Solar System Interiors, Atmospheres, and Surfaces Investigations via Radio Links: Goals for the Next Decade

SW Asmar[1] (*asmar@jpl.nasa.gov, 818-354-6288*), RA Preston[1], P Vergados[1], DH Atkinson[1], T Andert[2], H Ando[3], CO Ao[1], JW Armstrong[1], N Ashby[4], J-P Barriot[5], PM Beauchamp[1], DJ Bell[1], PL Bender[6], M Di Benedetto[7], BG Bills[1], MK Bird[8], TM Bocanegra-Bahamon[1], GK Botteon[1], S Bruinsma[9], DR Buccino[1], KL Cahoy[10], P Cappuccio[7], RK Choudhary[11], V Dehant[12], C Dumoulin[13], D Durante[7], CD Edwards[1], HM Elliott[1], TA Ely[1], AI Ermakov[14], F Ferri[15], FM Flasar[16], RG French[17], A Genova[7], SJ Goossens[16,18], B Häusler[2], R Helled[19], DP Hinson[20], MD Hofstadter[1], L Iess[7], T Imamura[21], AP Jongeling[1], Ö Karatekin[12], Y Kaspi[22], MM Kobayashi[1], A Komjathy[1], AS Konopliv[1], ER Kursinski[23], TJW Lazio[1], S Le Maistre[12], FG Lemoine[16], RJ Lillis[14], IR Linscott[24], AJ Mannucci[1], EA Marouf[25], J-C Marty[9], SE Matousek[1], K Matsumoto[26], EM Mazarico[16], V Notaro[7], M Parisi[1], RS Park[1], M Pätzold[8], GG Peytaví[2], MP Pugh[1], NO Rennó[27], P Rosenblatt[13], D Serra[28], RA Simpson[20,24], DE Smith[10], PG Steffes[29], BD Tapley[30], S Tellmann[8], P Tortora[31], SG Turyshev[1], T Van Hoolst[12], AK Verma[32], MM Watkins[1], W Williamson[1], MA Wieczorek[33], P Withers[34], M Yseboodt[12], N Yu[1], M Zannoni[31], MT Zuber[10]

1: Jet Propulsion Laboratory, California Institute of Technology
2: Universität der Bundeswehr München, Germany
3. Kyoto Sangyo University, Japan
4. National Institute of Standards & Technology
5. Observatoire Géodésique de Tahiti
6. University of Colorado
7. Università di Roma (Sapienza), Italy
8. Universität zu Köln, Germany
9. Centre National d'Etudes Spatiales, France
10. Massachusetts Institute of Technology
11. Space Physics Lab., VSSC, Trivandrum, India
12. Observatoire Royal de Belgique
13. Université de Nantes, France
14. University of California, Berkeley
15: Università degli Studi di Padova, Italy
16. NASA/Goddard Space Flight Center
17. Wellesley College
18. University of Maryland
19. Universität Zürich, Switzerland
20. SETI Institute
21. The University of Tokyo, Japan
22. Weizmann Institute of Science, Israel
23. PlanetiQ, Inc.
24. Stanford University
25. San Jose State University
26. National Astronomical Observatory of Japan
27. University of Michigan
28. Università di Pisa, Italy
29. Georgia Institute of Technology
30. The University of Texas at Austin
31. Università di Bologna, Italy
32. University of California, Los Angeles
33. Observatoire de la Côte d'Azur, France
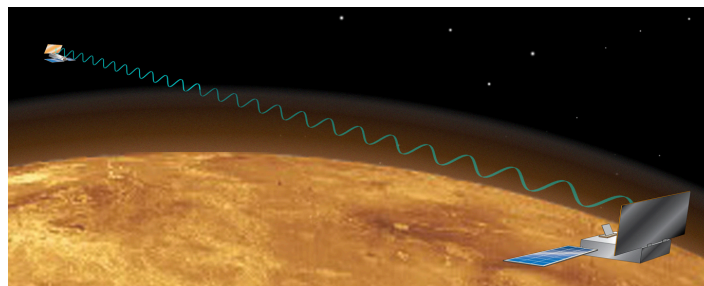34. Boston University

Illustration of two members of a constellation of small spacecraft at Venus with crosslinks for radio occultations that can lead to global coverage with high spatial and temporal resolutions.

