1

Investigations and Techniques

1.0 Introduction

Space agencies send robotic missions to explore the Solar System and deliver the important scientific data obtained by onboard instruments to control centers and science teams via radio communication links. From the early missions, scientists realized the utility of the radio links themselves as fundamental scientific tools for exploration and research. Many phenomena at Solar System targets affect the characteristics of the radio signals in a manner that reveals the targets' scientific properties.

Over the past six decades, scientists have made an extensive set of discoveries about Solar System bodies using spacecraft radio science (RS) investigations and techniques. They have inferred the presence of liquid oceans beneath the icy surfaces of Titan, Enceladus, and Europa, where possible future missions might search for life. They have also profiled the atmospheres and characterized the surface properties of many planetary bodies, key information to also aid potential future human exploration. From the Sun and Mercury to the outer reaches of the Solar System, this field has our increased understanding of the Universe.

Monitoring spacecraft radio signals enables researchers to precisely measure the changes in the link's frequency, amplitude, and polarization, and other electromagnetic wave parameters. With these measurement tools, scientists investigate ionospheres, neutral atmospheres, rings, surfaces, shapes, internal structure, orbital motion, and the dynamics of Solar System bodies. These techniques are also used to investigate the solar corona and fundamental physics, including tests of the general theory of relativity (GTR).

RS will continue to be an essential field for Solar System exploration. Goals have been identified for additional scientific advances in the future enabled by developing innovative instrumentation, advanced calibration techniques, and experimental scenarios that significantly improve the data quality. Future exploration concepts at various planetary bodies include wind profiles from entry probes or balloons, detailed atmospheric structure from radio occultations (ROs), electrical properties and roughness from surface scattering (bistatic radar), as well as interior structure from high-precision planetary gravity fields are among the future exploration concepts at various planetary bodies. The focus will increase on applications of small spacecraft and constellations of spacecraft with crosslinks between them.

The story of RS covers numerous domains in Solar System exploration: science, engineering, technology, signal processing, data analysis, mission operations, and

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communication systems. The future outlook for the field is filled with exciting possibilities for additional scientific breakthroughs.

1.1 Historical Background

Wireless communications via radio technology is one of the defining developments of the modern world. Asmar (2010) outlines how, in 1901, Guglielmo Marconi wirelessly received the simple Morse code for the letter S across the Atlantic Ocean and created an alternative to the use of a wire to communicate information. Advancements in this budding technology accelerated over the next three decades, as narrow-band transmitters replaced spark gaps and the device became more popular. United States President Warren Harding installed a radio in the White House and was also the first president to have his voice transmitted by radio. Later, in 1925, President Calvin Coolidge gave the first radio-specific inaugural address broadcast to homes throughout the country.

Within 20 years, video transmission utilizing radio waves brought television to living rooms; then, increases in transmitter power and antenna size allowed nearly global coverage. The invention of the transistor reduced power consumption, device size, and cost. Consequently, the age of small digital devices began, eventually leading to smart phones. Data transfer rates are reaching terabits per second, an enormous leap over Marconi's few dots.

With these technological advances, big antennas were also built and pointed toward the sky. On assignment for Bell Laboratories, Karl Guthe Jansky built a rotating antenna and, in 1933, discovered radio waves emanating from the Milky Way. Inspired by this finding, Grote Reber built the first parabolic radio telescope in his backyard in 1937, which he then used to conduct a radio survey of the sky, confirming the presence of natural radiation. Consequently, the budding field of radio astronomy established a new way of exploring an invisible part of the Universe.

In the mid-1940s, scientists transmitted radio signals toward the Moon and received echoes; this was repeated two decades later at Venus and Mars. This new technique, called planetary radar, revealed variations in the surface scattering properties of the planets and is still in use for the detection of possible hazardous near-Earth objects. Since Marconi's 1901 observation that radio waves propagate beyond the horizon, "radio physicists" investigated the idea of a reflecting layer in Earth's ionosphere. The Nobel Prize for Physics for 1947 was awarded to Sir Edward Appleton who demonstrated the existence of an ionized region capable of reflecting electromagnetic waves and higher region from which the shorter radio waves are reflected and later investigated the reflection of radio waves from meteors. According to the prize announcement, his work was invaluable in allocating suitable frequencies for practical radio communication, broadcasting, and other applications.

In the early 1950s, radio signals were used to study Earth's ionosphere via examining echoes of transmitted pulses and as well as the scattering of radio waves from meteoric ionization (Eshleman and Manning 1954, based on V. R. Eshleman's 1952 Stanford University's dissertation). In that period, the term "radio science" started to appear in some literature to describe the study of Earth's environment using radio waves. The term was later adopted by the planetary science community for investigations based on radio signals transmitted from spacecraft to ground stations. In the

1960s, publication of a research journal titled *Radio Science* began and continues to this day by the American Geophysical Union.

In a parallel historical development, in the mid-1930s, a group of California Institute of Technology (Caltech) students began experimenting with rockets on the campus with Professor von Karman. For safety reasons, they were relocated to an isolated area in an arroyo a few miles away, at a site that would become the Jet Propulsion Laboratory (JPL) in 1944. About 14 years later, the National Aeronautics and Space Administration (NASA) was formed and JPL became NASA's laboratory. By the 1960s, NASA began to launch robotic spacecraft to study the Earth environment and explore the Solar System and beyond.

To enable NASA's deep space missions, large steerable antennas, similar in shape to the early radio telescopes, were developed at JPL to control the spacecraft and receive the valuable scientific data collected during encounters with their distant planetary targets. Unlike communication with satellites in Earth's proximity, deep space communication addresses the challenge of the signal level decrease proportional to the square of the vast distance. A global network of stations for communications, tracking, navigation, and science was named the deep space network (DSN), an engineering marvel.

The Solar System distances are measured in astronomical units (au), the distance from the Sun to Earth. Voyager 1 is the most distant human-made object in space at nearly 150 au, or nearly 23 billion kilometers (km, ~14 billion miles), away. At this distance, its radio signal, produced by a 23-watt (W) transmitter, drops to about 10^{-23} watts per square meter (W/m^2) when it reaches a 70-meter (m) diameter DSN station and still delivers important scientific information. Note that when the DSN transmits a signal to the Voyager spacecraft (the reverse path), it is 20 kW or 1000 times stronger than what Voyager transmits. Traveling at the speed of light, the round-trip radio signal takes about 40 hours when transmitted from the DSN to Voyager 1 and received back at the DSN (Asmar 2010).

1.1.1 The Field of Radio Science

To carry out its increasingly challenging tasks and complement the advancing capabilities of spacecraft radios, the DSN was instrumented with specialized technologies, such as atomic clocks for frequency and timing reference, accurate antenna pointing, and sensitive signal receivers, with some elements cooled to about 5 Kelvin (°K) to minimize the ambient noise (maximize the signal-to-noise ratio [SNR]).

Although other tracking stations and radio telescopes have made significant contributions to the field, the high-resolution RS measurements can only be carried out using instrumented facilities such as those found at the DSN and selected stations of other space agencies.

The modern field of spacecraft RS was made possible by the successive instrumental developments on both ends of the link (onboard spacecraft and at ground stations) that maximized telecommunications performance, increased the system sensitivity to receiving weak signals as well as spacecraft signals with high dynamics in frequency and/or amplitude. Signals transmitted by spacecraft and propagated to ground stations, and in recent cases, from one spacecraft to another, are themselves employed as an additional effective tool to study the planets and their environments.

Many notions came to define this field such as occultations and precision Doppler measurements, illustrated in Figure 1.1, which are representatives of the two broad categories of RS investigations, described in Section 1.2.1. In an occultation experiment, a spacecraft transmits a radio signal to Earth, or to another spacecraft, through the atmosphere of a planet. The signal is perturbed in its electromagnetic properties due to the interaction with the gas material and then examined by scientists to understand the planetary atmospheric structure.

A spacecraft flying near a planet transmits a communications radio signal to a ground station that undergoes an additional Doppler shift. The shift occurs when the planet's gravitational field causes perturbation of the spacecraft's motion. The received signal is examined by scientists to deduce information about the interior planetary structure, as a leading example. The same precision Doppler is a tool for spacecraft navigation.

With these techniques, radio scientists examine changes in the characteristics of electromagnetic waves, such as the frequency, phase, amplitude, line-width, polarization, and round-trip light time, to study planetary atmospheres, ionospheres, rings, and surfaces. They also deduce planetary masses and density distributions from gravitational fields, monitor the solar corona, and test theories of relativity. The signal characteristics are altered due to propagation effects caused by intervening media, scattering surfaces, or due to the additional relative motion caused by the mass and density distribution of the planets or moons, among other effects.

RS experiments have been conducted on almost every Solar System exploration mission through teamwork between academic and government research facilities as

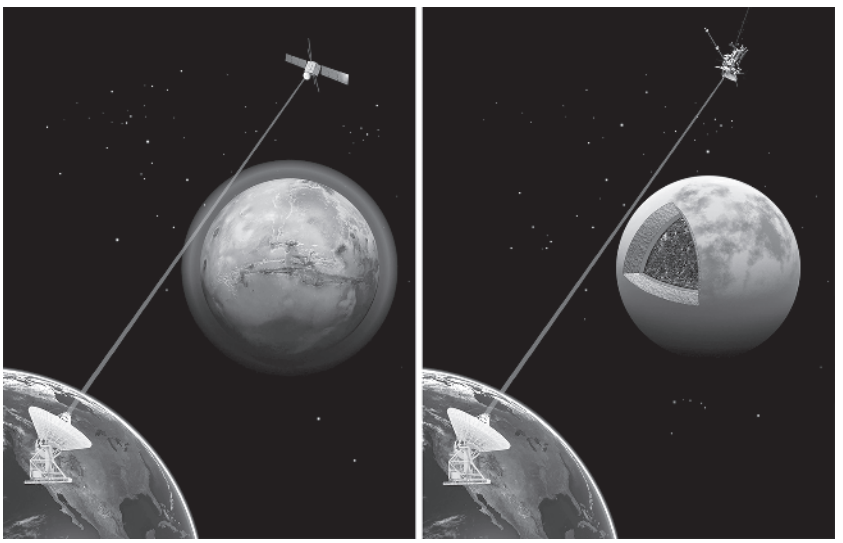

Figure 1.1 Illustration of two representative categories of radio science experiments. On the left, a spacecraft transmits a radio signal to Earth through the atmosphere of a planet. The propagation of the signal occulted by the atmosphere is perturbed by the interaction with the gas material, which reveals the atmospheric structure. On the right, a spacecraft flying near a planet transmits a signal to a ground station that is Doppler-shifted due the perturbation of the spacecraft's motion by the planet's gravitational field, which reveals information on the mass distribution and constrains models of the interior structure.

well as strong international collaboration. These experiments have led to numerous discoveries published in leading scientific journals and conferences.

For six decades, science teams have investigated the interior structure of every planet in the Solar System and several of their satellites, the Moon, and several comets and asteroids; sounded the atmospheres of the planets, Pluto, and several large satellites, as well as the Io Plasma Torus, and Saturn's and Uranus' rings; investigated planetary surface properties via bistatic scattering; investigated the solar corona and the interaction of the solar wind with planetary atmospheres; and conducted tests of the theories of General Relativity.

Selected accomplishments in RS are detailed in Chapters 2–4 and summarized in Appendix 1A along with near-term and long-term future experiments planned by various space agencies to further explore Mercury, Venus, asteroid Psyche, Jupiter's Galilean satellites, and other planetary bodies. These are aligned with community white papers for the Decadal Surveys of the National Academies of Sciences, Engineering, and Medicine, reproduced in Appendices 6A and 6B.

After initially using equipment shared with telecommunications and navigation systems, the RS community introduced science-specific flight and ground instrumentation and supplementary radio links at higher frequencies (e.g., Ka-band on Cassini, Juno, BepiColombo, JUICE and other planned missions). This lowers the noise caused by dispersive media, the electrically charged gas that affects the signal propagating through it as a function of the signal's wavelength. Lower frequencies (e.g., S-band introduced on Cassini for RS only) increase sensitivity to planetary ionospheres under study or ring particle size distribution.

