Planetary Radio Science: Investigations of Interiors, Surfaces, Atmospheres, Rings, and Environments

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Summary

Scientists utilize radio links between spacecraft and Earth or between two spacecraft to examine changes in the phase/frequency, amplitude, line-width, and polarization, as well as round-trip light time of radio signals to investigate atmospheres and ionospheres, rings and tori, surfaces, shapes, gravitational fields, orbital motion and dynamics of solar system bodies (planets, satellites, asteroids, and comets). Beyond planetary science, the tools and techniques of Radio Science (RS) on planetary missions are applied to investigations of the solar wind, corona and magnetic field, as well as tests of fundamental physics including the theory of General Relativity. RS techniques are also highly important in monitoring mission critical maneuvers or spacecraft emergencies under conditions of low signal level and/or high signal dynamics.

Radio Science will continue to be an important tool for solar system exploration in the coming decades. New scientific advances could be enabled or enhanced by recent development in RS instrumentation and calibration techniques that improve the data quality by an order of magnitude over current technology. Investigations of the solar system icy satellites, for example, will benefit from these improvements for probing from the crust to the deep interior, and possibly detecting a global subsurface water ocean. Studies of atmospheric occultations and surface scattering will be improved by uplink occultation instrumentation to overcome signal-to-noise ratio (SNR) limitations and by links between orbiters at the same planet to provide global coverage.

Background

The broad sense of *Radio Science* is the use of propagating electromagnetic waves to explore the universe. RS observations can be passive, as in observations of naturally occurring emissions, or active, as in the results of probing with artificial signals. In planetary exploration, the term RS has been commonly used for about four decades to describe the scientific utilization of radio signals from spacecraft as opposed to natural celestial radio emissions. This field is distinguished from other sciences by its definition in terms of methods rather than by objects of study.

The current investigations include microwave radio occultations by planetary rings, ionospheres, and neutral atmospheres, propagation through the solar corona, reflection from surfaces, and distance/velocity measurements leading to determinations of mass and density distribution and construction of models for gravity fields and interior structure. The investigations can be grouped into two classes: *propagation* and *gravitation*, where the first investigates the effects of media on the signals and treats the effects of spacecraft motion as noise to be calibrated out of the data, and the second investigates the effects of forces on the spacecraft causing shifts in the signal and treats the effects of media as noise to be calibrated out of the data. Atmospheric balloons, descending probes and atmospheric drag experiments constitute a hybrid category of RS investigations based on measuring perturbations in spacecraft position and velocity caused by the medium.

RS often benefits from collaborative fields such as the interactions between waves and charged particles, radar surface imaging, planetary topography, accelerometry, spacecraft navigation, VLBI precision measurements of angular motion, and relativistic gravity. The discipline came of age in 1964 when the National Bureau of Standards renamed Section D of its *Journal of Research* to *Radio Science*; the journal has been published by the American Geophysical Union since 1969. In addition to *Radio Science*, planetary RS papers appear regularly in *Science*, *Nature*, *JGR*, *Icarus*, and others. RS data are preserved for future generations within the Planetary Data System since the measurements are self-calibrating and never outdated; as long as quality instrumentation is operated properly, measurements made today can be included in future analyses for very long periods of time.

Historical Opportunities and Discoveries

With strong international collaboration, RS experiments have been conducted on almost all deep space missions in the past half-century. Selected examples of historical discoveries include:

- First estimate of Martian surface pressure
- Determination of ring structure and particle size distribution for Saturn and Uranus
- First measurement of surface pressure of Titan and Triton
- First detection of ionospheres of Titan and Triton
- Measurement of electron column density profile of the Io Plasma Torus
- Discovery of lunar mascons
- Determination of masses and modeling of bulk compositions of Jupiter, Saturn, Uranus, Neptune, Titan, Triton, Mars, Venus, and the Moon
- High resolution gravitational fields of the Moon, Mars and Venus
- Drag deceleration measurement in the comae of comets Halley and Grigg-Skjellerup
- Modeling large-scale coronal structure and electron densities in streamers and holes
- First evidence for the acceleration of coronal mass ejections far from the Sun

