caused large ground noise. The Viking seismometer did not detect any positively identifiable seismic event, quite possibly because its sensitivity was too poor to detect seismic signals, even if they were present. Since the Viking seismometer was installed on the lander instead of directly on the ground, the observed background noise was mostly due to wind shaking the lander.

Expected background noise is extremely low on a planetary body with no atmosphere or ocean. For bodies with atmospheres, some noise due to the ground/atmosphere interaction (wind) is expected. Even then, it is best to start with the highest practical instrumental sensitivity consistent with the expected background noise. Once we obtain some data on actual seismic activity and background noise, then more appropriate ranges of frequency and sensitivity may be adopted to maximize information content of the returned data.

4.1.7. Number of Stations

The number and distribution of seismic stations recording simultaneously on a planetary surface greatly influence the quality and quantity of information that can be derived from the acquired data. Generally, the larger the number of stations, the more detailed the information on the planetary interior that can be obtained. Although there is no clear threshold in the number of stations below which no useful information is obtained, at its lower end, each increment in the number of stations significantly increases the usefulness of the acquired data.

To start with, even if we have only one station on a given planet, we can still expect certain useful information. Data from one seismic station will tell us at least (1) the level and other properties of the background noise and (2) the characteristics of the signals that may prove to be from natural seismic events. In the initial stages of exploration of a planet, such information is highly valuable in designing instruments that are to be deployed later to maximize the information return in future missions. In addition, (3) if the internally generated seismic signals can be unambiguously differentiated from noise, the level of seismic activity of the planet can be determined, and (4) if there is a seismic event large enough to excite detectable normal modes, even a single station with a sufficient low-frequency response may also provide deep structural information.

Two seismic stations operating simultaneously on a planetary surface will significantly increase the information content of the acquired data, especially if they are separated by at least a few tens of degrees of arc on the surface. Events detected nearly simultaneously at both stations positively identify them to be from natural sources, not artifacts originating from the landing vehicles themselves. If the types of seismic phases, e.g., P and S arrivals, can be identified based on ground motion recorded on three orthogonal components, an approximate distance and rough direction to the source may be estimated assuming seismic velocities inside the planet.

When the number of stations increases to three, again assuming they are operating simultaneously, the source of observed seismic events can be located for an assumed internal structure. With four stations, for the first time we will start getting information on the seismic velocity structure in the planet from natural sources, assuming that the internal structure is approximately radially symmetrical. An ideal configuration for this array is roughly 60° spacing between each of three of the stations, with the fourth station placed on the opposite side of the planet, near the antipode of the three-station triangle.

The four-station network is probably within the grasp of the current planetary program and would provide extremely valuable information about the interior of a planet. Should the opportunity arise, there is a great deal more that could be learned from more ambitious seismic networks. For a large planetary body, a group of four seismic stations in a regional network, like the Apollo seismic network on the Moon, provides detailed information on only one region of the planet. To obtain a global structure, a few more regional networks are needed. Four networks of four stations each, located roughly at four apexes of a tetrahedron, would give a reasonable global coverage of an entire planet. The networks may also be arranged in such a way that one of the stations is located near the antipode of a known or suspected seismically active region, specifically to obtain information about deep structure. Beyond this number, further deployments of seismic stations would probably be made to satisfy certain specific objectives, such as to determine detailed lateral variations in structure or to investigate tectonic activity in a particular area or region.

4.1.8. Duration and Deployment

There is a significant advantage to maximizing the time spent making seismic measurements on a planet. In seismology, the interior structure is determined not from the analysis of a single seismic event, but is arrived at through the accumulation of many such events, each of which contributes statistically to the result. Tens to hundreds of recorded quakes are necessary to make meaningful inferences about the interior. On the Earth, a seismometer at a quiet site can record a globally detectable event roughly every day. On the Moon, only a few dozen large quakes were recorded over the nine-year lifetime of the experiment (although thousands of smaller events were recorded due to the extremely low noise floor, and many of these proved useful for interior studies). Clearly, long durations are required, especially on planets that are relatively tectonically inactive, in order to obtain the full benefits of a seismic investigation. A mission duration of months to a year is strongly recommended. Such long-duration surface missions pose engineering challenges, particularly with regard to power systems and maintaining instrument sensitivity and calibration. On some planets, such as Venus and Mercury, thermal aging is a great concern.