Researchers also developed uplink atmospheric occultation instrumentation with processors onboard spacecraft to enable a higher received SNR, which was utilized during the New Horizons mission's flyby of Pluto (Tyler et al. 2009), and demonstrated as early as 1967 at Venus (Fjeldbo and Eshleman 1969). This was, in effect, a return to the original theoretical concepts of uplink ROs formulated in the 1960s. Onboard RS processors also benefit spacecraft-to-spacecraft crosslinks by achieving global planetary atmospheric occultation coverage significantly faster than downlink spacecraft links to Earth. Furthermore, RS researchers are preparing for the era of laser communications from deep space with plans for optical link science.

1.2 Fundamental Concepts

Solar System exploration missions currently use centimeter–wavelength radio frequency (RF) space links between spacecraft and Earth. Spacecraft transmit to ground station signals carrying the telemetry, the science data acquired by onboard instruments (payload) along with health and status reports. Spacecraft also receives signals from Earth stations carrying updated instructions and sequences called commands (or telecommands).

The basic radio signal used for spacecraft communication is a sinusoidal carrier that is phase modulated with data. Depending on engineering considerations, data are placed on either the carrier itself or on subcarriers (side carriers offset in frequency from the primary carrier). The telemetry sent by the spacecraft to the ground is transmitted in either real-time or is time-sequenced for transmission from data recorders when there is a ground station scheduled in the view period. The commands are also sent via uplink from the ground station to the spacecraft for either immediate execution at

reception or at programmed times. For details on communications systems with deep space missions, see Yuen (1983), Doody (2011), and Taylor (2016).

At vast distances, the strength of the radio signals captured on Earth can be extremely weak in some cases, yet still provide useful information that can be critical to mission success. This is accomplished via high-quality flight and ground systems specially developed for deep space communications. Meter-wavelength signals in the ultrahigh frequency (UHF) band are used for proximity links between Mars landers and orbiters, for example.

The types of Solar System exploration missions include the following, each with communication links either directly to Earth, relay via another spacecraft, or both, with implications to possible RS experiments:

- Planetary flybys.
- Planetary orbiters.
- Stationary planetary landers.
- Roving planetary landers.
- Surface-exploring drones or helicopters.
- Sample collectors for return to Earth.
- Planetary atmospheric entry probes.
- Atmospheric balloons or ballutes.
- Formation-flying spacecraft with crosslinks between them.
- Futuristic concepts include sail planes and other aerial vehicles.
- Future concepts of short-lived low-cost small spacecraft exploring targets considered highly risky but have high science return.

For all types of missions, design teams minimize technical risks, conserve the overall mass and power resources, and extensively plan each mission's operational scenarios. They consider factors such as the expected frequency of contact with the ground stations to deliver the acquired data, the proximity to solar conjunctions that can be disruptive to communications, and the availability of relay assets when needed.

In the formulation and developments phases of a space mission, design choices in communications, navigation, and RS systems include

- Science requirements to which design parameters are traceable.
- Link budget parameters such as the transmitter power, antenna size, etc.
- Number of spacecraft antennas and their fields of view.
- Signal carrier wavelength(s) (e.g., S-, X-, Ka-bands, UHF, optical, etc.).
- Regulatory spectrum allocations and channel assignments to prevent radio interference among users.
- Telemetry modulation schemes.
- Data coding schemes.
- Signal polarization.
- Error budget of science parameters.
- Available proven technologies.
- Expected rate and volume of data.
- Consideration of cost.
- Contributions from other space agencies/external partners.

Mission design is the term used to describe the method of delivering spacecraft to their targets and includes maneuvers for interplanetary trajectories and other critical events such as gravity-assist flybys, orbit insertion, and, in some cases, descent and landing. Mission design teams collaborate with navigation (also known as flight dynamics) teams to implement the maneuvers and place the spacecraft on the planned trajectories. A state vector of the spacecraft position and velocity as a function of time is provided to mission users, communications engineers, and radio scientists for planning science operational activities.

Since the design of the spacecraft and the mission affect the quality of RS data, radio scientists participate in the development phases of a project life cycle and provide feedback on the proposed design and implementation possibilities and constraints, as well as performance requirements and specifications that maximize the scientific return of the planned RS experiments.

As previously noted, communication links are also utilized for additional functions. Radiometric measurements of the received radio signals are the primary method of determining and predicting spacecraft trajectories by navigation teams. Precise measurement of the carrier frequency and determination of its Doppler shift establishes the spacecraft relative velocity along the line-of-sight (LOS) between the spacecraft and the tracking station. In addition, the distance between a spacecraft and a station is accurately measured by ranging methods carried out by modulating predefined code onto the carrier signal and measuring the time of its travel at the speed of light from the station to the spacecraft and back (accounting for delays in electronic devices).

Since the distance and velocity measurements, called range and range-rate (RARR), are determined along the LOS, there are cases where a component in the plane of the sky is also important to measure. Radio interferometry across intercontinental baselines at multiple tracking stations are used to determine the position and velocity of the spacecraft in the plane of the sky via a technique called delta differential one-way ranging (delta-DOR), described in Thornton and Border (2003). Delta-DOR measurements and the more general very long baseline interferometry (VLBI) measurements are of high value to RS investigations as they provide astrometry and ephemeris information to aid in optimizing, as well as interpreting the science observations.

Radiometric measurements exemplify the first application of RS techniques. This measurement of perturbations of the expected RARR profiles illustrated how the communications links could be synergistically exploited to probe planetary and interplanetary environments. The intervening media along the propagation path lead to further perturbations in phase and amplitude. While communication engineers treat these perturbations as noise to be corrected for, radio scientists examine them for possible important information embedded in the wave's time of arrival, amplitude, frequency, phase, and polarization, as outlined above.

The interplanetary and ionospheric plasma are dispersive propagation media and the index of refraction depends on the frequency of the signal. Code and timing signals are delayed with respect to the vacuum, affected by the group delay. The phase of the carrier wave itself appears to speed up in the ionosphere for example, which is known as phase advancement. In a descriptive way, the wavelength in a plasma is enlarged with respect to the vacuum case. The absolute value of both effects is the same and depends on the same properties of the electron content.

Compared to telecommunications and navigation tracking applications, RS investigations typically require higher end-to-end link quality, especially higher signal frequency/phase stability. This is achieved via rigorous modeling, calibration, and bounding known sources of error and limiting factors (see Table 1.1) that include

- Uncertainties in the knowledge of the Earth's rotation and polar motion.
- Earth tropospheric path delay.
- Ionospheric and interplanetary plasma dispersion (also a function of proximity to solar conjunction or opposition periods).
- Stability of reference clocks/oscillators.
- Unmodeled nongravitational forces including spacecraft maneuvers interrupting the experimental data arcs, or thruster imbalance that bounds spacecraft dynamical stability.

Table 1.1 Radio science investigations, observables, experiment mode, and limiting factors.

Target [category]	Science products	Observables [radio mode]	Limiting factors
Planetary atmospheres [*Propagation through media*]	• Temperature-pressure profiles • Neutral density • Ionospheric density • Wave properties • Wind velocity • Abundance of key molecules • Shape or equipotential models • Turbulence and scintillation effects • Magnetic fields	• Frequency/ Phase • Amplitude • Polarization • *[One-way or crosslinks]*	• Phase stability • Amplitude stability • Signal-to-noise ratio • Fresnel zone size • Absorption • Geometrical coverage • Temporal density • Orbital accuracy • Multipath interference
Planetary surroundings [*Propagation through media*]	• Ring particle sizes • Ring wave structure • Ring density • Torus electron density • Cometary comae • Planetary ejecta	• Amplitude • Phase • *[One-way]*	• Phase stability • Amplitude stability • Signal-to-noise ratio • Fresnel zone size • Absorption • Geometrical coverage • Temporal density • Orbital accuracy
Solar corona and solar wind [*Propagation through media*]	• Electron density • Turbulence and structures • Coronal ejecta • Coronal and solar wind speed • Scintillation effects • Magnetic fields	• Doppler • Range • Amplitude • Polarization • *[One or two-way]*	• Signal-to-noise ratio • Phase stability • Range calibration
Planetary surfaces [*Scattering off surfaces*]	• Electrical properties • Roughness • Material type • Near-surface layering	• Amplitude • Polarization • Doppler • *[One-way or crosslinks]*	• Signal-to-noise ratio • Geographic resolution • System calibrations • Orbital opportunities

(Continued)

Table 1.1 (Continued)

Target [category]	Science products	Observables [radio mode]	Limiting factors
Planetary interiors from gravity [*Remote sensing and rotational dynamics/ geodesy*]	• Planetary bulk mass • Mass/density distribution • Interior structure models • Thickness of layers • Libration • Admittance • Gas giants wind patterns • State of the core • Total and core moments of inertia • Tidal response • Natural oscillations • Size and density of core and mantle • Length of day variations • Mass transport/redistribution • Chandler wobble • Ephemeris	• Doppler • Range • *[Two-way or crosslinks]*	• Frequency stability • Unmodeled nongravitational effects • Trajectory design • Orbital accuracy • View geometry • Length of data arcs • Topography/shape/ equipotential models
Fundamental Physics [*Perturbation in spacecraft motion*]	• Gravitational radiation • Relativistic time-delay • Post-Newtonian parameters • Redshift—Equivalence principle	• Doppler • Range • *[Two-way except redshift]*	• Frequency stability • Calibrations
Atmospheric dynamics [*In situ*]	• Wind velocity • Molecular abundance from absorption	• Doppler • *[Crosslinks or one-way]*	• Frequency stability • View geometry
Atmospheric Density [*In situ*]	• Density from drag effects • Cometary mass flux	• Doppler • *[Two-way]*	• Phase stability • Trajectory

Notes

Target column:

- Planetary refers to all objects in the Solar System: planets, moons, asteroids, comets, etc.
- Planetary surroundings refer to material from planetary rings, plasma tori, comets, ejecta, etc.
- Planetary geodesy includes rotational history of precession, nutation, and polar motion.
- Fundamental physics refers to tests of aspects of the theories of relativity.

Science products column:

- Atmospheric RO determines the total density profile and sometimes specific constituent profiles.
- High temporal density of measurements is important to study atmospheric dynamics.
- High-resolution temporal and spatial densities are important for atmospheric/ionospheric wave studies.
- Wind velocity from RO is derived from the shape of equipotential surfaces and pressure gradients.
- Planetary radiometry and polarimetry also utilize RS instrumentation and techniques for investigations of planetary atmospheres.
- RO technique for in-situ measurements with balloons leads to a derived wind speed and direction indirectly via temperature and pressure by applying criteria such as cyclostrophic conditions.
- Planetary shape models derived from RO can be used to interpret gravity data and interior structure.
- Phase scintillation effects detected in planetary atmospheres and the solar corona.

(*continued*)

Table 1.1 (Continued)

- Planetary ejecta includes volcanoes, plumes, jets, etc.
- Magnetic fields are derived from the Faraday rotation (polarization) in ionospheres and solar corona.
- For the solar corona, space–time localization of the inner heliospheric plasma turbulence can be carried out via multiple radio links.
- Mass transport in planetary atmospheres such as Mars polar material moving seasonally and atmospheric tides and barometric pressure variations have implications to atmospheric occultations as well as gravity field measurements. This is part of the research of geophysical events and atmospheric sensing that also includes seismic activity through surface-atmospheric coupling and topography-induced atmospheric gravity waves.
- Ephemeris improvements are used for cosmological frameworks and studies of cometary jets of material leaving the surface.
- Observations of the redshift contribute to the validation of the Einstein equivalence principle.
- At the gas giants, gravity investigations involve examination of wind patterns and the deep atmospheric structure.

Observables column:

- Observables are the raw data with physical dimensions such as distance, velocity, signal power level, etc. that are input to scientific analysis tools after calibration. There is a lower level of data from the open-loop receiver in the form of the I and Q digital samples of the sine wave propagating in space (with noise).
- Delta DOR is a secondary RS observable that aids in reaching better navigational products and reduces experimental errors.

Limiting factors column:

- Trajectory design refers to proximity to target, speed of flyby, timing of maneuvers, and other events that can change the sensitivity or affect the quality of the RS experiment.
- Orbital accuracy refers to the orbital reconstruction, which is required for RS analysis.

- Unmodeled relativistic effects.
- Suboptimal pointing and attitude control.