Summary

From Mercury to the outer reaches of the solar system, the past six decades have witnessed a vast set of discoveries utilizing radio science (RS) methods. For example, based on key gravitational evidence, sub-surface oceans have been inferred at Titan, Enceladus, and Europa, where potential future missions may search for life.

The ability to precisely measure properties of spacecraft radio signals — frequency, phase, delay, amplitude, polarization — provides unique leverage to extract new information about atmospheres, ionospheres, rings, surfaces, shapes, and internal structure of solar system bodies (Asmar et al., 2019). In addition to planetary sciences, RS observables such as precision Doppler and ranging are critical to studies in fundamental physics and solar dynamics such as observing effects on signal passage through the Sun's gravitational field and solar wind, investigating gravitational waves, and monitoring planetary motion to study gravitational theory and solar mass loss (Armstrong et al., 2003; Genova et al., 2018; Smith et al., 2018; and Woo, 1993; Armstrong, 2006).

RS remains a powerful and cost-effective tool for many solar system investigations planned or conceived in the coming decade. Additional science discoveries could be enabled by developing new technologies and mission concepts such as:

- Deployment of small spacecraft missions for high spatial and temporal resolution of atmospheric and gravitational mapping (see cover page illustration),
- Novel instrumentation and calibration techniques to improve data quality by up to an order of magnitude over current levels, and
- Exploitation of uplink transmissions from Earth such as those used by New Horizons at Pluto, to improve sensitivity by orders of magnitude.

> **Recommendations for Next Decade:** Scientific studies using spacecraft radio links have led to numerous discoveries. In the next decade, technological advances, and use of small spacecraft with increasing radio capabilities that approximate those of full-scale spacecraft, could enable many additional scientific breakthroughs in atmospheric dynamics, interior structures, and surface properties. Development of new techniques and technologies to reach these goals can enable all solar system missions to benefit from this enhanced low-cost science capability.

Current Status of RS Investigations

To plan for the future, it's vital to understand RS current status. Major accomplishments include:

- ***Interior Structure:*** Detailed gravity fields of Mercury, Venus, Mars, the Moon, Jupiter and Saturn leading to refined models for their interior structures; fundamental insights into the interiors of Phobos, Eros, Vesta, Ceres, Lutetia, Bennu, cometary nuclei, Triton, and many Saturnian and Galilean satellites, leading to evidence for fluid layers in icy moons.

- ***Atmospheric structure, dynamics, & composition:*** Temperature-pressure profiles from Venus to Neptune, Pluto, Titan, and Triton; ionospheric electron densities; Jovian deep wind speeds; wind height profiles on Titan, Jupiter and Venus; Venus temporal wind variations and gravity wave spectra, abundances of key molecules on Jupiter (ammonia) and Venus (sulfuric acid).

- ***Planetary Rings & Tori:*** Particle size distribution and internal dynamics of Saturn's rings and Jupiter's Io Plasma Torus; total ring masses measured with implications to age determination.

- ***Surface properties:*** Surface characteristics of Venus, Moon, Mars, Titan, comet 67P/ Churyumov-Gerasimenko, Pluto, Vesta, and Kuiper Belt Object Arrokoth.

Ongoing RS experiments will continue in the next decade as MAVEN and Mars Express further investigate Mars' atmosphere, Akatsuki investigates Venus' atmosphere, InSight's Rotation and Interior Structure Experiment characterizes the Martian core, and Juno investigates Jupiter's interior structure, Jupiter's satellites and the Io plasma torus. New investigations are also planned:

- ExoMars' Lander Radioscience (LaRa) will examine Mars' rotation and interior.
- ExoMars' AMELIA payload will estimate Mars' wind velocity.
- Trace Gas Orbiter will investigate Mars' seasonal variations and polar mass deposits.
- Trace Gas Orbiter and Mars Express will attempt crosslink atmospheric radio occultations.
- BepiColombo will investigate Mercury's interior structure.
- Europa Clipper will investigate the Jovian satellite's interior structure.
- JUICE will study Jovian atmosphere and Galilean satellites' internal structure & ionospheres.
- Hera will measure Didymos' gravity via Juventas crosslink tracking.
- Psyche will investigate the interior structure of asteroid 16 Psyche.
- Lucy will determine the mass of five Trojan asteroids.
- The Martian Moons eXploration (MMX) mission will investigate Phobos' interior structure.