There are three main issues associated with deployment of seismometers on a planetary surface: isolation from noise sources, coupling with the ground, and knowledge of orientation.

The greatest problem with the Viking seismometer measurements stemmed from the fact that the instrument was mounted on the large lander. This lander presented a large cross section, and there was considerable shaking by the wind. Additionally, all other mechanical activities of the lander created acoustic noise that was transferred to the seismometer. On the Moon, the seismometers were deployed tens of meters from the landing stage of the LEM, but even at this distance lander noise is apparent in the records. The smaller size envisioned for future landers will partially alleviate this problem. In addition to lander-induced noise, the sensitivity of unprotected seismometers is, especially in the presence of an atmosphere, severely limited by environmental influences. These include temperature, air pressure, and wind.

Ideally, the seismometer would be buried at a depth exceeding the seasonal thermal skin depth at a distance of perhaps 100 m from the spacecraft, although this is almost certainly impractical within probable mission constraints. A reasonable alternative would be to deploy it from the end of an extendible boom, placing some distance between the seismometer and the lander. Wind and thermal noise can be reduced considerably by covering the instrument with an insulating "tent." Penetrator deployment provides one method of "burying" a seismometer, and provides good isolation from environmental noise.

In order to sense the very small motions of the surface that comprise seismic waves, the detector must be well coupled to the ground. Again, mounting on the deck or interior of a lander is clearly a poor choice. Relatively good coupling can be obtained with three sharp "feet," which will make positive contact with a hard (rock) surface or will penetrate into a soft (soil) surface. Care must be taken that noise isolation techniques (such as thermal insulation) do not screen the desired signals as well. We note that a penetrator deployment offers excellent ground coupling in addition to its environmental noise isolation advantages, although orientation (see below) and a long-term power supply are issues that need to be addressed.

It is critical to know the orientation (in addition to the position) of the seismometer relative to the planetary geodetic grid in order to locate detected seismic events. Although extreme precision is not required at the level of these investigations, it will be necessary to locate sources to within few hundred kilometers or so. This will require knowledge of the orientation of the seismometer to no worse than 5°. The easiest way to accomplish this (in the absence of a strong dipolar magnetic field) is to use a directional Sun sensor. For seismometers deployed on the surface, this should not present a problem. For penetrators, it would seem to require the inclusion of an "aft body" that detaches from the main penetrator and remains at the surface.

4.1.9. Present Instrument Technology

Examples of state-of-the-art terrestrial broadband seismometers are the Strekheisen STS-2 and the Guralp CMG-4. These instruments have a peak sensitivity of about 10^{-10} m/s^2 (generally following the terrestrial ground noise level shown in Fig. 4.1) over a frequency range of 10^{-3} to 10 Hz, with decreasing sensitivity outside this range, and a dynamic range of roughly 10^6.

Two seismometers have been flown on planetary missions (not including the Ranger seismometers, which never operated): the Apollo ALSEP seismometer (e.g., *Latham et al.*, 1971, 1973; *Nakamura et al.*, 1982) and the Viking lander seismometer (*Anderson et al.*, 1972, 1976, 1977). The Apollo missions placed five instruments on the Moon, the first of which failed after several weeks of operation. These seismometers were actually composed of two instruments each, a short-period (SP) and a long-period (LP) seismometer. The sensitivity of these instruments is shown in Fig. 4.1. The peak sensitivity was comparable to terrestrial instruments (when operated under ideal low-noise conditions), although the bandwidth was much narrower. The ALSEP package had a mass of about 9 kg, much too large for current missions. The Viking instrument was extremely constrained in terms of mass, power, and telemetry. As can be seen in Fig. 4.1, it had a much lower sensitivity than terrestrial or lunar instruments, and in fact did not unambiguously detect any natural seismic activity.