Nongravitational forces acting on the spacecraft that can be calibrated via onboard precise accelerometers or other methods include

- Solar radiation pressure.
- Out-gassing of spacecraft components.
- Thermal effects.
- Thruster imbalances.
- Momentum of the high gain antenna (HGA) radiation.
- Factors unique to the target planet such as atmospheric drag, albedo, and infrared radiation.

1.2.1 Categories of RS Investigations

Based on their scientific objectives and primary observing techniques, RS investigations can be grouped into two broad categories; numerous discoveries have been made in each category and their branches as described in the corresponding chapters:

1. Investigations of phenomena affecting the *signal propagation* where the signal travels through, and is occulted by, planetary and/or interplanetary media occulting the path, or scattered by planetary surfaces.

2. Investigations of phenomena affecting the *perturbation of spacecraft motion* due to the gravitational forces, relativistic effects, or in-situ atmospheric densities or winds.

In the first category, scientists investigate the perturbation of the signal's electromagnetic properties along the path between the transmitting asset (spacecraft or ground station) and the receiving asset due to interactions with occulting media or by scattering off planetary surfaces. The effects of scientific interest arise from sounding planetary ionospheres, neutral atmospheres, the solar corona, cometary comae, plasma tori, ring particles, and other Solar System material.

Scattering effects result from the electrical and mechanical properties of planetary surfaces and near surfaces that can reflect a portion of the signal's energy to a receiving asset. This reveals the surface or subsurface reflectivity and roughness. Note that surface scattering, commonly called *bistatic radar*, and RO were historically developed in the same time period by the same early pioneers and share common methods and terminology.

In the second category, scientists investigate the precise perturbations in the relative motion between two assets that produce additional Doppler shifts in the signal frequency. The effects of scientific interest arise from remotely sensing gravitational fields or locally observing *planetary geodesy* via surface landers. Newtonian gravitational forces arising from the bulk mass and density distribution of the planetary targets perturb the motion of the spacecraft and enable radio scientists to determine the gravity fields and deduce the planetary interior structures; relativistic effects are also carefully investigated. This RS category intersects two branches of physics, dynamical forces and electromagnetic propagation, where the motion of the spacecraft is measured from precision detection of the electromagnetic Doppler effect.

Spacecraft throughout the Solar System are always in motion unless they are stationary landers on planetary surfaces such as Mars landers, some of which are equipped with instrumentation that enables the detection of planetary motion, including rotational nutation and precession. Measuring the latter via Doppler tracking of stationary spacecraft aids in constraining the physical characteristics of planetary cores. Other in-situ effects include measuring planetary wind speeds and directions while spacecraft (entry probes) descend through atmospheres and are thus subject to wind forces, and determining the atmospheric density via measuring the drag on spacecraft surfaces, among other examples.

Note that, in the first category, inevitable changes in the signal properties resulting from the relative motion of the assets are quantified or modeled and then removed from the data via calibration techniques described below. In the second category, inevitable changes in the signal properties resulting from propagation through media are quantified or modeled and then removed from the data via calibration techniques described below.

In some cases, there is overlap in scientific interest between the two categories. For example, RO techniques used to generate a shape model of a planetary body can be utilized by gravity researchers to correlate the gravitational field and shape model and study the interior structure. Annother example is investigating the seasonal transport of Mars' polar material via atmospheric occultation and gravity science. Also, ionospheric waves are investigated in some cases for attribution to surface or subsurface effects such as seismic activities.

Representative RS investigations and relevant experimental configurations are outlined in Figure 1.2. Note that in some literature, RO techniques can also be referred to as limb sounding techniques or similar terminology and that gravity investigations are occasionally referred to as celestial mechanics in some literature, including documents of the Galileo mission to Jupiter. Table 1.1 lists most of the known or anticipated RS investigations with associated observables and limits of sensitivity. Table 1.2 provides a traceability matrix for functional and performance requirements of instrumentation 5to be developed to meet future scientific needs discussed in Chapter 6. In the figures and tables, the terms "one-way" and "two-way" are explained in Section 1.4 and graphically illustrated in Chapter 5.

1.2.2 Related Fields

Scientific interpretation of RS data often requires utilization of other data types and collaboration with other science teams. As a result, many RS investigators are often involved in collaborative fields and instruments such as planetary altimeters, radar, imagers, radiometers, accelerometers, gradiometers, polarimeters, and in-situ atmospheric sounders. Furthermore, work in the field of RS is multi-disciplinary and often requires expertise in science, engineering, instrument technology, software tools, operations, and mission support.

There are science investigations that utilize instrumentation and techniques overlapping with RS, sometimes considered a passive branch of this field. Planetary

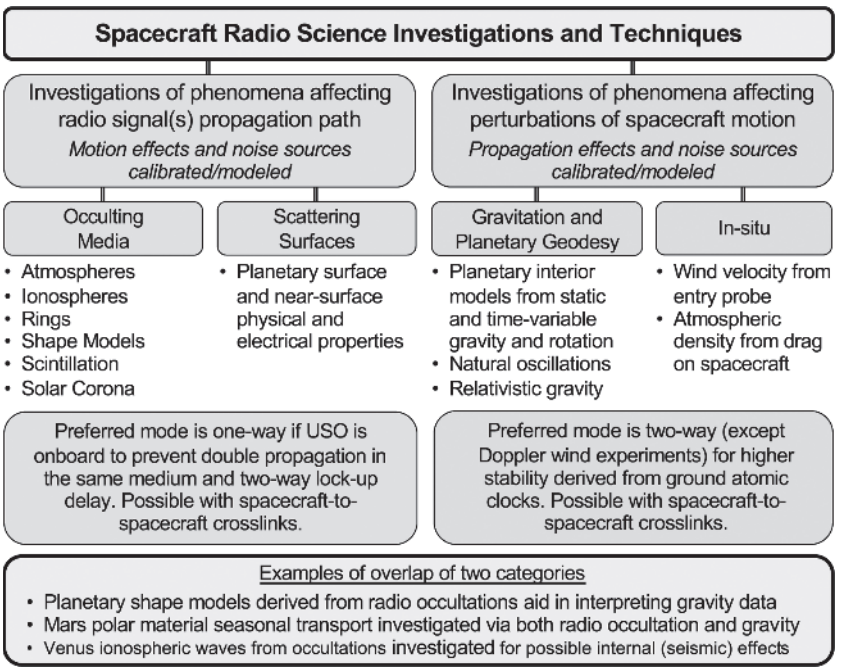

Figure 1.2 Examples of spacecraft radio science experiments grouped into two broad investigation categories and subcategories with representative science products and notes on typical instrumental configurations (USO is ultra-stable oscillator).

Table 1.2 RS functional and performance requirements traceable to science products.

Science targets	Functional requirements	Performance requirements
Planetary atmospheres and rings *via radio occultations*	• Ultrastable links (two links preferred) • One-way or dual one-way if USO; two-way if no USO limited to occultation ingress	• Allan deviation ~1×10^{-13} (~100 s) • Phase noise and spectral purity ~–90 dBc/Hz at 10 Hz offset • Amplitude stability ~0.1 dB over 60 s
Planetary surfaces *via signal scattering*	• One-way or crosslinks; good geometry • Signal power at dual polarizations • Multiple signals for uplink experiments	• Allan deviation ~1×10^{-12} (~100 s) • Amplitude stability ~0.1 dB over 60 s • Precision power measurement calibration
Planetary interiors *via Doppler tracking*	• Precisions two-way Doppler link(s); one-way possible if atomic clock onboard • Shorter wavelength less noisy	• Allan deviation ~1×10^{-14} (~1000 s) • Dynamically stable spacecraft • Calibration of nongravitational forces and propagation media effects
Planetary winds *via Doppler tracking*	• Cross- or one-way Doppler links with stable oscillators at both ends • Signal power if monitoring absorption	• Allan deviation ~1×10^{-11} (~100 s) • Amplitude stability ~ 0.1 dB over 60 s • Multiple links aid in wind vectors recovery
Solar science *via radiometric observables*	• Stable dual Doppler links • Phase at two circular polarizations • Ranging (two-way) for coronal densities	• Allan deviation ~1×10^{-12} (~100 s) • Amplitude stability ~0.1 dB over 60 s • Modelled antenna polarization if monitoring Faraday rotation
Fundamental physics *via radiometric observables*	• Precisions two-way Doppler link(s) • Shorter wavelength less noisy • Precision ranging	• Allan deviation ~1×10^{-14} (~1000 s) • Dynamically stable spacecraft • Calibration of nongravitational forces and propagation media effects

Notes
- Science targets are grouped by both science objectives as well as observation method.
- Functional requirements are the required spacecraft and ground systems capabilities.
- All investigations assume favorable orbits and geometrical configurations.
- USO: Ultrastable oscillator.
- Performance requirements are the engineering specifications to meet known or typical science requirements and can vary depending on the mission and investigation scenarios and constraints.
- Allan deviation (sometimes Allan variance) is a measure of fractional frequency instability for classes of clocks and oscillators.
- Dynamically stability is determined by spacecraft thruster balance or timing of spacecraft maneuver or solar electric propulsion events that disturb the Doppler data quality.
- Precision power calibration is required for comparing small variations in the two polarizations of received signals.

radiometry, for example, can utilize RS-type of open-loop receivers (OLRs) to capture surface brightness temperature in a radiometer mode. For example, Stern et al. (2018) and Bird et al. (2019) described the New Horizons Radio Science Experiment (REX) as an uplink RS instrument with radiometer capabilities (disk-averaged to ±0.1 K) that

conducted atmospheric radiometric measurements during the Pluto flyby by analyzing the variation of the RF signals passing through the atmosphere that are received by the spacecraft.

Similarly, the DSN RS OLRs are utilized for related scientific applications such as radiometry and differential interferometry. The latter is a technique used to examine planetary rotational state and tidal deformations by tracking multiple landers or spacecraft from one or multiple stations on Earth in order to suppress many common noise sources and enhances the signals of interest.

Another example is planetary radio polarimetry, a technique used to examine precipitation or water vapor detection in planetary environments, that can also utilize RS instrumentation and data-processing techniques.

Occultations by planetary bodies of natural radio sources, such as pulsars, active galactic nuclei, and masers, can also utilize RS instrumentation and techniques. Withers and Vogt (2017) described occultations of distant astrophysical radio sources as probes of planetary environments, especially magnetic field strength, plasma density, and neutral density. They also examined cases for Jupiter and possible applications to exoplanets occulting their parent stars. They found significant changes in polarization angle due to Faraday rotation occur for radio signals that pass within 10 Jupiter radii, and that significant changes in frequency and power occur from radio signals that pass through the neutral atmosphere.

1.3 Historical Development

The history of RS studies began conceptually with the radiometric measurements for celestial mechanics and radio navigation. The earliest use of the term in the context of planetary exploration goes back to ROs in the early 1960s. Professor Von Eshleman of Stanford University first proposed the method in 1962, building on earlier work with the formulation of mechanisms for radio reflections from meteoric ionization (Villard et al. 1953).

Independently, Dan Cain at NASA's JPL, California Institute of Technology, a navigator studying the effects of refraction in the Earth's atmosphere on the accuracy of the observed Doppler frequency shift, realized the potential for applying sensitive phase measurements to the study of the atmospheres and ionospheres of other planets (Kliore et al. 1964; Cain et al. 1966). Graduate student Gunnar Fjeldbo, who later changed his Norwegian name to Gunnar Lindal, advanced the occultation technique by utilizing a theoretical uplink configuration during his dissertation research with Von Eshleman (Fjeldbo 1964). Fjeldbo/Lindal later joined the Mariner and Voyager science teams during his subsequent employment at JPL, where his colleague Arvydas Kliore was the first RS principal investigator on a planetary mission.

The occultation technique was demonstrated for the first time in 1965 when Mariner IV flew by Mars and determined the salient features of the Martian atmosphere (stories were reported of mission managers needing to be convinced that such an occultation posed no risk to the safety of the mission); the resulting historic occultation profile is reproduced in Figure 1.3. The observations showed that the surface pressure is less than 1% of Earth's; an order of magnitude less than had been previously thought (Kliore et al. 1965; Fjeldbo et al. 1966). Mariner V flew by Venus in 1967 and conducted the second atmospheric occultation experiment (Kliore and Cain 1968; Eshleman et al. 1968).