Recent Opportunities and Discoveries

Since 1995, RS has had a significant role in subsequent missions and is credited with the following additional accomplishments:

- First detection of Martian core and bulk seasonal CO2 deposition at poles (Mars Pathfinder)
- Vastly improved gravity field of Mars, with determination of Love number and correlation with topography (MGS, Odyssey, MRO, and Mars Express)
- First detection of planetary gravity field variations other than Earth (MGS)
- First determination of the mass of Phobos (MGS)
- First non-spherical gravity field of an asteroid (NEAR mission to Eros)
- High accuracy profiling of Martian atmospheric structure from radio occultations (MGS)
- Detection of ionospheres on the Galilean Satellites (Galileo)
- Jovian deep atmospheric wind speeds and ammonia concentration (Galileo Probe)
- State-of-the art tests of General Relativity and search for gravitational waves (Cassini)
- Improved gravity field of Mercury (MESSENGER)
- Measurement of Mars upper atmospheric density from spacecraft drag (several orbiters)
- Surface characteristics of Venus, Moon, Mars and Titan from bistatic radar experiments
- Detection of meteor layers in ionospheres of Mars and Venus (Mars Express, Venus Express)
- Modeling the mass distribution in the interiors of the large moons of Jupiter (Galileo)
- Height profile of winds on Titan with the Doppler Wind Experiment (Huygens)
- High resolution gravitational field of the Earth via spacecraft-to-spacecraft links (GRACE)
- Gravitational field of Saturn and its large satellites (Cassini)
- Atmospheric Structure of Saturn and its large satellites (Cassini)
- Profiling of internal dynamics and of particle size distribution within Saturn’s rings (Cassini)
- First direct gravity measurements in the lunar farside (SELENE (Kaguya)).

Future Opportunities

Future missions will include significant RS investigations such as:

- **Dawn**: Coherent X-band Doppler tracking will enable the measurement of the gravity field of Vesta and Ceres and constrain their interior structure.
- **Rosetta**: RS objectives include measurements of cometary nucleus mass, bulk density, and internal structure as well the composition and roughness of the nucleus surface.
- **Juno**: Coherent X- and Ka-band links will enable precise measurement of spacecraft motion during close polar orbits to determine the gravity field, distribution of mass, core characteristics, and convective motion in the deep atmosphere.
- **GRAIL**: Spacecraft-to-spacecraft radio links at Ka-band, timing synchronization at S-band, and X-band Doppler links to Earth will enable the Gravity Recovery and Interior Laboratory to measure the lunar gravity field in unprecedented detail to be used to probe the Moon's interior from crust to core, reveal its subsurface structure, reconstruct its thermal history, and place limits on a possible inner core.
- **New Horizons**: High-precision uplink radio occultation will allow derivation of Pluto's atmospheric structure while Doppler tracking will constrain interior structure.
- **ExoMars**: Links from a Mars lander/rover or network will improve knowledge of the interior structure by determining the total moment of inertia, core moment of inertia and state of the core in order to constrain the evolution of the planet Mars.
- **BepiColombo**: Order-of-magnitude improved Ka-Band Doppler and ranging will enable: (1) investigating the interior structure of Mercury, (2) testing relativistic gravity and significantly improved General Relativity post-Newtonian parameters, (3) testing any time variation of the gravitation constant to high accuracy, (4) determining the solar oblateness to high accuracy (5) characterizing the structure of the solar wind in and out of the solar ecliptic.
- **Jovian satellite orbiters**: Simultaneous coherent X- and Ka-Band tracking data (two orders of magnitude more accurate relative to Galileo) with NASA's Jupiter-Europa mission and/or ESA's Jupiter-Ganymede mission. Both will yield detailed information about satellite interiors from gravity measurements, and together offer the possibility of spacecraft-to-spacecraft radio occultations of Jupiter's atmosphere and possible satellite surface scattering observations.
- **Saturnian satellite orbiter(s)**: Similar internal structure objectives to the Jovian missions and emphasis on Titan atmospheric investigations as well as surface scattering and rings.