Key Science Goals for the Next Decade

Scientific goals to be pursued in the next decade include higher geographic and temporal resolution measurements of atmospheric and ionospheric structure from radio occultations (RO), new opportunities for wind profiles from entry probes and balloons, more detailed interior structure from high-precision radiometric tracking, and increased exploration of surface electrical properties and roughness from scattering/bistatic radar. The emphasis is on improved measurement precision, utilization of small spacecraft individually, in pairs, or in constellations, and communication via crosslinks between spacecraft. Table 1 lists selected science goals and enabling technology goals.

Table 1: Radio Science-Based Science and Technology Goals for the Next Decade

Investigation	Representative Science Goals	Technology Goals
Interiors	• Core & mantle size/density/composition • Interior structure models • Formation mechanism • Thermal history • Tidal and natural oscillations	• Spacecraft constellations crosslinks • Same antenna beam tracking • Advanced radiometric calibrations • Atomic clocks • Small spacecraft orbit insertion
Atmospheres, Rings, & Other Media	• Temperature-pressure profiles • Neutral & ionospheric densities • Wave structures and origins • Shape models	• Spacecraft constellations crosslinks • Advanced software-defined radios • Miniaturized stable oscillators • Small spacecraft orbit insertion
Atmospheric Winds	• Wind velocities	• Small spacecraft delivery/entry
Surfaces	• Electrical properties & roughness	• Uplink & crosslink instrumentation
Surface-Atmosphere Interactions	• Seasonal ice deposition on Mars • Geophysically-induced waves	• Geographical & temporal resolution

Atmospheres/Ionospheres: RS can obtain data key to scientific drivers centered on understanding the 3D structure and variations of atmospheric composition and thermodynamics, the underlying processes that drive global dynamics such as thermal tides, the physical coupling of the surface-atmosphere system, including any ionospheric layer, and the global and local radiative balance and its relationship to atmospheric state and circulation. RO refractivity measurements by small

spacecraft constellations at Mars, Venus, and Titan potentially provide orders of magnitude improvements in the geographic and temporal resolution of the atmospheric vertical temperature, pressure, and density profiles (Mannucci et al., 2018; Lillis et al., 2020). Refined measurements of rotational dynamics improve knowledge of CO_2 seasonal movements. This can enhance Martian climate science with foundational data for global atmospheric modeling and meteorological information for atmospheric stability, geostrophic and isothermal winds, and geopotential height. Global observations of Titan's atmospheric structure would provide a leap in understanding its atmospheric dynamics. For Saturn, Uranus and Neptune, detailed vertical variations of winds provide insights into the circulation, thermodynamics, and evolution of their atmospheres.

For Venus, detailed spatial and temporal characterization is possible for large-scale atmospheric wave structures such as planetary waves, jet streams, and polar vortices. This improves our understanding of their formation, evolution, and role in global circulation including insight into the spectra and structures of lower atmosphere thermal tides, hypothesized to sustain super-rotation. By exploiting the strong coupling between the surface and dense atmosphere, long-term observations may allow detection of waves in the neutral or charged regions possibly generated by seismic events. RO absorptivity profiles could allow for the retrieval of chemical species of the sulfur acid cycle for accurate chemical composition abundances over prolonged periods.

Interiors: Key drivers for planetary interiors center on modeling the density and composition, leading to understanding their formation and thermal history. RS provides key evidence towards these goals through high-resolution gravity fields and their time-variations due to tidal response and mass transport. Rotational dynamics provide clues about interiors such as core size via radio tracking of landed spacecraft or long duration orbiters. Investigation of small-body interior structure through their gravity fields can reflect formation mechanisms.