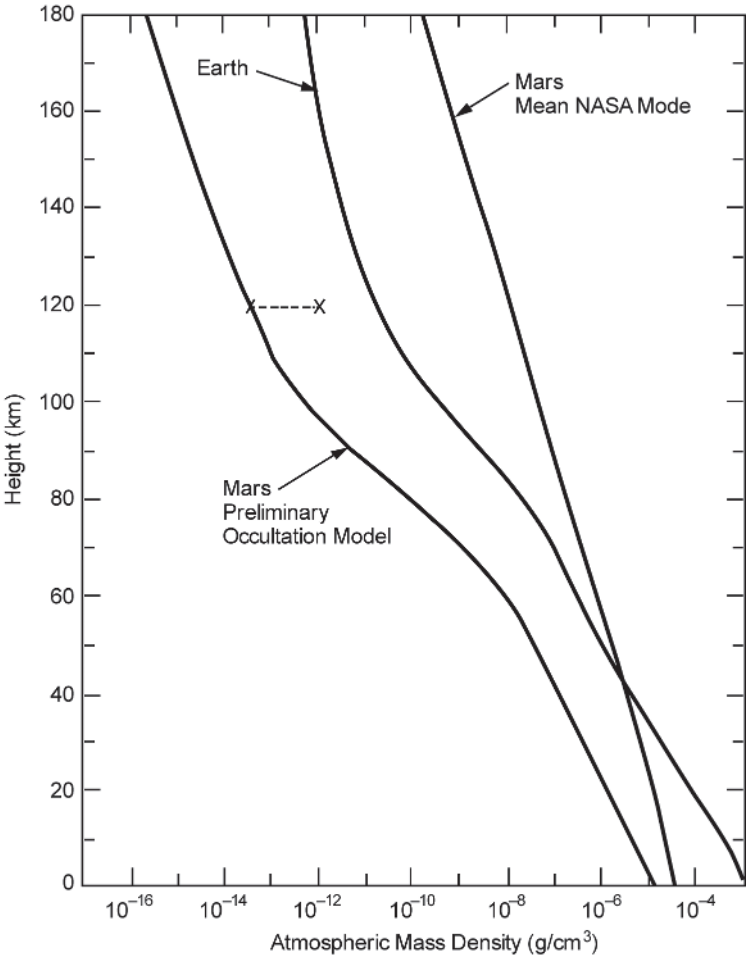

Figure 1.3 A reproduction of the result from the first planetary radio occultation. The technique was demonstrated in 1965 when Mariner IV flew by Mars and determined the salient features of the Martian atmosphere (Kliore et al. 1965; Fjeldbo et al. 1966).

After the successful occultation experiments with the Mariner mission series and as additional scientists and their students trained in this field, planning moved toward other planetary targets and many additional experiments produced notable discoveries. Eshleman et al. (1977) and G. L. Tyler (1987) described the RS experiments with Voyager; Figure 1.4 shows the classical results of the Voyager 2 atmospheric occultations of the four large gaseous planets.

Howard et al. (1992) described the Galileo RS experiments planned at the time (many of which were not carried out due to the Galileo HGA anomaly); Bird et al. (1992a) described the Ulysses Io plasma torus occultation experiment; Tyler et al. (1992) provided an overview of Mars experiments using the Mars Global Surveyor; Pätzold et al. (1993) described RS investigations using the Giotto mission to Halley's Comet; and Pätzold et al. (2016a) described the RS experiments performed with the Rosetta mission to comet 67P/Churyumov–Gerasimenko (67P). Mars Express and Venus Express RS

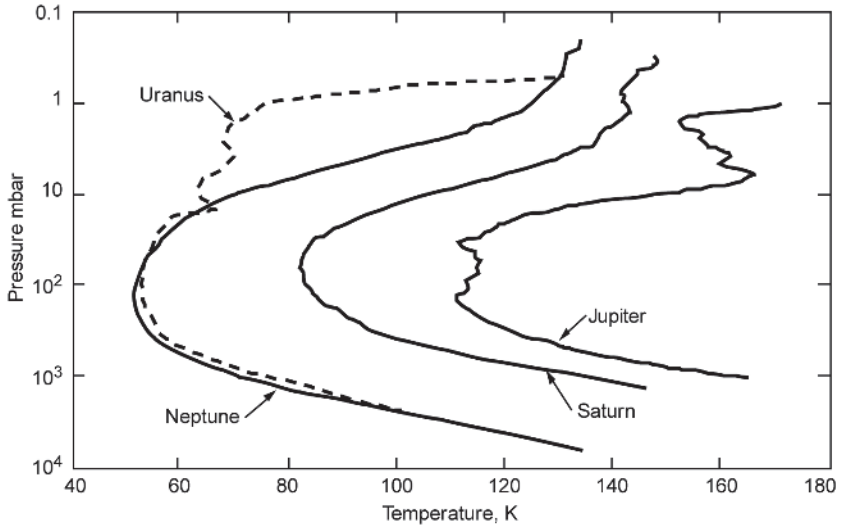

Figure 1.4 Classic results of radio occultation experiments showing the temperature–pressure profiles for the giant planets from radio occultation data acquired with the Voyager 2 spacecraft flybys (Lindal 1992).

experiments are described in Pätzold et al. (2016b) and Häusler et al. (2006), respectively. Kliore et al. (2004) described the Cassini RS experiments for the gravity and atmospheres of Saturn and its large moons, as well as Titan's surface and Saturn's rings.

Additional pioneering work from various space agencies and research centers advanced additional scientific techniques such as:

- Inferring surface morphology from the scattering of the radio signals historically known as bistatic radar (Tyler and Howard 1973; Marouf 1975), first demonstrated with Luna-11 (Yakovlev and Efimov 1966); Yakovlev (2002) describes several experiments on Soviet/Russian missions.
- Techniques for using RO to investigate planetary ring structure (Marouf et al. 1986).
- Radio scintillations reveal small-scale structure in planetary atmospheres (Hinson 1986).
- RO techniques to study planetary ionospheres (Kliore et al. 1967).
- Scintillation studies of solar wind turbulence and structures (Woo 1993).
- Power spectral analysis of the interplanetary plasma (Armstrong and Woo 1981).
- P. Steffes (1985) took the lead on laboratory measurements of the microwave opacity and absorption, especially simulating conditions in the atmosphere of Venus.
- ESA missions utilized RS techniques for extended observations of the solar corona with the Helios mission (Volland et al. 1977; Pätzold et al. 1987; Bird and Edenhofer 1990; Andreev et al. 1997).
- The SELENE mission from the Japan Aerospace Exploration Agency (JAXA) measured the gravitational field of the lunar far side from four-way (see Section 5.2.1.4) Doppler links (Namiki et al. 2009), which utilized a subsatellite with a four-leg link from the ground to the orbiter to the sub-satellite and back.
- Doppler-based vertical wind profiles of the Venus atmosphere from the Venera probe (Kerzhanovich et al. 1983).

- Flow of the Venus winds using measurements of the Vega Venus balloons' position and velocity using Doppler and VLBI observables (Sagdeev et al. 1986a, 1986b; Preston et al. 1986).
- Dual-frequency investigations of planetary ionospheres were performed in the 1970s and 1980s with Luna 19 and 22 at the Moon (Vyshlov 1976), with Mars 2, 4, 5, and 6 at Mars (Savich et al. 1976; Kolosov et al. 1976), with Venera 9, 10, 15, and 16 at Venus (Aleksandrov et al. 1977; Savich 1981; Savich et al. 1986a; Ivanov-Kholodny et al. 1979) and with Vega 1 and 2 at Comet Halley (Savich et al. 1986c; Andreev and Gavrik 1993).
- Venera orbiters' radio sounding of the solar corona (Efimov et al. 1977; Kolosov et al. 1982).

RS experiments have also refined our understanding of post-Newtonian physics. Frank Estabrook pioneered the search of gravitational waves via Doppler tracking (Estabrook and Wahlquist 1975). Later, using the Cassini spacecraft, precision Doppler observations in the cruise phase were used to place upper limits on the strength of low-frequency gravitational radiation (Bertotti et al. 1995; Armstrong 2006). Also using Cassini during its cruise phase, RS tests of aspects of the theories of relativity used Doppler tracking to improve the parameterized post-Newtonian formalism (Bertotti et al. 2003).

Gravitational fields are used in combination with shape models or detailed topography to constrain the interior structure of the planets and other objects in the Solar System. One of the most recent and notable examples of measuring gravity fields is the ultra-high-resolution gravity field of the Moon produced by the GRAIL team (Figure 1.5). This mission has provided an unprecedented view into the interior of the Moon, with a spherical harmonic degree/order-1500 (or higher) field (equivalent to a spatial resolution of a few km), utilizing spacecraft-to-spacecraft links supplemented by links to the DSN (Zuber et al. 2013b; Konopliv et al. 2014b). GRAIL is based on the techniques developed by the GRACE Earth mission (Watkins et al. 1995) and has led to tremendous gain in our knowledge of the Earth's time-varying gravity and the water cycle.

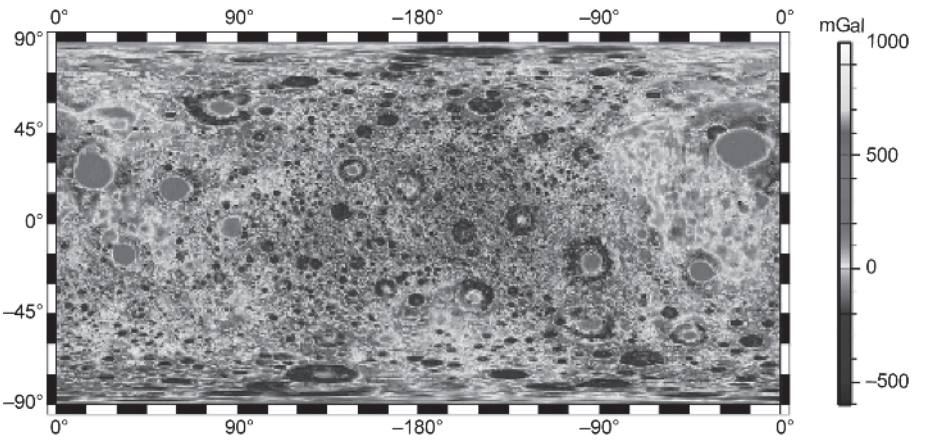

Figure 1.5 Example of significant results of gravity experiments showing a map of the gravitational field of the Moon from the GRAIL mission utilizing crosslinks and links to the DSN. Surface acceleration resolution is better than 1° and on the order of 1500 degree and order in spherical harmonic expansion (based on Konopliv et al. 2014a); see Chapter 3. (Note: mGal is 0.001 Galileo, which is 1 cm^2/s).

In general, the gravity fields of terrestrial planets have been measured to high spatial resolution, while the gravity fields of the gas giants and large moons of the outer Solar System have been measured to low resolution. This is because the resolution of the gravity field is determined by the proximity to the target, duration of measurements, and the overall noise/error budget (see Chapter 3). All the inner planets have been investigated by orbiters at relatively lower altitudes and for extended periods.

Folkner et al. (1997b) pioneered the measurement of planetary precession using the Mars Pathfinder lander. This experiment was also carried out by the InSight mission (Banerdt et al. 2020) and planned for the ExoMars lander mission. Konopliv et al. (2016, 2011) demonstrated that a combination of lander and orbiter data improves the knowledge of the precession; see also Dehant et al. (1993) for an analytical approach. Kuchynka et al. (2014) demonstrated Mars precession measurement obtained from orbiter data only. Derivations of planetary shape models from RO data are discussed in Cain et al. (1972) and Asmar et al. (1999).

RS experiments on atmospheric probes included Doppler wind experiments and other investigations on Venera (Kerzhanovich et al. 1972), Pioneer Venus Probe (Counselman et al. 1980), Venus Balloons (Preston et al. 1986), Galileo Probe (Atkinson et al. 1997), and Huygens (Bird et al. 2005). Rosenblatt et al. (2012) carried out the first in-situ observations of Venus' polar upper atmosphere density using the tracking data of the Venus Express Atmospheric Drag Experiment.