The **Jovian orbiters** illustrate the range of potential science. The Galilean satellites represent two classes of internally active bodies that likely maintain subsurface water layers beneath a modest ice layer above and in contact with a rocky ocean sea floor or between a thick outer ice shell and high-pressure ice phases below. RS teams will investigate: (1) the deep interior structure: the radial density distribution of the deep satellite interiors will be inferred from improved measurements of moment of inertia and low-degree gravity field coefficients; the assumption of hydrostatic equilibrium will be tested by separate determination of the static components of the gravitational field coefficients J_2 and C_{22}; (2) crust and lithosphere: the gravitational signature of intrinsic density anomalies and regional topographic features will be inferred from higher-degree gravity data in combination with altimetry, imposing constraints on the thermal evolutions of the moons; (3) oceans: characterization of any global subsurface water ocean and the overlying ice shell which require measuring the response of the shell to tidal forces exerted by Jupiter along the slightly eccentric orbit of each satellite using gravity and altimetry data. The dynamical tidal Love number k_2, characterizing the variation in the gravitational potential due to the satellite's time varying tidal distortion, is inferred from time-variable contributions to J_2, C_{22} and S_{22} of the gravitational field while the Love number h_2, characterizing the radial displacement, will be determined from altimetry.

In addition to the gravity measurements by each orbiter described above, when **two orbiters are present around Jupiter**, radio links between them can be used to (1) probe the neutral atmosphere of Jupiter to produce temperature-pressure profiles to new depth and profile the spatial and temporal variability of the atmospheric small-scale structure (e.g., waves and turbulence) as well as map the global distribution of ammonia; (2) probe the ionosphere of Jupiter to high accuracy in electron density; (3) profile the ionospheres of Io, Callisto, Europa, and Ganymede and to search for potential tenuous neutral atmosphere around Europa and Ganymede; (4) examine Europa and Ganymede's surface properties via surface scattering; (5) image surface emissivity with passive radiometry and dual spacecraft interferometry.

The **ExoMars** experiment illustrates the utility of lander tracking which allows the determination of: (1) planetary spin rate, direction of rotation pole and polar motion, (2) precession and nutation for freely rotating bodies, or physical librations for synchronous bodies, are sensitive to internal structure such as a core or a subsurface ocean, (3) changes in rotation rate and the direction of the rotation pole can be due to tides, changing polar caps, atmosphere changes and an active interior, (4) tidal displacements of the surface depend on Love numbers h_2 and l_2 that, like k_2, depend on the interior elastic properties and the size of any core or liquid layer. Knowledge of the state of Mars' core and its size is important for understanding the planet's evolution, deduced from the dynamics of its mantle and core. The evolution and the possibility of dynamo magnetic field generation in its core are highly dependent on the planet's ability to develop convection in the core and in the mantle; a core magneto-dynamo is related either to a high thermal gradient in the liquid core (thermally driven) or to the growth of a solid inner core (chemically driven) or both. The state of the core depends on the percentage of light elements in the core and on the core temperature, which is related to the heat transport in the mantle.

Landing on Mars requires knowledge of likely atmospheric density during descent and landing. Radio occultation profiles provide very valuable information due to their absolute altitude scale, good vertical resolution, and well-understood uncertainties. Yet mission planners often find that few occultation profiles are available at the needed location, season, and time of day. Acquisition of radio occultation data whenever opportunities allow would provide a richer database than scheduling them as special events of interest only to a designated RS team. Furthermore, multiple spacecraft orbiting the red planet, if properly equipped for spacecraft-to-spacecraft links, can provide global coverage with links between them without scheduling ground resources.

Technological Advances in Flight Instrumentation

The fundamental RS observations parameters are amplitude, frequency, phase, time, polarization, and direction of propagation of the wave. Measurement accuracy depends on the phase and amplitude stability of the equipment and signal-to-noise ratio. Extraction of the highest quality science requires calibration of the intervening medium and non-gravitational forces as well as accurate reconstruction of position, attitude, and motion of the transmitter, receiver, and target. Precision time/frequency standards are essential; when possible, multiple links, water vapor radiometers, accelerometers and noise power standards lead to accurate calibration of the data observables.