Uranus and Neptune, whose interior structures are fundamentally different from Jupiter and Saturn, are potential targets of upcoming missions in the next decade. Searching for a possible liquid layer in Neptune's moon Triton is also a key RS goal. Icy Giant gravity data via Doppler tracking of an orbiter, preferably with a subsatellite, will be crucial to understanding their internal structure by significantly reducing the error bars on J_2 and J_4 and possibly detecting J_6. Current uncertainties don't allow unique compositional solutions (Bailey and Stevenson, 2020; Helled et al., 2020). Hofstadter et al. (2017) noted that the interior structure was a future mission's highest priority. Understanding it will provide clues to the origin of exoplanets since Neptune-sized bodies are prevalent around other stars. Detecting giant planet normal modes when orbiters pass through their resonances offers a possible new RS approach to interior studies (Durante et al., 2017).

Surfaces: Signal reflection from planetary surfaces and near-surface regions reveal their structure and composition. Space-based reflectometry and scatterometry techniques are utilized to study Earth's surface roughness and dielectric constant. This is possible between a flagship planetary mission and a small spacecraft or by a small constellation. Comparing the power between circularly polarized transmitted radio signals and oppositely polarized reflected signals provides information about icy moons' surface properties. Speculatively, mass flux could also be detected on Venus by a nadir-viewing spacecraft monitoring specific areas for changes between coherent and incoherent scattering that signify mass transport or surface terrain variations. Doppler delay maps from the differential travel time between transmitted and reflected signals could provide information on surface topography. Tracking landed spacecraft can be used to study seasonal surface deposition (e.g., CO_2 on Mars) and finer scale surface and near-subsurface properties.

Radio Science Techniques for Achieving the Science Goals of the Next Decade:

Spacecraft Constellations for Atmospheric Structure & Dynamics*:* Compared to spacecraft-to-Earth radio occultations, substantial increases in global coverage as well as spatial and temporal resolution are possible using crosslinks among a constellation of small spacecraft, akin to GPS-based RO constellations at Earth. At Mars and Venus, for example, simulations showed that nearly global coverage can be accomplished in a couple of weeks with two spacecraft in optimized orbits as compared to many years via the traditional downlink to Earth. Such crosslinks (see crosslink demo carried out with Mars orbiters in Ao et al., 2015) can profile the atmosphere through clouds and aerosols and detect the signature of phenomena such as gravity waves, planetary waves, turbulence, and jet streams, and for Venus, the possibility of detection of seismically-induced waves, potentially opening a window into possible current tectonic activity.

Spacecraft Constellations for Interior Structure & Dynamics: Precision gravity experiments via spacecraft-to-spacecraft crosslinks have been utilized at Earth (GRACE, Tapley et al., 2004) and the Moon (GRAIL, Zuber et al., 2013, and SELENE's farside subsatellite) for high-impact studies of planetary interiors and monitoring mass transport. Applying this concept to other rocky, icy, or gaseous bodies, would enable rapid high-resolution global coverage and provide stringent constraints on the thickness of ice and the characteristics of subsurface oceans at icy moons.

Differential Interferometry for Planetary Rotational State & Tidal Deformations: Tracking multiple landers or spacecraft from one or many Earth stations suppresses most common noise sources, enhancing the sensitivity to the desired science goals (e.g., gravitational fields, rotational states, tidal deformations, and winds). The benefits of same-beam differential interferometry were recognized by Counselman et al. (1972) and advanced by Preston (1974), Edwards et al. (1992), Bender (1994) and others, and applied to examine librations (ALSEP) and gravity field (Selene) of the Moon, studying winds on Venus (Pioneer probes and Vega balloons), and observing Huygens' descent on Titan. New uses have been proposed for the Moon, Mars, and Jupiter.