Presently envisioned planetary seismometers have taken advantage of 20 years of technological advances in material, fabrication techniques, and electronics to achieve higher performance from designs that are orders of magnitude less

TABLE 4.1. Planetary seismometer parameters.

Apollo	
Mass	11.5 kg
Power consumption	13.4 W
Frequency range	10^{-3}–10 Hz
Sensitivity	10^{-10} m/s^2
Viking	
Mass	2.2 kg
Power consumption	3.5 W
Frequency range	0.1–10 Hz
Acceleration sensitivity	5×10^{-7} m/s^2
Guralp	
Suspension	Pivoted cantilever with coiled spring
Mass	0.32 kg
Power consumption	280 mW
Size	7.5 cm × 5.0 cm (one component)
Frequency range	0.0027–50 Hz
Velocity output	750 V/m/s
JPL Microseismometer	
Suspension	Micromachined silicon, 10-Hz resonance, 6×10^{-9} m/s^2/$\sqrt{\text{Hz}}$ noise floor
Transducer	UHF capacitive displacement, 5×10^{-13} m/$\sqrt{\text{Hz}}$ sensitivity
Configuration	Tetrahedral (three-components of acceleration plus one redundant)
Mass	<0.1 kg
Power consumption	100 mW
Size	5 cm on edge
Acceleration sensitivity	Better than 10^{-8} m/s^2
Frequency range	0.01–100 Hz
OPTIMISM	
Mass	0.35 kg (one component)
Power consumption	20 mW
Size	9 cm × 9 cm × 9 cm
Frequency range	0.001–8 Hz
Velocity output	750 V/m/s
Acceleration sensitivity	1×10^{-9} m/s^2
ISAS Lunar Penetrator Seismometer	
Mass	0.35 kg (one component)
Power consumption	20 mW
Size	5 cm (diameter) × 5 cm (length)
Velocity output	950 V/m/s
Frequency range	0.5–8 Hz

demanding in terms of mass and power requirements. Several examples of current designs are described below.

Guralp planetary seismometer. Guralp Ltd. (of Reading, U.K.) design and manufacture broadband seismometers that are used worldwide in diverse environments, including boreholes and ocean-bottom installations. They have now put their 20 years of terrestrial experience to bear on designing a prototype seismometer for use on Mars. The specifications of the instrument are given in Table 4.1. It is an accelerometer, similar to those in use on Earth, with promising sensitivity and response. A coiled supporting spring allows considerable size reduction over a more standard leaf spring. The design includes a motor for mass centering, which will allow compensation for diurnal and seasonal temperature variations. It also features a new locking mechanism for isolating the delicate pivots and holding the mass secure during launch and hard landings. The seismometer can operate in any orientation. Thus a single instrument design can be used for detecting both vertical and horizontal motions, and there would be no need to level a three-component instrument. A prototype instrument is scheduled to be built in 1996.

JPL micromachined seismometers. Over the last decade micromachining of semiconductor materials using techniques developed in the microelectronics industry has been applied to the production of accelerometers. The resulting structures, compact and robust, meet the requirements for the next generation of planetary seismometry, although in general the high resonant frequencies (kilohertz and above) of the suspension have led to insufficient sensitivity. However, by reducing the resonant frequencies to the range of 10–100 Hz and employing ultrasensitive position transducers, micromachined seismometers can offer performance to rival that of conventional terrestrial seismometers. A program has been established at the Jet Propulsion Laboratory to explore novel approaches to micromachined suspensions and ultrasensitive position transducers. The prototypes are now sufficiently developed for proposal to planetary mission opportunities.