RS investigation of planetary magnetic fields by observing the Faraday rotation was planned to study the Jovian magnetic field with the Galileo mission (Howard et al. 1992) but was not carried out due to an anomaly with the spacecraft HGA. Investigations of the magnetic field in the solar corona via Faraday rotation have been carried out by several teams (Levy et al. 1969; Stelzried et al. 1970; Pätzold et al. 1987; Bird and Edenhofer 1990). Hinson (1984) discuss dual-wavelength radio observations during the occultations of Voyagers 1 and 2 and how they provided data on Saturn's ionospheric irregularities and how magnetic field orientations in Saturn's ionosphere were inferred from the direction of alignment of the anisotropic irregularities.

The use of precision Doppler tracking to model the gravitational fields of planets and moons using techniques described in Chapter 3 was pioneered by investigators that included Bill Sjogren, Dave Smith, Georges Balmino, John Anderson, and many others. One of the earliest historical discoveries was the lunar subsurface mass concentrations, called "mascons" (Müller and Sjogren 1968; Sjogren et al. 1972). Mathematical formulations for gravity research as well as spacecraft navigation applications are described in Moyer (2003).

1.4 Overview of the Radio Science Instrumentation System

Table 1.3 lists the majority of Solar System exploration missions that have carried out RS experiments. A scientific payload for a space mission is selected in a process that starts with the space agency soliciting the community for instruments that meet stated scientific objectives. The instruments are typically self-contained units accommodated onboard the spacecraft (e.g., imager, spectrometer, magnetometer, or altimeter).

Table 1.3 Selected Solar System missions with radio science experiments.

Target	Mission	Experiment
Sun	Helios	SC, FR
	Ulysses	SC, FR, REL
	Other solar missions include Pioneer 5–9, Proba2, SOHO, WIND, ACE, DSCOVR, STEREO, Parker Solar Probe, ESA Solar Orbiter (*planned*), and Aditya (*planned*)	
	Solar conjunctions of Magellan, Galileo, Cassini, and other planetary missions	SC, FR, REL
Mercury	Mariner 10	GRV, SHP
	MESSENGER	GRV, SHP
	Planned: BepiColombo	*GRV, REL, SC*
Venus	Mariner 2	GRV
	Mariner 5	RO
	Mariner 10	RO, GRV
	Venera 4–16	RO (Venera 4)
	Pioneer Venus 1 Orbiter	RO
	Pioneer Venus 2 Probes	DWE, Interferometry
	VEGA 1, 2 Balloons	DWE, Interferometry
	VEGA 1, 2 Landers	DWE
	Magellan	GRV, RO, solar FR
	Venus Express	RO, GRV, BSR
	Completed flybys by many planetary missions	Doppler Tracking
	Planned flybys by BepiColombo, Solar Orbiter	Doppler Tracking
Earth	GRACE and GRACE FO	GRV
	GPS-COSMIC	RO
	GPS-Mir	RO, radio holography
	Flybys by many planetary missions	Doppler Tracking
Moon	*Many historical missions*	
	Pioneer 7	RO (ionosphere)
	Luna series	GRV, RO
	Apollo series	GRV, interferometry
	Clementine	BSR, GRV
	SMART 1	Libration demo, RO
	Lunar prospector	GRV, SHP
	SELENE (Kaguya)	GRV, RO
	GRAIL	GRV
	LRO	GRV, BSR, LR
	Hiten	Doppler Tracking
	LADEE	LASER, radio tracking
	Chang'E 3	Rotational dynamics
	Chandrayaan-1	RO
	Chandrayaan-2 (orbiter)	RO (planned)
	New horizons	RO

(*Continued*)

Table 1.3 (Continued)

Target	Mission	Experiment
	Many planned missions	
Mars	Mariner 4, 6, 7, 9	RO
	Mars 2, 4, 6	RO
	Mars 3	GRV
	Viking 1, 2 Orbiters	
	Mars Global Surveyor	RO, GRV, BSR
	Others include: Pathfinder- Sojourner (*rover*), Phoenix (*lander*), MSL-Curiosity (*rover*), Mars Orbiter Mission, Trace Gas Orbiter	
	Spirit, Opportunity (*entry probe/lander*)	Geodesy
	Mars Express	RO, GRV, BSR
	Mars Odyssey	GRV
	Mars Reconnaissance Orbiter	RO, GRV
	MAVEN	RO
	InSight	Geodesy
	Planned: ExoMars 2020	Geodesy
	Planned: Mars 2020, Hope, MOM-2, MMX	
Jupiter	Pioneer 10, 11	
	Voyager 1, 2	RO, GRV
	Galileo Orbiter	RO, GRV
	Galileo Probe	DWE
	Juno	GRV
	Flybys by: Ulysses, New Horizons, Cassini, etc.	
Saturn	Pioneer 11	
	Voyager 1, 2	RO, GRV
	Cassini	RO, GR, BSR, REL
	Huygens Titan Probe (*lander*)	DWE
Uranus	Voyager 2	RO, GRV
Neptune	Voyager 2	RO, GRV
Pluto	New Horizons	RO, GRV, BSR
Comets	Giotto	Doppler Tracking
	Rosetta	GRV, BSR
Asteroids	Dawn	GRV, BSR, SHP
	Hayabusa 1	Doppler Tracking
	Hayabusa 2	GRV
	NEAR	GRV
	OSIRIS-Rex	Doppler Tracking
	Planned: Psyche	GRV

Acronyms for Table 1.3

Missions	
• ACE: Advanced composition explorer	• MSL: Mars science laboratory
• COSMIC: Constellation observing system for meteorology ionosphere and climate	• Proba: PRoject for Onboard Autonomy
• DSCOVR: Deep space climate observatory	• SMART: Small missions for advanced research in technology
• GRACE FO: Gravity recovery and climate experiment follow-on	• SOHO: Solar and heliospheric observatory
• LRO: Lunar reconnaissance orbiter	• STEREO: Solar TErrestrial RElations Observatory
• MMX: Martian moons exploration	• VEGA: A contraction of Venera and Gallei, the Russian words for Venus and Halley
• MOM: Mars orbiting mission	• WIND: Solar Wind Laboratory
Experiments	
• DWE: Doppler wind experiment	• RO: Radio occultations
• FR: Faraday rotation	• SC: Solar corona
• GRV: Gravity	• SHP: Shape modeling
• REL: Relativity	• BSR: Bistatic radar

Radio scientists typically propose investigations that utilize instrumentation distributed between the spacecraft and ground stations centered on the mission's radio communications and navigation capabilities, as shown in Figures 1.6 and 1.7. Since the performance of the entire distributed instrument affects the quality of the scientific outcome, proper planning, implementation, maintenance, and calibration of each element are required. Calibration can encompass advanced techniques such as multiple radio links, water vapor radiometers, accelerometers, noise-temperature measurements, etc. The limits of experiment sensitivity are based on orbital and geometric considerations, frequency/phase stability of the link, its SNR, amplitude stability, spectral purity, calibration of nongravitational forces, calibration of the intervening media, and accuracy of the trajectory reconstruction.

A key concept to understanding the RS system and properly interpreting the data is the spacecraft transmitter mode. There are three common modes for the spacecraft transmitter operations, one-way, two-way, or three-way as detailed and illustrated in Chapter 5, which also describes other exotic modes and new technologies.

In the one-way mode, the spacecraft transmits a signal generated by an onboard oscillator that is part of its telecommunications subsystem—no uplink from the ground station required. There are two types of spacecraft oscillators; one that is built into every transponder and called the auxiliary oscillator and one that is an optionally added stand-alone instrument with an input line to the transponder called the ultra-stable oscillator (USO).

In the two-way mode, the station transmits a signal to the spacecraft, which receives it and transmits it back to the same station. This step is called coherently "transponding" the signal. The onboard auxiliary oscillator or USO are not involved.

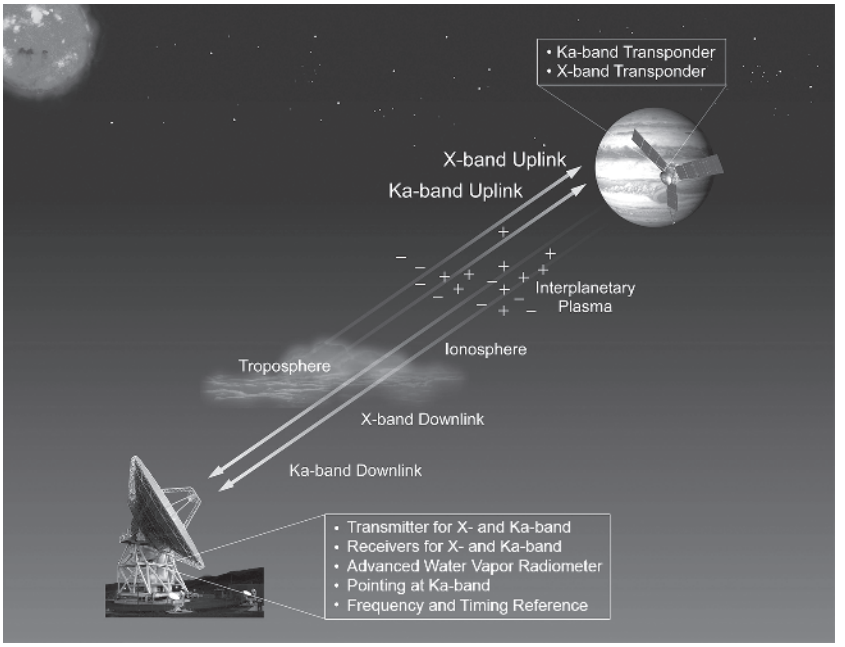

Figure 1.6 Illustration of the Juno spacecraft and a DSN station operating jointly as a gravity science instrument spanning a fraction of the size of the Solar System. The investigation partially calibrates dispersive media via the use of two wavelengths simultaneously and calibrates the Earth's tropospheric effects via an advanced water vapor radiometer. Signals at X- and Ka-bands are simultaneously transmitted from the DSN station to the spacecraft and transponded back to the station. Differencing the two signals isolates the effects of the charged particles. Finally, using a water vapor radiometer, shown adjacent to the station, measures the path delay in the troposphere.

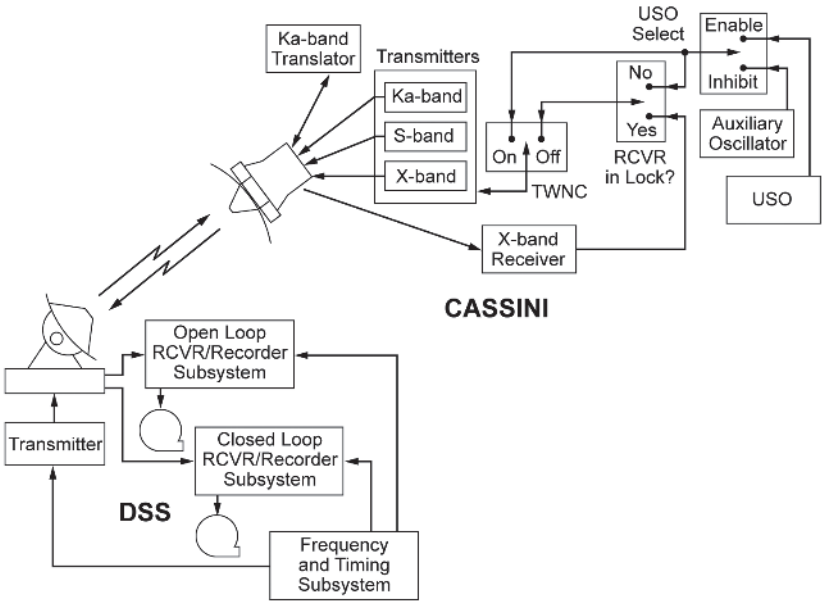

Figure 1.7 Conceptualized primary components of ground and flight communications and RS systems using a deep space station (DSS) and the Cassini mission, which had a radio system with links at three wavelengths (S-, X-, and Ka-bands).