Prior to the Voyager mission, RS experiments were conducted using the spacecraft and ground telecommunications and tracking without modification to enhance the science. Voyager was the first deep space mission to be equipped with an Ultra Stable Oscillator (USO), added to provide a higher quality “clock” for atmospheric and ring occultations. Voyager was also the first mission to employ two coherently related wavelengths simultaneously, S- and X-bands, which improved the ionospheric occultations and enabled calibration of dispersive noise sources. Galileo was upgraded with elliptically polarized transmission to investigate Faraday rotation but the payoff was not realized due to the deployment failure of the high gain antenna. Mars Global Surveyor used the next generation USO, more stable by an order of magnitude than the USO on Voyager; Cassini, New Horizons, GRACE, GRAIL, and other missions later used this class of USO. European deep space missions such as Ulysses, Rosetta, Mars Express, and Venus Express also had the capability for simultaneous S- and X-band links. Rosetta and Venus Express carry USOs.

Current state of the art in RS instrumentation was achieved with Cassini, which pioneered the use of coherent Ka-band, the shortest of the three possible wavelength in use by NASA's Deep Space Network (DSN). S-, X-, and Ka-bands (in decreasing susceptibility to interplanetary plasma noise) are available on Cassini. The Italian Space Agency contributed Ka-band radios to Cassini and Juno.

Future state of the art for RS starts with New Horizons, which is pioneering use of the uplink occultation configuration. The traditional downlink configuration (transmission from spacecraft to Earth) does not provide the necessary SNR to meet science objectives. By reversing the transmission direction, an improvement in sensitivity of about a thousand times can be achieved in probing Pluto's tenuous atmosphere at the cost of adding a miniaturized signal processor to the spacecraft radio.

The Future of Flight Instrumentation

Uplink Radio Science: Most radio occultation and surface scattering experiments have been conducted in the downlink configuration with data acquisition on the Earth where the received SNR is limited primarily by the spacecraft transmitter power (~20 W), the antenna gain and the earth-spacecraft distance. Acquiring the data onboard the spacecraft while transmitting from the DSN at ~20 kW improves the SNR by a factor of 1000 (some loss results from the spacecraft receiver noise being higher than noise in ground receivers), overcoming any SNR limitations of the experiments.

Crosslink Radio Science: Use of spacecraft-to-spacecraft links has many potential science applications. Crosslinks provide vastly improved global coverage with high SNR for atmospheric structure investigations, as has been shown with low Earth orbiting receivers and GPS transmitters. Instrumentation to conduct the basic observations is included on selected planetary spacecraft; proof-of-concept demonstration have been conducted at Mars using a UHF link from Odyssey to MRO. The demonstration illustrated the possible science return as well as the equipment limitations, enabling a better design for the next generation science-based instrument for crosslinks.

Ka-band transponders and Other Instrumentation: Since Doppler measurements used for interior structure determinations are limited by noise from fluctuations in the interplanetary plasma electron density, Cassini, Juno, BepiColombo, and the Jupiter satellite orbiters employ the less susceptible Ka-band wavelength for up- and downlinks as well as multiple links, when possible, to isolate this dispersive effect. Wider-band at Ka-band significantly improves ranging accuracy. Efficient and lightweight transmitters wavelengths benefit both the RS and telecommunications users especially form mass-limited landers. Routine inclusion of USOs in mission telecommunication systems will also be of utility to science, navigation, and communications.

Ground Instrumentation

NASA’s Deep Space Network: Ka-band uplink capabilities have been installed at one DSN station (designated DSS 25) specifically to support RS experiments; Ka-band downlink capabilities exist at all complexes. This RS upgrade included advanced systems for pointing at Ka-band and media calibration especially of the Earth troposphere with advanced water-vapor radiometers. Additional infrastructure improvements throughout the DSN, such as improved frequency and timing, general media calibrations, antenna pointing, antenna vibration reduction, and microwave amplitude and phase stability, also benefit RS.