Micromachining, predominantly of single crystal silicon, has a number of advantages over the conventional production of suspensions from metals. Single crystal silicon is a surprisingly strong material with, for example, a yield strength 20× that of steel. Being dislocation-free, and hence relatively immune to creep, it is very stable, not needing the controlled aging of metal springs. It has few energy dissipative modes, and hence very high *Q*s (in this case *Q* is the dissipation quality factor of the spring) of over 10,000 are possible in vacuum; the thermal noise floor of the suspension can thus be extremely low even with a small (<1 g) proof mass. Micromachining etching processes can give very fine tolerances, to tens of nanometers, greatly facilitating miniaturization. Bonding of components can be achieved almost seamlessly, minimizing long-term mechanical drift and allowing the production of hermetic seals for *in vacuo* suspension packaging. Selective metallization enables the formation of electrodes, wires, and contacts, and the use of silicon allows integration of the mechanical sensor and transducer electronics within one structure.

Micromachined structures lend themselves naturally to capacitive transducer schemes: Plate separations can be highly toleranced and hence very small (<5 μm). Such small separations are essential for acceptable sensitivity from 10- to 100-Hz suspensions. However, even with such geometrical gain factors, it is still necessary to use a very sensitive capacitive transducer. One such, the ultra-high-frequency capacitive (UHFC) transducer, has been developed at JPL for seismometry. The variable capacitance between a suspended moving plate and a fixed plate is made part of a tank (LC) circuit excited at near resonance (of up to 100 MHz). By implementing a highly peaked electronic circuit, the response at the half-power points of resonance can be made highly sensitive to changes in the variable capacitance. The

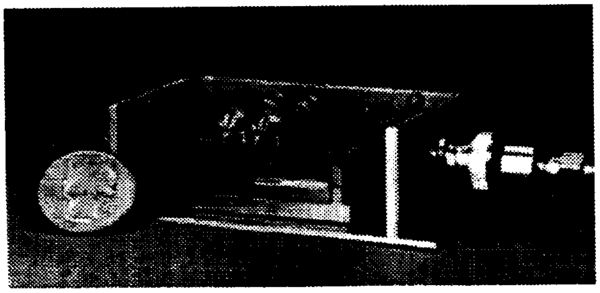

Fig. 4.2. Prototype JPL microseismometer.

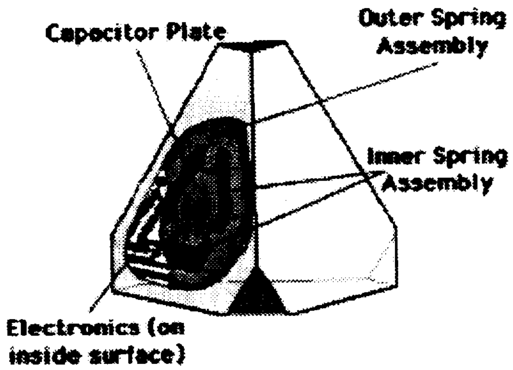

Fig. 4.3. Schematic of JPL microseismometer.

Fig. 4.4. Flight model of the OPTIMISM seismometer (left) and detail of the interior of the Ti half-sphere (right).

signal at these frequencies is demodulated from the excitation frequency and compared to the signal from either a fixed capacitance circuit or, more sensitively, the inverted signal from a second opposing fixed plate. Such an approach gives good rejection of frequency and amplitude fluctuations of the excitation signal. Additionally, the UHFC transducer gives a passive voltage gain of about 10, which can obviate the need for a preamplifier at the output of the seismometer. Alternative schemes with the potential for high sensitivity, though without the passive gain, are based on the switched capacitance approach. In this case care must be taken to minimize switching-induced errors and effects of instabilities in the supply voltages.

Figure 4.2 shows a prototype microseismometer using a silicon suspension and a UHFC transducer. Figure 4.3 shows a schematic of an integrated four-axis compact seismometer currently being proposed for Mars and cometary deployment. Specifications for this device are given in Table 4.1.

OPTIMISM seismometer. The OPTIMISM seismometer (Fig. 4.4), which has been designed and built by the Institut de Physique du Globe de Paris, the Institut Nationale des Sciences de l'Univers, and the SODERN company of France, will fly on the Russian Mars'96 mission. The OPTIMISM consists of a vertical seismometer, contained in a Ti half-sphere. The sphere can be leveled to within less than 0.2° by a gravity-driven gimbal after landing, and is then locked. The seismometer inside the sphere is a leaf-spring pendulum device, which uses a self-compensated spring alloy and achieves thermal compensation through careful design of the pivot and pendulum plate. Effective thermal coefficients as low as 0.2 µm/K can be achieved, which limits the displacement accuracy to about ±10 µm on Mars. The half-sphere also contains a temperature sensor and two getters for maintaining vacuum (to reduce viscous forces on the suspension).