The three-way mode is the same as the two-way mode, except that the station that transmits the uplink to the spacecraft is different from the station that receives the downlink from the spacecraft. This occurs when the round-trip light time travel to a distant spacecraft is longer than the view period of the transmitting station; after the transmission, the Earth has rotated enough such the station is not in view of the spacecraft and another station on a different continent has risen in view. The three-way mode can also occur if two stations at the same location are simultaneously supporting the same spacecraft; only one station can transmit to the spacecraft and this statin receives the returned signal in a two-way mode while the second station receives the same signal at the same time in a three-way mode.

Planning the tracking mode of operations is critically important to RS experiments because this determines the type of clock or oscillator that generates the reference signal. The auxiliary oscillator is the least stable oscillator of the options described above and is not typically useful for RS experiments. The USO can be two or more orders of magnitude more stable and is the preferred reference for occultation experiments. Two-way and three-way signal are referenced to an atomic clock at the ground station, called a hydrogen maser, which is about two orders of magnitude more stable than the USO and is preferred for gravity experiments, as explained more below and detailed in Chapter 5.

1.4.1 Flight System

Elements of the flight system enable RS experiments and affect their ultimate quality. At the heart of the system is the telecommunications subsystem, also known as the Telemetry, Tracking, and Command (TT&C) subsystem, which includes the antennas, transponders, and power amplifiers. There is typically one HGA on a planetary mission, several low-gain antennas (LGAs), and sometimes a medium-gain antenna (MGA). There are also redundant and highly reliable transponders that carry out the reception, transmission, modulation, demodulation, and tracking functions.

Additional transponders or translators (a designation given to transponders without modulation capabilities) can be incorporated in the flight system for RS experiments and handled as science payload elements. For example, as shown in Figure 1.7, the Cassini mission primary link for telecommunications, navigation, and RS is the X-band link supported by two redundant sets of transponders and power amplifiers. RS experiments can also require links at S- and Ka-bands (e.g., Cassini, which carried additional non-redundant radios).

Similarly, for the case of the Juno mission configuration, a separate Ka-band translator augments the X-band transponder in order to enhance the Jovian gravity experiments. Figure 1.6 shows the end-to-end Juno RS instrumentation and how the added Ka-band link enables the calibration of the ionosphere and interplanetary plasma. Tropospheric effects are calibrated via an advanced water vapor radiometer at one DSN station, DSS-25, at Goldstone, California.

The first flight instrument devised and flown specifically for RS enhancement was the USO, called the “single most dramatic improvement in radiometric performance” by G. L. Tyler (1987). A clock and frequency reference, the USO was developed for atmospheric occultation experiments starting with the Voyager mission in order to provide a stable reference to the transponder as it transmits a one-way downlink signal to Earth.

This configuration provides two advantages over carrying out the experiments in the two-way mode. The first advantage is eliminating the double propagation by the uplink and downlink signals in the planetary medium under study, such as atmospheric or ring material, which make the data interpretation more challenging. The second advantage is eliminating the delay due to the time needed by the transponder to lock-up on the uplink signal when the spacecraft is emerging from behind the occulting medium. Although the lock-up time is short (under a minute), for a thin atmosphere like that of Mars, this delay can be comparable to the length of the observation and cause the loss of the egress experiment at the lower atmospheric region.

Based on a thermally controlled quartz crystal, a modern USO model can reach a stability of ~10^{-13} Allan deviation (a measure of clock stability) at integration times between 10 and 100 s. After Voyager, USOs have flown on Galileo and Cassini as well as orbiters at Mars, Venus, and the Moon, and many other planetary and Earth missions listed in Asmar (2012b). In-situ probes, such as the Galileo probe, used a crystal-based USO while the Huygens Titan probe utilized a rubidium-based USO for the faster warm-up time required on short-duration missions.

Other spacecraft elements that can directly impact the quality of RS experiments include the attitude control subsystem, which controls the antenna pointing and overall stability of the spacecraft motion. Non-optimum pointing or attitude jitter can degrade the science experiments, so investigators place strict performance specifications on this subsystem. The attitude control subsystem is also required for special and sometimes complex limb-track maneuvers that optimize RO experiment performance by dynamically pointing the spacecraft HGA toward the limb of the target planet. As discussed in Chapter 5, investigators also account for numerous additional details in dynamical and kinematic nongravitational error sources including the optical properties of the spacecraft surfaces, uncertainties in the location of the center of mass, etc.

1.4.2 Ground System

The DSN includes 70- and 34-m diameter stations located at three continents with capabilities for transmission and reception at various frequency bands allocated by international agreement (see development history in Mudgway 2001). The bands in current usage are S, X, and Ka, corresponding to the wavelengths shown in Table 1.4. The frequencies of the transmitted uplink signals, also known as forward links, are related to the frequencies of the received downlink signals, also known as return links, by multiplicative factors called the turn-around ratios in order to prevent interference between them and keep coherency throughout the complete uplink/downlink chain.

The most common deep space communication band for contemporary missions is X-band, available throughout the DSN and partner networks. Use of Ka-band is increasing. Uplink at Ka-band is currently available at one DSN station (DSS-25 at Goldstone) for RS purposes, with plans for additions at the other complexes, while reception at Ka-band is available throughout the network. S-band capabilities are of lesser usage for planetary missions (deep-space band) but increasing usage for lunar missions (near-Earth band). The DSN is preparing for future optical links as this technology advances and gets demonstrated on future planetary missions.

1.4.2.1 Types of Receivers

The type of receiver at the ground station is a key factor in planning and interpreting RS experiments and data. Reception of the radio signal at the ground stations is

Table 1.4 Band names, wavelengths, and frequencies for links used for deep space, near-Earth, and proximity links relevant to RS and potential RS investigations.

(A) Deep space links (DSN, Telecommunications Link Design Handbook 810-005 Module 201)

Band	Wavelength (cm)	Uplink (forward) frequency range (MHz)	Downlink (return) frequency range (MHz)	Transponder ratio (downlink/uplink)
S	~13	2110–2120	2290–2300	240/221
X	~3.6	7145–7190	8400–8450	880/749 S–X: 880/221 X–S: 240/749
Ka	~0.9	34,200–34,700	31,800–32,300	14/15 (Cassini) 3360/3599 (Standard) X–Ka: 3360/749

(B) Near-earth links (for spacecraft less than 2 million km from Earth)

Band	Uplink (forward) frequency range (MHz)	Downlink (return) frequency range (MHz)
S	2025–2110	2200–2290
X	7190–7235	8450–8500
K	22,550-23,150	25,500–27,000

(C) Relay/Proximity ultra high frequency (UHF) links

Band	Wavelength (cm)	Forward link (MHz)	Return link (MHz)
Before Electra payload	~75	437.1	401.58
Electra (tunable full duplex)	~75	435–450	390–405

Notes
- Ka-band standard ratio is used for Juno, BepiColombo, and JUICE.
- Electra provides mode for 2-way Doppler coherency.
- Ka-band links for near-Earth missions are called K-band links in DSN documents.

accomplished via two methods. The first is the common closed-loop reception and tracking, in which a phased-locked loop receiver captures the residual carrier signal and precisely measures its phase in a preselected loop bandwidth to track the signal dynamics. Telemetry demodulation can then be performed. Navigation and RS teams use the precise Doppler and range information available in real-time from this type of receiver. However, this receiver has minimum thresholds on signal level and dynamics beyond which it can drop lock.

The second method is open-loop reception in which the receiver has no lock or tracking function. Instead, the OLR, also known as the *Radio Science Receiver* (RSR),

down-converts the signal via an oscillator driven by a prediction file based on the expected Doppler profile. It captures the pre-detection signal in a selected bandwidth and sends raw digital complex samples of voltages to the users (such data are ultimately made available to the science community via NASA's Planetary Data System (PDS), as explained in Section 1.6). Users employ their own software to detect the signal from the RSR file and recover the frequency transmitted by the spacecraft for further analysis. For RS experiments, the advantages of the open loop reception method are detailed in Chapter 5 and include capturing the signal during conditions of low SNR, capturing the signal during conditions of high signal dynamics in amplitude or frequency, capturing multipath signal conditions, and preserving the information in the entire spectrum.

1.4.3 Other Ground Stations

The European Space Agency (ESA) currently operates three 35-m diameter stations for deep space tracking known as the European Space Tracking (ESTRACK) network. They are located in New Norcia (Australia), Cebreros (Spain), and Malargüe (Argentina). The ESA stations often support NASA missions and the DSN often supports ESA missions within the framework of a cross-support agreement. ESA plans to expand its development of RS-specific services in the future. Japan, India, S. Korea, Russia, and China also have deep space tracking stations, and additional nations are planning to develop them.

Sensitive radio astronomy observatories are sometimes used for RS or mission-support signal reception when they possess unique advantages over the DSN such as the ability to receive in the UHF band. Planetary missions have benefited from RS collaborations with support of the Green Bank Telescope in West Virginia, Allen Telescope Array in California, Kashima in Japan, Noto in Italy, Parkes in Australia, and Narrabri in Australia. There is potential for collaboration with the Effelsberg Radio Telescope in Germany, the Sardinia Deep Space Antenna (also known as the Sardinia Radio Telescope) in Italy, and the Giant Metrewave Radio Telescope in India.

For RS purposes, the stations of other agencies and radio telescopes have been used to enhance DSN services. For example, an attempt was made to array a DSN station with the Usuda station in Japan for the Voyager Neptune encounter RO (Mizuno et al. 1992).

1.5 Noise, Error Sources, and Calibrations

The success of RS experiments relies on the thorough understanding, modeling, and calibration of error sources RS is the art of the error budget. These have been carefully studied and published for various experiments and are cited in later chapters. Using the Cassini mission as an example, Asmar et al. (2005b) detail the noise budget and achievable accuracy for precision Doppler tracking. The most sensitive achieved fractional frequency fluctuation noise was ~3×10^{-15} at 1000 s integration time, corresponding to better than the outstandingly small 1 μm (micrometer) per second velocity error, in a noise model of fluctuations in the spectral range ~10^{-3}–1 Hz.

In addition to systematic errors, other error sources are due to instrumental or propagation noise. The former are random errors introduced by ground or spacecraft systems and include phase fluctuations associated with finite SNR on the radio links, ground and spacecraft electronics noise, unmodeled bulk motion of the spacecraft or ground station, noise limits of the frequency reference, and antenna mechanical noise. Propagation noise consists of the random frequency/phase fluctuations caused by refractive index fluctuations along the line of sight and is caused by phase scintillation as the radio wave passes through the troposphere, ionosphere, and the interplanetary plasma (Armstrong and Woo 1981, Woo and Armstrong, 1992a, 1992b); see Figures 1.6–1.8.

The free electrons in Earth's ionospheric plasma give rise to both amplitude and phase scintillation. Variations in the Earth's neutral atmosphere, particularly variations in the water vapor content of the troposphere, cause a path delay in addition to amplitude variations. Some of these changes can be calibrated using existing and widely available technologies and models, but the unmodeled components of these distortions can limit the precision of RS measurements. In order to calibrate these effects, two technologies, multi-link systems and water vapor radiometers, have been developed and successfully utilized for the Cassini and Juno precision gravity measurements; variations are utilized for the BepiColombo mission and planned for the JUICE and VERITAS missions.

Calibration of the effect of charged particles is possible through the simultaneous use of two or more radio links at different frequencies. Plasma phase scintillation is dispersive; the refractivity depends on the wavelength and can be isolated with a multi-link system. After correction for the plasma phase scintillation, any remaining phase variation can be attributed to non-dispersive effects. Advanced water vapor radiometers determine the total water vapor content along a LOS by making measurements of the strength of microwave emissions from water molecules in the troposphere. By co-pointing the radiometer with the antenna tracking of a spacecraft, the signal delay is measured in the same path. Investigations that require a precision better than the perturbation of the troposphere on the signal would require this RS instrument, especially at Ka-band links which are less susceptible to charged particles, consequently making the tropospheric effect more pronounced.

For planning future experiments, the quality of RS observations is critically dependent on the relative angular elongation of the Sun (see Figure 3.2 in Chapter 3). Figure 1.8 shows the power spectral density of one-way plasma phase scintillation versus Sun–Earth–spacecraft angle (circles for S-band and crosses for X-band) as well as an approximate level of uncalibrated tropospheric scintillation noise and limits to antenna mechanical noise. Figure 1.9 shows actual data quality as Doppler noise in units of velocity, as a function of the Sun–Earth–Mars angle for three Mars orbiters; it explains the preference for conducting RS experiments at X-band at angles higher than 30°.