Doppler Wind Experiments for Measurement of Atmospheric Dynamics: Radio links from probes descending through planetary atmospheres provide information on atmospheric dynamics as demonstrated at Venus, Jupiter, and Titan. Links can be established with proximity spacecraft or ground stations, and, if multiple links are possible, recovery of complete wind vectors can be made. In some cases, ranging, VLBI techniques, and onboard observations provide additional information. A constellation of small probes and/or balloons can provide a global assessment of atmospheric dynamics. Absorption on the probe's radio link can be used to infer the integrated abundance of ammonia (giant planets), sulfuric acid (Venus), or other absorbers. Similar techniques can be applied to atmospheric balloons as was done on the VEGA mission at Venus.

Scattering Studies for Surface Properties: In a bistatic scattering experiment, a spacecraft downlink signal is reflected off a planetary surface and received on Earth or another spacecraft. Information can be deduced about the surface and near subsurface electrical properties and roughness. Reversing the path via an uplink provides higher signal-to-noise ratio (SNR), as shown by New Horizons and Lunar Reconnaissance Orbiter (LRO); multiple simultaneous uplinks with frequency offset can improve the SNR and resolve subsurface degeneracies. A constellation of small spacecraft makes global characterization feasible and yields information at scales useful to the safety of planned landers. Scattering from subsurface structures provide added exploration opportunities where redundancies can be resolved using polarization, wavelength, and obliquity variations. Use of bistatic techniques with landed spacecraft can provide finer spatial resolution.

Technology Development Needed in the Next Decade

The RS observational accuracy depends primarily on the phase and amplitude stability of the end-to-end system and the SNR of radio links. Furthermore, extracting high quality science requires calibration of the intervening media and non-gravitational forces as well as accurate reconstruction of position, attitude, and motion of the transmitter-target-receiver system. Precision time and frequency standards are essential; multiple frequency links enable isolating dispersive media; water vapor radiometers enable calibrating Earth's tropospheric effects; and precise onboard accelerometers enable calibrations of non-gravitational forces for optimized scientific results.

Table 2 lists the technology methods needed to address challenges and meet the RS decadal goals, using general investigation cases, which will be refined as specific science objectives, planetary targets, and mission configurations are identified. The Allan deviation values represent fractional frequency instability for classes of clocks (ultra-stable oscillator (USO), for 1-way mode or hydrogen maser for 2-way mode). Dynamical stability is determined by thruster balance or timing of spacecraft maneuver or solar electric propulsion events that disturb the Doppler data quality, and precision power calibration is required for comparing small variations in the two polarizations of received signals.

Table 2: Radio Science Technology Methods & Typical Requirements for the Next Decade

Investigation	Method	Requirements
Interiors	• Precision 2-way Doppler link(s); 1-way possible if atomic clock onboard • Shorter wavelength less noisy (multiple wavelengths preferred)	• Allan deviation $\sim 1\times10^{-14}$ (1000 s) • Dynamical stable spacecraft • Calibration of intervening media and non-gravitational forces
Atmospheres, Rings, & Other Media	• Ultra-stable links (2 preferred) • 1-way or dual 1-way with USO; 2-way if no USO, limited to RO ingress	• Allan deviation $\sim 1\times10^{-13}$ ($\sim$100 s) • Phase noise $\sim$ -90 dBc/Hz, 10 Hz offset • Amplitude stability $\sim$ 0.1 dB at 60 s
Atmospheric Winds	• Cross or 1-way Doppler links with stable oscillators at both ends • Signal power if monitoring absorption	• Allan deviation $\sim 1\times10^{-11}$ ($\sim$100 s) • Amplitude stability: 0.1 dB at 60 s • Multiple links for better wind vectors
Surfaces	• 1-way or crosslinks at good geometry • Signal power at dual polarizations • Multiple signals (for uplink case)	• Amplitude stability $\sim$0.1 dB at 60 s • Allan deviation $\sim 1\times10^{-12}$ ($\sim$100 s) • Power measurement calibration
Fundamental Physics	• Precision 2-way Doppler link(s) • Shorter wavelength less noisy • Precision ranging	• Allan deviation $\sim 1\times10^{-14}$ ($\sim$1000 s) • Dynamical stability • Calibration of known noise sources
Solar Science	• Ultra-stable link(s) • Dual links to isolate dispersive media • Ranging for coronal densities	• Allan deviation $\sim 1\times10^{-12}$ ($\sim$100 s) • Amplitude stability: 0.1 dB at 60 s • Dual polarization receivers

To meet the new RS goals for the next decade, we have identified essential technology developments needed in radios for small spacecraft, stable oscillators, data calibration, and atomic clocks. Insertion of small spacecraft into planetary orbits is also a key technology area for future missions along with advances in optimizing spacecraft orbits and attitude stability for precision measurements. Ground station resources for constellation missions are being considered by the DSN. Finally, preparation for the coming age of optical links is discussed below.