The natural frequency of the seismometer is 2.3 Hz and the seismometer can run in either of two modes. The first mode uses a high-sensitivity (160 V/m/s) velocity transducer, which can be used to achieve extreme sensitivity close to the natural frequency. The second mode uses a displacement transducer, hybridized in the core of the suspension, based on a differential capacitive measurement. Resonance flattening is achieved by feedback.

ISAS penetrator seismometer. The Japanese lunar mission, LUNAR-A, to be launched in 1997, aims to study the lunar interior using a seismic network that will be established with three penetrators. The seismometer installed in the penetrator must be strong against the shock loading expected at impact of the penetrator into the lunar surface and yet must be sensitive enough to detect very small seismic signals.

The principle of the ISAS penetrator seismometer is the same as that of electromagnetic seismometers widely used on the Earth. A coil wound with 20-µm Cu wire acts as a pendulum, which is supported by three spiral leaf springs. The coil is positioned in a strong magnetic field produced by a newly developed rare-earth magnet. The strength of the magnetic field and number of the turns of coil control the sensitivity of this seismometer, both of which are in turn constrained by the mass and size of the seismometer. For the seismometer in a penetrator, it is important to make the natural frequency of the coil-pendulum system compatible with its mechanical strength. It is easy to make a short-period seismometer strong enough against shock loading, but it is technically difficult to make a long-period seismometer strong enough, because the long-period seismometer requires a weak (less stiff) spring. This problem is partly addressed for the ISAS seismometer using a nonlinear property of the spring material.

The damping constant of this seismometer is adjusted by appropriately selecting the material and structure of the coil bobbin. The characteristics of the ISAS seismometer are given in Table 4.1. Note that the high-frequency limit of the frequency range given in Table 4.1 is not due to the seismometer itself but is determined by the sampling rate of the LUNAR-A penetrator.

4.2. HEAT FLOW

The importance of planetary heat flow measurement has long been recognized. Heat flow is the only direct indicator of the internal temperature and heat transfer mechanism of planets that can be measured at the surface. Some planetary bodies are believed to be convective, whereas others are thought to be inactive or "dead." A convective planet like Venus probably develops thermal boundary layers at the surface, which may mimic the movements of the lithospheric plates of the Earth (e.g., *McKenzie,* 1994). Heat flow observations would provide constraints on their thermomechanical properties and time evolution (e.g., *Sclater et al.,* 1980; *Stein and Stein,* 1994). In addition, constraining the global heat budgets of planets would help to understand their individual histories and the history of the solar system as a whole.

4.2.1. Balance Between Scientific Objectives and Logistical Limitations

Generally speaking, knowledge increases with the amount of data. However, the time and monetary constraints of planetary missions severely limit the opportunities of data collection. Thus, scientists must know in advance what scientific objectives are likely to be accomplished with a very limited number of measurements. We believe that even a single heat flow measurement on a planet would be useful in providing a rough constraint on the internal temperature, especially for thermally inactive ("dead") planets, because there should not be drastic horizontal variation in thermal structure. However, lateral variations in topographic elevation and megaregolith thickness can lead to some variation in heat flow on "dead" planetary bodies. This effect is believed to be important in interpreting heat flow data from the Apollo 15 and 17 landers, both of which were sited at mare-highlands boundaries (*Warren and Rasmussen,* 1987).

If the planet is likely to be "alive," or convective, it is highly desirable that heat flow is measured at multiple stations that are strategically distributed. In this case heat flow through the planetary lithosphere will probably show a large variation. For example, heat flow through oceanic lithosphere of the Earth varies from >2000 mW/m^2 on young, shallow seafloors to ~40 mW/m^2 on old, deep seafloors. Thus, the first-order question for another convective planet like Venus would be whether heat flow varies systematically between the highlands, which are considered by many to be upwelling points, and the low basins (*McKenzie,* 1994). For such a purpose, the surface topography of the planet also needs to be mapped before the heat flow mission.