The challenge to achieve the required performances is illustrated in Asmar et al. (2013d), which provides quantification of errors for precision Doppler in spacecraft-to-spacecraft links. The integrated scientific measurement system of the GRAIL mission comprises flight, ground, mission, and data system elements. Early modeling and simulation efforts influenced and optimized the design as well as the implementation and testing of each element. Errors are grouped into either dynamic or kinematic sources; the former are forces acting on the spacecraft and perturb their orbit or motion, and the latter are local effects such as thermal variations. Dynamic nongravitational accelerations are due to solar radiation pressure, spacecraft thermal radiation (largest dynamic error), lunar albedo and lunar thermal emission, and acceleration due to unmodeled forces.

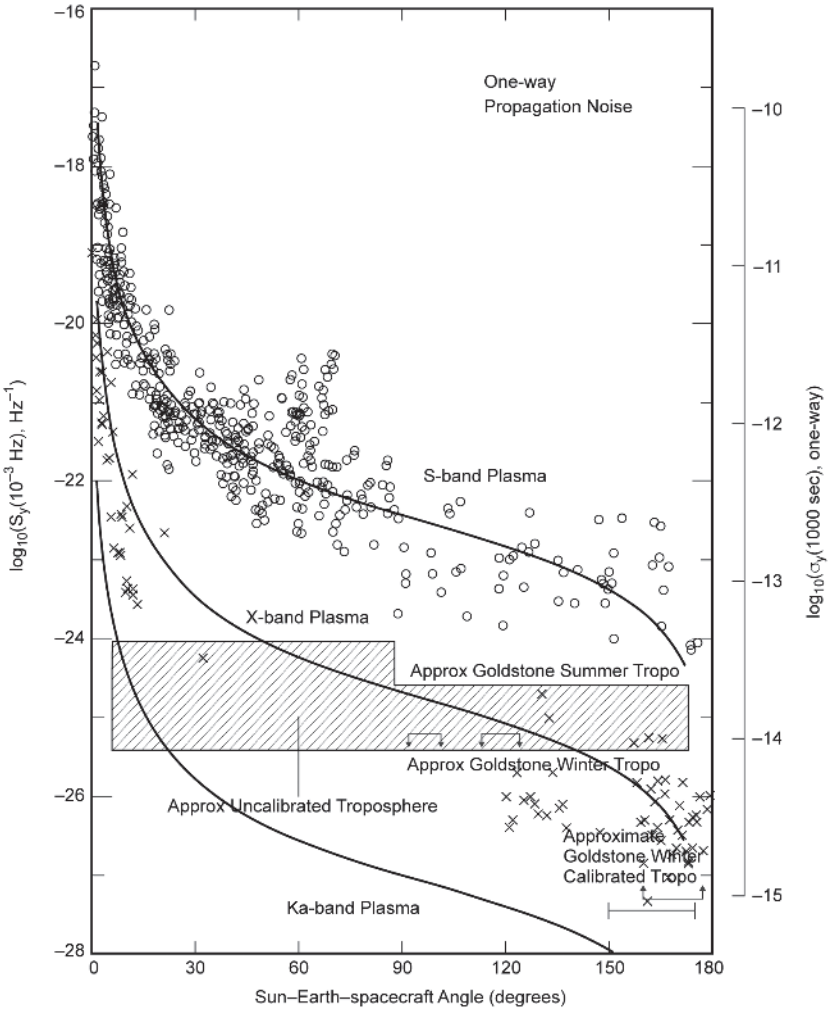

Figure 1.8 Power spectral density of one-way plasma phase scintillation at $f = 0.001$ Hz versus Sun–Earth–spacecraft angle (circles for S band and crosses for X band), approximate level of uncalibrated tropospheric scintillation noise (diagonal-lined area), and limits to antenna mechanical noise (area fenced in by dashed lines). The right-hand scale is the equivalent Allan deviation at 1000 s integration time, assuming a Kolmogorov spectral shape (by J. W. Armstrong in Asmar et al. 2005a).

Kinematic errors directly affect the inter-spacecraft range-rate measurement and spacecraft-to-DSN Doppler observables. Most of the kinematic corrections are estimated as local parameters affecting the data arcs (such as payload bias, drift, and cosine and sine once per revolution estimated amplitudes)—see Chapter 3 for a description of the estimation methodology. The latter result from the spacecraft going between sunlight and shade and the thermal consequences on the spacecraft surfaces. These errors include timing offsets, USO drift in the relevant spectrum, spacecraft attitude jitter, and offset of the phase center from the line connecting the center-of-mass from each spacecraft, which are minimized by actively pointing the spacecraft to align the phase centers. Changes in the temperature of the payload antenna and related hardware are

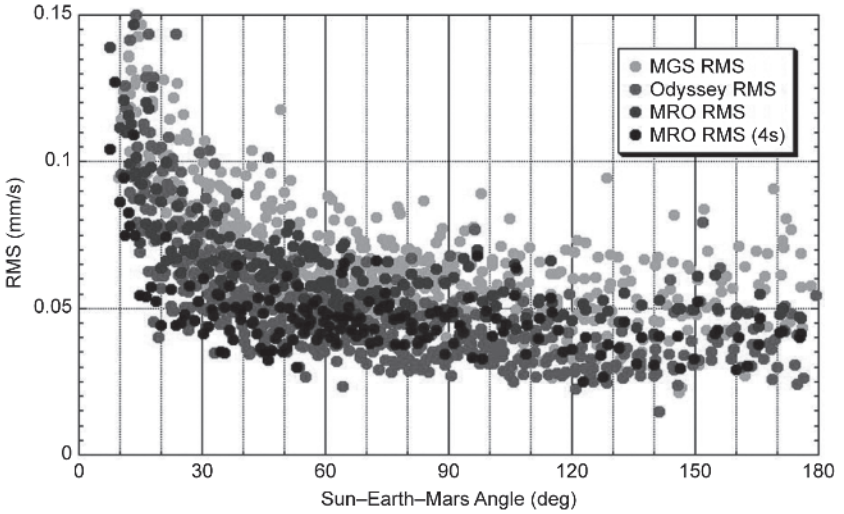

Figure 1.9 Example of the quality of the Doppler observable in terms of the root mean square (RMS) Doppler noise in units of velocity as a function of the Sun–Earth–Mars angle for three Mars orbiters (reproduced from Konopliv et al. 2011b) shows significant degradation at angles of less than 30° at X-band. As shown in Figure 1.8, the noise would be larger at S-band and smaller at Ka-band. MGS is the Mars Global Surveyor and MRO is the Mars Reconnaissance Orbiter.

modeled as a systematic trend in the observables. Amplitudes of the sinusoidal once and twice per orbit signatures depend on the Sun angle. Errors due to sloshing of the fuel in the spacecraft fuel tank are negligible for this particular design.

1.6 Experiment Implementation, Data Archiving, and Critical Mission Support

RS experiments are implemented through a rigorous system engineering process. Science objectives are used to develop the observational design used to allocate resources to instrument components. The need to ensure high confidence in data acquisition is especially crucial when observations represent very rare opportunities such as the Voyager flybys of the Outer Planets or the New Horizon mission to Pluto.

In addition to expertise at academic institutions and other research centers, project-supported teams at JPL function as the focal points of RS experiment implementation. They participate in the planning and design to ensure that spacecraft and ground elements are configured to perform to the required specifications. They perform engineering studies and trade-off analysis, simulations, and coordinate the work of several technical organizations supporting the experiments, as well as participate in mission sequence planning and reviews. The DSN allows trained JPL specialists to remotely configure the RSRs in the network for data acquisition. The acquired science data are validated, calibrated, and delivered along with ancillary information and documentation to science teams as well as archived with NASA's PDS.

Asmar et al. (2014b) describe the PDS data products in detail for the Cassini mission as an example. For each RS experiment, the following types of files are available:

- Science observables files that include tracking and navigation files (TNF).
- Radio science receiver (RSR, also known as OLR) files.
- Calibration and ancillary information that includes Earth orientation parameters (EOP).
- Media calibration troposphere (TRO and ionosphere (ION) data.
- (Advanced) water vapor radiometer (WVR/AWVR) data.
- DSN monitor data.
- Spacecraft engineering telemetry (TLM).
- Spacecraft and planetary kernel (SPK) or orbit ephemeris message (OEM).
- Spacecraft orientation C-kernel (CKF).

The tools, techniques, and expertise developed for RS have proven to be very useful for supporting deep space missions' special applications beyond scientific observations. They are especially suited for searching for or characterizing spacecraft in distress or monitoring the radio signals during critical maneuvers where knowledge of the state of the spacecraft might be uncertain due to high dynamics in signal amplitude or frequency, or due to very low SNR. Under such conditions, the DSN's closed-loop tracking receiver might not achieve or maintain a lock on the signal carrier. The RSR/OLR captures the radio signal's spectrum in the selected recording bandwidth and enables users to apply signal detection algorithms after the event and optimized for the specific signal conditions.

Asmar (2012a) describes the cases of orbit insertion maneuvers and entry, descent, and landing (EDL), a highly critical mission period when regular communication is typically challenging. RS specialists have been able to detect and report in near real-time the successful landing of all Mars landed missions from the Mars Pathfinder, which introduced the concept of communicating by semaphores from deep space (Wood et al. 1997), to Curiosity, as well as the Huygens probe landing on Titan. The information is derived from a Doppler profile, not telemetry, where detection of the carrier signal frequency shift reveals the dynamics such as acceleration or deceleration due to events such as parachute deployment and engine firing. Figures 1.10 and 1.11 show representative events described in Asmar (2012a).

1.7 Radio Science at Home

As noted above, radio signals of known properties were used in the 1950s to study Earth's ionosphere via scattering of radio waves. This led to the creation of the field of RS for studying Earth's environment using radio waves. Since then, there has been a strong link between planetary science and Earth science in this field. GPS RO of Earth's atmosphere has become a very advanced field with crosslink applications to science, as well as weather applications, as an aid in aviation safety, and in supporting the detection and monitoring of volcanic clouds.

For example, Kantha et al. (2013) describe how the Constellation Observing System for Meteorology, Ionosphere, and Climate (COSMIC) project has proven the utility of RO in the extraction of temperature profiles in the global atmosphere for numerical weather forecasting applications, as well as to the extraction of information on the location and intensity of turbulence in the global atmosphere. Such information is of considerable importance to aviation safety. Biondi et al. (2017) reported on studies of the altitude of volcanic clouds and the atmospheric thermal structure after volcanic

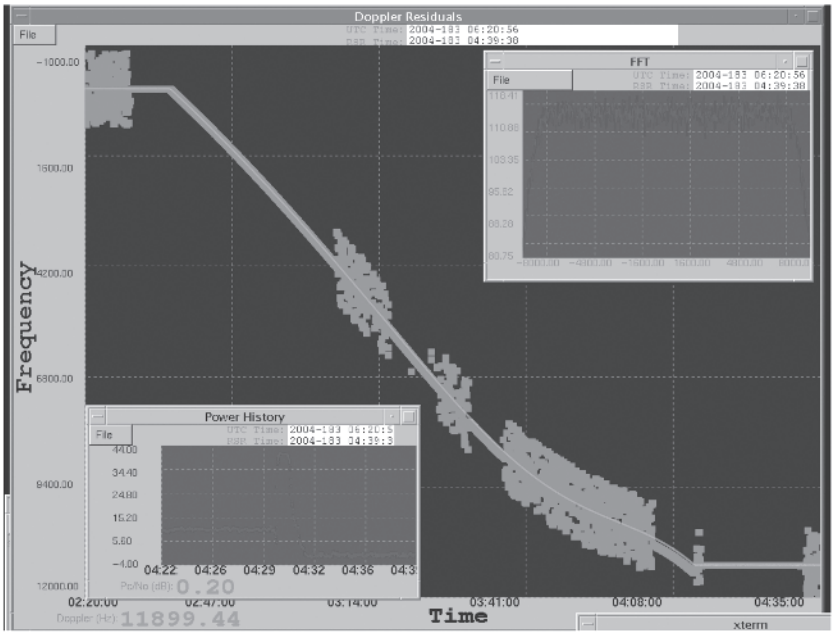

Figure 1.10 Image of the frequency profile as a function of Earth-received time (ERT) of the X-band radio signal received by the DSN from the Cassini spacecraft during the critical Saturn orbit insertion maneuver. During this maneuver, the HGA was pointed in the direction of spacecraft travel to shield the spacecraft from ring particles, and a rear LGA was used for communications, but the LGA link margin was insufficient to receive telemetry. The RSR was utilized to receive the Doppler-shifted carrier signal frequency and display it in real-time in red over a predicted model in yellow. Thick portions indicate occultation by ring material. The lower inset shows the signal's power history, and the upper inset shows a Fourier spectrum at an instant in time (Asmar 2012a).