Small Spacecraft Enabled for Radio Science: The highest technology priority is the maturation of multi-band crosslinks between robust small spacecraft in suitable planetary orbits. This requires advances in miniaturized radios, stable oscillators, and orbit insertion. A critical need is the development of key technologies *for software-defined radios (SDR)* size-suitable for small spacecraft. The Iris SDR used for the MarCO mission (Asmar and Matousek, 2016) provided experience for further advances towards science-quality radiometric and functional capabilities (e.g., simultaneous open-loop recordings at multiple wavelengths and agility to swap the transmit/receive frequencies). *USOs* have been critical instrumentation for RO experiments since the Voyager mission. Small spacecraft cannot accommodate the mass and power of the current top-of-the-line flight USO (Allan deviation $\sim 2 \times 10^{-13}$ at ~ 100 s) such as those flown on MGS, Cassini, GRACE/GRACE Follow-On, GRAIL, New Horizons, VEX, Rosetta, Akatsuki, and LRO. The goal is to mature smaller units with comparable stability based on newer technologies.

Advanced Calibrations at the Deep Space Network: The most accurate RS experiments to date were achieved during Cassini's gravitational wave observations; further improvement is possible. A leading source of radiometric noise is Earth's troposphere, which is partly calibrated via water vapor radiometers. An order of magnitude precision improvement is possible by pointing along the same path as the signal arriving at the antenna, rather than being nearby. The next noise source is unmodeled mechanical motion of the ground antenna's phase center. A method (Armstrong et al., 2008) for suppressing this intrinsic noise is to combine the 2-way data from the principal antenna with Doppler data received at a smaller stiffer antenna; early testing by Notaro et al. (2020) has shown promise. Another concept involves measuring the antenna surface motion with laser or microwave beams and combining those data with a mechanical antenna model in post-processing.

Enhanced Planetary Gravity via Atomic Clocks: Spaceborne atomic clocks would revolutionize spacecraft tracking methods (Ely et al., 2014). Future one-way (downlink, uplink, or crosslink) observations enabled by these onboard clocks, as they are get further improved in stability and reduced in size, could achieve performance comparable to two-way coherent links referenced to ground station atomic clocks. This could enable nearly continuous tracking using smaller ground stations, enhancing the science at lower cost. A prototype atomic clock with Allan deviation of $\sim 2 \times 10^{-14}$ (1000 s) is being tested in Earth orbit and a prototype "micro Mercury trapped ion clock" with the same stability is currently under development.

Small Spacecraft Orbit Insertion: A big challenge in planning small spacecraft missions is the method of their insertion into orbits around solar system bodies. Small spacecraft could be carried to orbit by larger orbiters if suitable attachment systems were available. Placing conventional propulsion systems onto small spacecraft has thus far not been practical and more suitable systems are needed. This challenge needs to be solved through a dedicated technology or alternative insertion techniques in order to achieve the full potential of small spacecraft for RS experiments. Aerocapture and aerobraking technologies for small spacecraft can enable them to achieve orbit of some bodies as discussed in Austin et al. (2020).

Enhanced Science via Optical Links: Although the previous discussion has addressed the science possible with radio links, optical links are expected to be demonstrated on future deep space missions. Laser links can provide measurements in most areas already pioneered by RS but, in many cases, with new scientific capabilities and precision. Occultations could better probe upper atmospheres and Doppler measurements could provide improved gravity fields measurements. In the next decade it is important to lay the technological framework for future optical link science.