Even though some scientific objectives require multiple stations, it does not necessarily follow that all the measurements need to be done on a single mission. Even if only one measurement is possible on a single mission, several such missions to one planet would, over time, accomplish the objectives.

4.2.2. Measurement Technique

Heat flow is usually obtained as the product of two separate measurements: thermal gradient in and thermal conductivity of the near-surface rock/soil. In order to obtain the thermal gradient, one needs to measure temperatures at different depths. On unmanned missions, a penetrator is well suited for such measurements. The essence of the technique is similar to that of measurements made routinely on the terrestrial seafloor, which also use a probe penetrating into the sediments (e.g., *Nagihara and Lister,* 1993). The penetrator probe would consist of a thin metal tube containing thermistors that are spaced along its length. When the probe pushes into the rock/soil, its temperature rises due to the dissipation of the mechanical energy, and the temperature then slowly decays and approaches an equilibrium. The thermal gradient can be calculated from the equilibrium temperatures measured at individual thermistor locations. The probe should also contain a heater, which can apply an intense, calibrated heat pulse to the surrounding soil or rock after the probe temperature has reached thermal equilibrium. The *in situ* thermal conductivity can be calculated from the temperature decay pattern of this heat pulse (pulse-probe method: *Lister,* 1979; *Hyndman,* 1979; *Nagihara and Lister,* 1993).

4.2.3. Environmental Concerns

The shallow (<2 m) surface layer, where planetary heat flow measurements are likely to be made, is highly susceptible to temperature changes at the surface. The thermal signals from diurnal and seasonal variations can easily wipe out the subtle geothermal signal from depth. Therefore, it is crucial that scientists monitor the temperature over a long period in order to eliminate the environmental signal from the data. It would be ideal if this period covered at least one complete cycle of seasons, but it may be possible to extrapolate the variation fairly accurately based on data from one-fourth of the cycle. A planet like Venus, which is covered by a thick atmosphere, has little surface temperature fluctuation, and thus has a relatively benign environment for heat flow measurements. In contrast, Mars and the Moon have fluctuations of large amplitudes and present a very difficult situation for heat flow investigations. On Mars, the thermal wave associated with orbital element variations (timescale ~10^5 yr) may significantly perturb the near-surface thermal gradient from its long-term (>10^7 yr) average value. Modeling suggests that the magnitude of this effect varies substantially with location on the surface (*Mellon and Jakosky,* 1982).

4.2.4. Instrumentation Requirements

Both geothermal gradient and *in situ* thermal conductivity can be obtained from the temperature recorded as a time series by individual thermistors placed at a number of depths. The resolution of the temperature measurement should be on the order of milliKelvins. This is based on the fact that the lowest typical geothermal gradients measured on the Earth and the

Moon are ~0.01 K/m (*Langseth et al.*, 1976; *Sclater et al.*, 1980) and on the assumption that the depth of measurement be limited to ~1 m. The conductivity measurement would require a sampling interval of ~10 s, but the long-term monitoring can be done with one measurement per day. As far as the electronics and communication technologies are concerned, no major difficulty is anticipated except for protection from the extremes of high and low temperature encountered on some planets.

In mechanical design, the penetrator requires the strength to withstand the enormous deceleration force at the impact. However, efforts should be made to minimize the diameter of the probe. The *in situ* thermal conductivity measurement requires a quick thermal response by the sensor tube (*Nagihara and Lister,* 1993). For example, the sensors used for marine measurements are typically of 0.4–1 cm diameter. The thin diameter is desirable also for the long-term temperature monitoring, because a thick-diameter probe may significantly alter the geothermal field due to the high contrast of thermal conductivity between the metal tube and the surrounding rock.