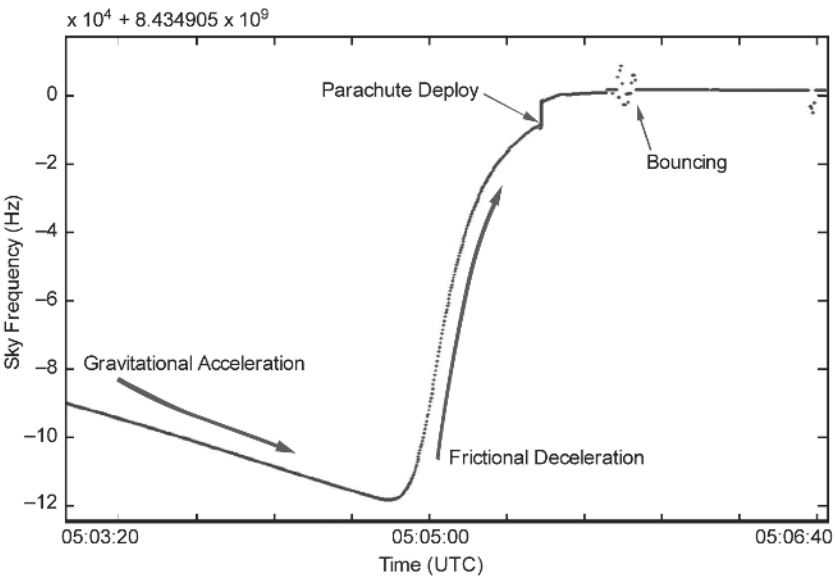

Figure 1.11 Signal observations of the Opportunity Mars rover EDL critical event sequence as captured in the DSN's Radio Science Receiver. The Doppler shift shows dynamical events of the spacecraft (Asmar 2012a).

eruptions using RO profiles colocated with independent radiometer images of ash and sulfur dioxide plumes.

The high resolution of Earth's gravitational field data from the GRACE mission RS crosslink technique has contributed to monitoring important climate issues, such as water storage depletion in Texas (Long et al. 2013), Western and Central Europe (Li et al. 2012), Southwest China (Long et al. 2014), and East Africa (Swenson and Wahr 2009).

1.8 Future Directions

All spacecraft will continue to have telecommunication links, and utilizing these links as tools for high-value science will further enhance the missions. The outlook for future directions in RS investigations and techniques for deep space exploration is described in Chapter 6. The field will continue to thrive as innovations advance in science, engineering, technology, instrumentation, methods, algorithms, mission design, and experiment operations. Furthermore, future observations will benefit from the infusion of new technologies expressly developed to enhance this field of science, or for innovative telecommunications or navigation purposes not yet fully utilized for RS applications.

Future scientific breakthroughs are anticipated in the area of icy world exploration. Europa, Ganymede, and other bodies in the outer Solar System will host dedicated missions which are currently in the development phase. These missions will apply RS techniques proven by the Galileo and Cassini missions to explore the interior structures and detect subsurface liquid layers, as in the cases of Titan and Enceladus. The BepiColombo mission will further explore tests of the theories of general relativity during a long cruise period of numerous solar conjunction periods.

Opportunities for innovations are accelerating as new concepts have been advanced in the area of atmospheric occultations. For example, the traditional one-way downlink from a spacecraft to a ground station can be supplemented or replaced by uplink occultations or spacecraft-to-spacecraft links, for the advantages explained in Chapter 6, as illustrated in Figure 1.12. Similar concepts apply to gravity field measurements and surface scattering research. Special emphasis should also be given to the study of the transportation of momentum in planetary atmospheres, leading to effects such as the atmospheric super-rotation at Venus. Furthermore, Figure 1.13 (also see cover graphic) illustrates an innovation that is likely to significantly alter this field in the future, namely, less costly small spacecraft with capable radio systems that can take additional risks to obtain high-value science. The example in the figure shows the first planetary CubeSat mission, Mars Cube One (MarCO), that accomplished its primary mission in 2018 (Asmar and Matousek 2016). As explained in Chapter 6, this is likely to serve as a baseline of a small spacecraft design for future planetary missions that can carry out RS experiments that advance the field by providing distinct features.

1.9 Summary and Remaining Chapters

This chapter provided a broad overview of the science and technologies that make up the multi-disciplinary field of RS. Scientists investigate radio links between transmitting and receiving radios that can be altered in their characteristics due to

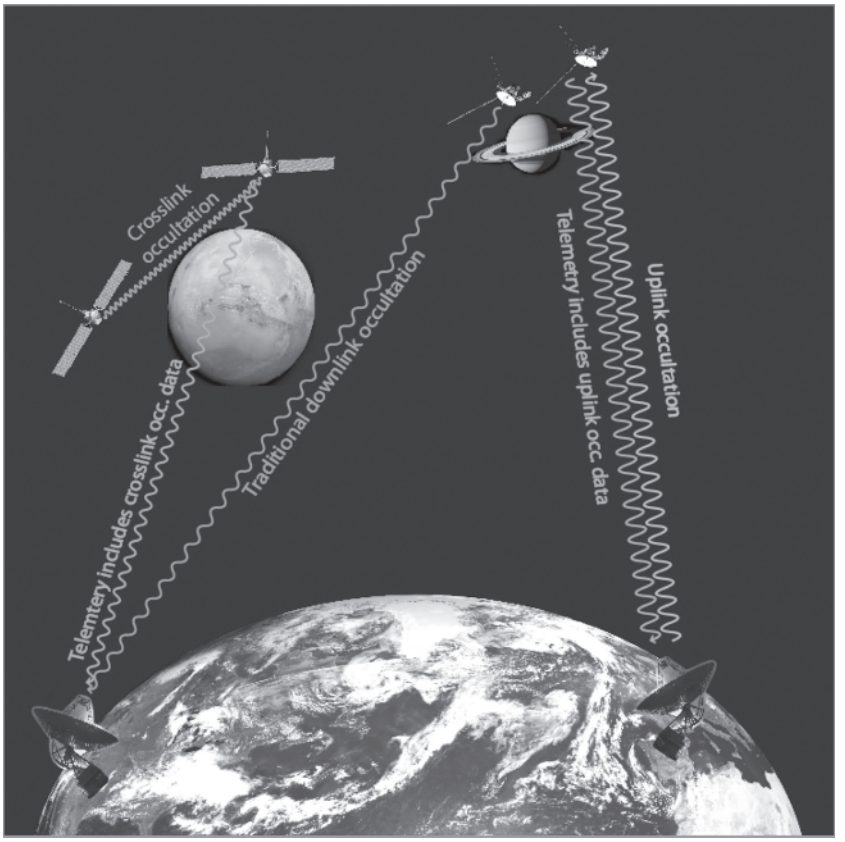

Figure 1.12 An artist's conception of uplink, crosslink, and downlink radio science experimental configurations. On the right side, an uplink signal is occulted by planetary rings and acquired on the spacecraft. The data packets containing the occultation science are then transmitted from the spacecraft to the ground station as telemetry files. The middle link illustrates a traditional one-way downlink occultation experiment where the signal is occulted by the rings prior to arrival at the ground station. On the left side, two spacecraft carry out crosslink occultation and then transmit the data packets to station as telemetry.

propagation effects caused by intervening media or scattering surfaces, or due to the additional relative motion caused by the mass and density distribution of the planets or moons, among other effects. The fundamental scientific observables include the time profiles of the amplitude, frequency, phase, and polarization of the received signals. From these, planetary interiors, atmospheres, rings, and surfaces are investigated along with explorations of the Sun and aspects of fundamental physics.

Readers were familiarized with the concepts of ROs, atmospheric profiles, precision Doppler, gravitational fields, studies of planetary rings, wind and surfaces, signal carrier characterization, effects of the interplanetary plasma, utility of USOs and OLRs, the DSN, and the link configurations known as one- and two-way modes as well as error budgets and calibration techniques.

The remaining chapters detail techniques and accomplishments in the various areas of the field.

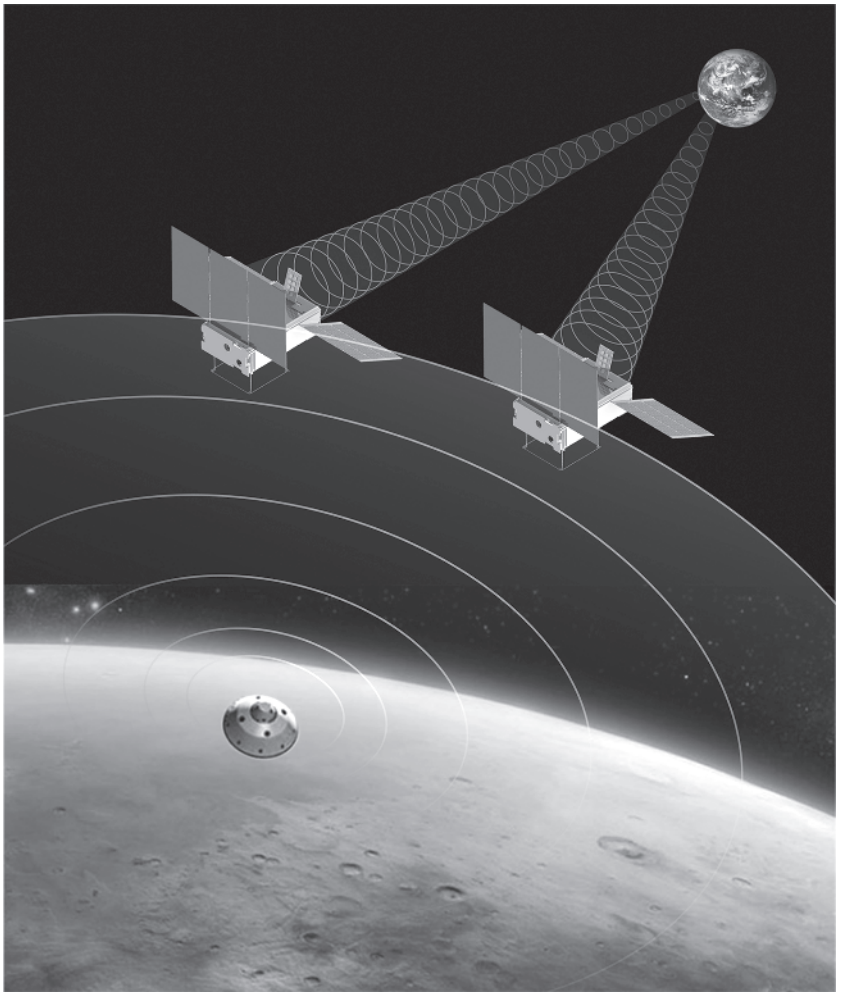

Figure 1.13 An artist's conception of the MarCO CubeSat mission to Mars with potential capabilities for RS experiments (Asmar 2015a). The first CubeSats in deep space were intended to provide real-time relay capabilities during the critical landing phase of the InSight mission onto the Martian surface but can serve as platform to plan future planetary RS experiments as shown in Chapter 6 (also see cover graphic).

- Chapter 2 describes the investigation of planetary atmospheres, ionosphere rings, and surfaces using ROs and bistatic radar techniques.
- Chapter 3 describes investigating planetary interiors from measuring their gravitational fields using precision Doppler tracking techniques.
- Chapter 4 describes tests of relativistic theories via precision radiometric observables, as well as and solar studies via occultation of the corona.
- Chapter 5 details the instrumentation and technologies utilized or being developed for this field or related applications that benefit RS investigations.
- Chapter 6 discusses the future outlook for the field as advances continue in various areas.