A key component for RS DSN observations is the Radio Science Receiver, which was developed (in predecessor design) to preserve the characteristics of the enhanced downlink signals from Voyager. It is a specially designed ultra-stable multi-channel open-loop receiver independent of the tracking receivers, comprised of a dedicated full-spectrum processor tuned by a prediction file. The current digital generation receives a down-converted signal in a pre-selected bandwidth appropriate to the specific RS experiment. The multi-mission Radio Science Receiver is operated remotely from JPL by science teams and their staff for optimal configuration, reaction to fast changes (requires high-speed data return) increase the scope of RS activities and allow for improved feedback when needed. and low operational cost.

Precision distance measurements with ranging data are fundamental radio tracking observables. A concept for an advanced ranging instrument that utilizes wider bandwidths at Ka-band and open-loop receivers will, when implemented, improve the ranging resolution by an order of magnitude for science as well as navigation applications.

Other Facilities: Science as well as mission have benefitted from utilizing radio telescopes external to the DSN, especially when the spacecraft transmit at non-DSN frequencies. The Greenbank Telescope, Usuda (Japan), Noto (Italy), Parkes and Narrabri (Australia) and other facilities often support RS activities and a portable DSN Radio Science Receivers has been developed for this purpose. It is anticipated that the new large Sardinia (Italy) radio telescope will be instrumented for full RS support of future missions. The Square-Kilometer Array (SKA) precursor arrays in Australia and South Africa offer expanded capability, and by ~2017 the SKA itself should be the most sensitive telescope in the world, eventually reaching the sensitivity of ~100 DSN 70-m antennas in ~2022, opening entirely new opportunities for RS and mission design (low power probes, probe telemetry direct to Earth)

New Communications Architectures: Arrays and Optical Links

RS investigations are closely linked to communications architectures. As the latter advance, RS opportunities arise. Two future relevant architectures are arrays of ground stations and optical links. The future DSN will likely comprise arrays of many antennas, individually smaller than the 70-m antennas in use today but with an effective SNR comparable to, or better than, the existing large antennas. The new antennas will need to be equipped for multiple frequencies and dual-polarization, a capability present today only at the 70-m antennas. In the array era, RS investigators will utilize the new facilities. As optical communications come into use on deep space missions, comparable link science will be conducted to investigate the same phenomena. The RS community is investigating the limitations and the opportunities for science using optical links.

Conclusion and Goals

The future of RS will witness a leap in technical capabilities and subsequent scientific opportunities and discoveries. RS experiments flying on solar system missions will provide advances not only in planetary science, but also in solar physics and relativity, often with the same instrument package. Design of instrumentation (e.g., coherent Ka-band transponders for Doppler and ranging along with compatible ground systems, on-board open-loop receivers and processors), advances in techniques (e.g., uplink occultations, spacecraft-to-spacecraft links) and improved calibration methods (e.g., media calibration, antenna mechanical noise reduction, etc.) will enable an order of magnitude improvement in data quality for the benefit of future missions. The RS community aims to carry the existing strong science capabilities into the next generation of flight and ground communications architectures, multi-mission low cost infrastructures and instrumentation with continued technical improvements.

Specific technical goals of the RS user community for the next decade include:

- Ensuring a proper replacement for the 70m stations that meet RS requirements
- Expanding Ka-band uplink capability to the other DSN complexes with accompanying pointing and media calibration systems in order to increase the sensitivity and experiment coverage.
- Increasing occultation experiment sensitivity by expanding the capability for uplink RS experiments using highly stable high power transmitters, especially in the array era.
- Utilizing dual or multi-frequency links on future mission in order to calibrate or measure the charged particle effects for propagation experiments
- Adding dual polarization receiving systems to the 34-m stations.
- Develop advanced Ultra-Stable Oscillators, transponders, on-board open-loop receivers and signal processors, and the technology for quiet and precisely pointed spacecraft.
- Developing spacecraft-to-spacecraft links for planetary orbiters, probes, and relay satellites
- Placing spacecraft with RS instrumentation in permanent solar occultation orbits for solar and relativity investigations.
- Developing an advanced ranging instrument for dual X- and Ka-band wide band coherent links utilizing open-loop ground receivers
- Developing the next generation DSN open-loop Radio Science Receiver including portable receivers for support at radio telescopes
- Studying the performance of RS investigations for arrays and links in the optical spectrum

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