4.3. MAGNETISM

Magnetic measurements yield information both on the electromagnetic material properties (primarily resistivity) of the interior of a planet and on processes of internal field generation (such as a dynamo). The primary magnetic measurements of a planet are better suited to orbital techniques. However, surface measurements can play an important role in investigating the interior through electromagnetic sounding.

The transient variations of the magnetic field at the surface of a planet have a primary external source, the interaction between the environment of the planet and solar radiation, and a secondary source, the electric currents induced in the conductive planet. Continuous recording of the transient variations of the magnetic field at the surface can therefore provide information on its internal structure. The depth of penetration of an electromagnetic wave in a conductive medium depends on both the period of the wave and the electrical resistivity of the medium. The larger the period and the resistivity, the greater the depth of penetration. Electromagnetic sounding can determine the presence (or absence) of sharp variations in the resistivity to 400–500 km depth and thus provide information on the thermodynamic conditions within this zone.

Electromagnetic sounding techniques are based on the analysis of the electromagnetic field observed at the surface of the planet. The resistivity distribution within the Earth is usually determined by measuring the magnetotelluric tensor, which relates, in the frequency domain, the horizontal components of the electric field to those of the magnetic field simultaneously recorded at a station. When (1) the resistivity varies with depth only, and (2) the externally originating variations are, as a first approximation, homogeneous at the scale of the studied area, the magnetotelluric tensor is antisymmetric; the antidiagonal terms are equal to plus or minus the transfer function between the magnetic and electric fields respectively. This transfer function is called the impedance of the conductive medium.

Within the same approximation, the impedance may also be deduced from the ratio, in the frequency domain, between the vertical and horizontal components of the magnetic field at a given station, provided the geometry of the source (which is provided by the interaction of the interplanetary field with the planet and/or its ionized environment) is known. In this case, the relative error in the impedance determination is on the order of the relative error of the source wavelength determination. The electromagnetic sounding technique can therefore allow the determination of the resistivity distribution even in the case of one magnetic station operating at the surface of the planet. The effectiveness of the technique can be strengthened considerably by the addition of a magnetometer in orbit to assist in the source determination.

The impedance is directly related to the variations of the resistivity with depth. Information about these variations can then be deduced from the observed frequency dependence of the impedance. The resistivity is dependent on the petrological nature of the materials and their thermodynamic conditions. Laboratory results on terrestrial materials show that the electrical resistivity varies greatly with respect to the thermodynamic conditions such as the temperature and the percentage of conductive fluids within the solid matrix (e.g., partial melting, water-rich fluids). For nonhydrated rocks, the resistivity remains very high for temperatures up to 1200°C or even 1800°C in some cases. Molten rocks have low resistivities (1–0.1 Ω/m), and in the presence of partial melting, the effective resistivity falls sharply by several orders of magnitude at constant temperature. In the presence of even a small fraction of a conductive liquid phase the resistivity sharply drops.

Extremely light, sensitive magnetometers have been developed over the years for many deep-space and planetary missions. These instruments can be easily adapted for use on planetary surfaces. The primary difficulties encountered on the surface are deployment away from magnetically noisy landers (extremely long booms are impractical) and the extremes of temperature often encountered.

4.4. GEODETIC MEASUREMENTS

Geodetic measurements, as defined here, are precision measurements (as a function of time) of position and orientation of a point on the surface. These measurement can yield the dynamics of the planetary body as a whole or local strain in its crust, depending on the reference for the measurement.

On the Earth, GPS measurements and local strain determinations are making great contributions to our understanding of tectonics. However, these types of measurements will be extremely difficult and costly on other planets, and this group could not envision a practical scheme for performing such an investigation in the foreseeable future. Thus the only technique that we will consider here is precision tracking of a lander for planetary dynamics.

These types of measurements can be particularly sensitive to the deep interior structure, through its effect on the rotational dynamics of the planet (e.g., precession, nutation, variations in angular velocity), and are complementary to seismology, which is most effective in determining crust and upper mantle structure.