References

- Ao, C. O., Edwards, C. D., Kahan, D. S., Pi, X., Asmar, S. W., & Mannucci, A. J. (2015). A first demonstration of Mars crosslink occultation measurements. *Radio Science*, 50(10).
- Armstrong, J. W., F. B. Estabrook, S. W. Asmar, L. Iess, and P. Tortora (2008). Reducing antenna mechanical noise in precision spacecraft tracking. *Radio Science* 43, 03.
- Armstrong, J. W., Iess, L., Tortora, P., and Bertotti, B. (2003). Stochastic Gravitational Wave Background: Upper Limits in the 10^{-6}-10^{-3} Hz Band, *ApJ*, 599, 806-813.
- Armstrong, J. W. (2006). Low-frequency gravitational wave searches using spacecraft Doppler tracking. *Living Reviews in Relativity*, 9(1), 1.
- Asmar, S. W., et al., (2019). Future of planetary atmospheric, surface, and interior science using radio and laser links. *Radio Science*, *54*(4)
- Asmar, S. W., & Matousek, S. (2016). Mars Cube One (MarCO) shifting the paradigm in relay deep space operation. In *14th International Conference on Space Operations* (p. 2483).
- Austin, A., et al., (2020). Enabling and Enhancing Science Exploration Across Solar System: Aerocapture Technology for SmallSat to Flagship Missions, Decadal Survey 2023-2032.
- Bailey, E. and DJ Stevenson (2020). Thermodynamically Governed Interior Models of Uranus and Neptune. Accepted by *Planetary Science Journal.*
- Bender, PL (1994). Proposed microwave transponders for early lunar robotic lander. *Advances in Space Research,* 14(6), 233-242.
- Counselman C. C., Hinteregger, H. F., & Shapiro, I. I. (1972). Astronomical applications of differential interferometry. *Science*, 178(4061), 607-608.
- Durante, D., Guillot, T., & Iess, L. (2017). The effect of Jupiter oscillations on Juno gravity measurements. *Icarus*, 282, 174-182.
- Edwards JR, C., et al. (1992) Mars planetary geodesy using earth-based observations of Mars landers. Astrodynamics Conference.
- Ely, T. A., Murphy, D., Seubert, J., Bell, J., & Kuang, D. (2014). Expected performance of the deep space atomic clock mission. In *AAS/AIAA Space Flight Mechanics Meeting*.
- Genova, A., et al., (2018). Solar system expansion and strong equivalence principle as seen by the MESSENGER mission. *Nature communications*, 9(1).
- Helled, R., Nettelmann, N., & Guillot, T. (2020). Uranus and Neptune: Origin, Evolution and Internal Structure. *Space Science Reviews*, *216*(3), 1-26.
- Hofstadter, et al. (2017). A vision for ice giant exploration. Planetary Science Vision 2050.
- Lillis, R. J., et al., (2020). Mars Orbiters for Surface-Atmosphere-Ionosphere Connections (MOSAIC). LPI, (2326), 1733.
- Mannucci, A., et al., (2018). Globally Distributed and High-Resolution Mars Atmospheric Profiles from Small Spacecraft Constellations. 42nd COSPAR Assembly, B0.2-15-18.
- Notaro, V., Iess, L., Armstrong, J. W., Asmar, S. W. (2020). Reducing Doppler noise with multi-station tracking: The Cassini test case. *Acta Astronautica*.
- Preston, R. A. (1974). Dual-Spacecraft Radio Metric Tracking" *DSN Progress Report* 42-22.
- Smith, D. E., et al., (2018). Trilogy, a planetary geodesy mission concept for measuring the expansion of the solar system. *Planetary & Space Sci 153*
- Tapley, B. D., Bettadpur, S., Ries, J. C., Thompson, P. F., Watkins, M. M. (2004). GRACE measurements of mass variability in the Earth system. *Science*, *305*(5683).
- Woo, R. (1993). Solar cycle variation of interplanetary disturbances observed as Doppler scintillation transients. *Journal of Geophysical Research: Space Physics*, *98*(A11).
- Zuber, M. T., et al., (2013). Gravity field of the Moon from the Gravity Recovery and Interior Laboratory (GRAIL) mission. *Science, 339.*