Dynamical measurements are fundamentally different from the other techniques discussed here in that they are not made by an instrument as such. Instead, they rely on precision (on the order of centimeters to a meter or so) tracking of the lander from Earth. Thus, advances in communications technology are expected to result in improvements in measurement. For example, the transition to higher-frequency transponders (S to X to Ka band) gives much higher precision for tracking. Laser communication links could provide an additional improvement.

Perhaps the greatest short-term improvement in obtaining scientifically useful information from tracking measurements could come from a change in the way such experiments are typically handled. Traditionally, these investigations are treated as an opportunistic low- or no-cost add-on augmentation to the navigation function. A much greater value could be obtained if investigators were involved early in the mission and hardware planning stages, and these investigations were made an integral part of the mission design.

4.5. RECOMMENDATIONS FOR DEVELOPMENT FOCUS

Many technologies needed for performing interior measurements on planetary surfaces have already been pursued for terrestrial applications, as very similar constraints are often encountered. Other technologies that would benefit interior measurements are generic, such as the development of lightweight, low-power, high-temperature, and/or low-temperature electronics, and will be pursued in the general course of space hardware development. However, we have identified a few specific areas in which technologies would directly benefit some of these instruments.

4.5.1. Seismology

Seismology has a somewhat unique requirement for the capability to record ground motion over an extremely wide dynamic range, over 11 orders of magnitude (see Fig. 4.1). On the Earth, this is often accomplished using multiple specialized instruments, each designed to respond to a narrower range. We do not have this luxury in extraterrestrial seismology, and thus would like to be able to respond to both the teleseismic signal just above the noise on an airless body (with accelerations of order 10^{-10} m/s^2) and the strong motion from a relatively close event (say, ~10^{-4} m/s^2). Present space-qualified analog-to-digital converters have a maximum range of around 16 bits, and are inadequate for this task. The development of a 24-bit A/D would greatly benefit any future planetary seismometer.

Data compression will be required for any seismic experiment in the foreseeable future. This is due to the immense volumes of raw data generated by a sensitive, high-frequency three-component seismometer (of order 1 Gbit/day) and the limits imposed by practical telemetry systems. Lossless compression techniques are well understood, and can result in savings of perhaps a factor of 5. "Lossy" compression can achieve much higher compression ratios, at the expense of some degradation of the signal. This degradation has been intensely studied for voice and image compression, and techniques have been developed that are tailored to these applications, destroying data that is relatively unimportant for their analysis. Similar studies need to be done for seismic signals to develop data compression algorithms that will preserve the information required by seismologists.

4.5.2. Heat Flow

Effective heat flow measurements are dependent on devices for emplacing the temperature probes at depth. Penetrators have long been touted as ideal for this application (as well as for seismology), but there remains skepticism within the planetary science spacecraft community about the viability of this type of lander. This appears to be due in large part to the obscure nature of the existing literature on penetrator development and testing. Thorough validation and testing of penetrator technology should be done, although considerable confidence could be generated by the successful use of penetrators in the upcoming Russian Mars'96 and Japanese Lunar-A missions.

Similarly, low-power, lightweight drill technology could be developed and used for the emplacement of thermistors, and would benefit many other investigations that require access to the near subsurface of a planet.

4.5.3. General

On several planets, very high (e.g., Venus, Mercury) or low (e.g., Mercury's pole, outer planet satellites, comets, and asteroids) temperatures will be encountered, which will place demands on electronic components. Therefore development of electronic technologies that will allow reliable operations at extreme temperatures will be necessary. This is particularly critical for instruments such as seismometers and magnetometers, which must be deployed well away from a spacecraft and its thermal control systems for extended periods of time.

Another common requirement for the types of measurements discussed here is for long duration. All these investigations would benefit from measurements that spanned at least a local year on the surface, or even longer. Thus longevity should be emphasized in the development of electronics and systems for both the instruments and the spacecraft.

Across the board, a critical factor for most surface measurements related to the interior is the number of independent measurement sites. Thus any system-wide (including all spacecraft and mission systems, as well as payload) development that helps to enable multiple landers (with sufficient resources and capabilities) within today's tight cost constraints would directly benefit these types of investigations.

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