Radio-Occultation Projects in Space Programs of Japan

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Abstract

The history of radio-occultation studies in Japanese spacecraft projects began in 1985, when the Institute of Space and Astronautical Science (ISAS) realized the Sakigake mission, targeted to explore the solar wind and its interaction with the comet Halley. The next project was accomplished through the cooperation of NASA and ISAS in the investigation into the Neptune atmosphere, during the Voyager mission. In July of 1998, the NOZOMI spacecraft was launched toward Mars, with the primary objective of the program being to study the interaction of the Martian upper atmosphere with the solar wind. Among its experiments was the dual-frequency measurement. Three spacecrafts of the SELENE mission, which is a joint space program of ISAS and the National Space Development Agency of Japan (NASDA), will become the orbiters of the moon in 2005. The radio-occultation technique will be applied for the investigation of the plasma clouds above the lunar surface. Recently, another ISAS project, "Planet-C," has been officially approved. In this project, the spacecraft should be driven into orbit around Venus in 2009, and its radio communication system will be used for the exploration of the Venusian atmosphere and the solar corona.

1. Introduction

The radio-occultation technique was developed during several decades of solar-system exploration. The traditionally employed method of retrieving atmospheric profiles from radio-occultation measurements is based on the Abel inversion and Geometric Optics [1, 2, 3]. Later, a new method of data processing, based on scalar diffraction theory, was developed, to consider the effects of multipath propagation [4, 5]. The changes in the phase, amplitude, and polarization of the waves are also caused by wave propagation in inhomogeneous interplanetary plasma [6, 7, 8].

In radio-occultation measurements, the perturbations of radio signals propagating from a transmitter to a receiver are used to study the medium of interest, such as planetary atmospheres and interplanetary plasma. To control spacecraft, ISAS constructed a 64-meter-diameter antenna at the Usuda Deep Space Center (UDSC), in Japan. Among the facilities developed was a signal recording system for radio occultation (Figure 1). Having at its disposal these ground facilities and realizing its own spacecraft missions, Japan successfully started various scientific space programs. Radio-occultation experiments are included in those missions as an important means of space exploration. This article summarizes the past and future ISAS programs of radio-occultation experiments.

2. Previous Missions

The first radio-occultation experiment in Japan was accomplished using a first Japanese interplanetary spacecraft Sakigake, which was launched in 1985 as a member of the international comet Halley armada. The Sakigake project was targeted to directly measure the solar wind, magnetic fields, and plasma waves in interplanetary plasma, especially during the comet Halley encounter, although the distance between Sakigake and the comet Halley was quite far, about 7×10^6 km [9]. Sakigake also conducted radio-occultation measurements of the solar corona during the solar conjunction in 1988. The frequency broadening observed with Sakigake during this period is consistent with that observed before by other interplanetary spacecraft (Figure 2).

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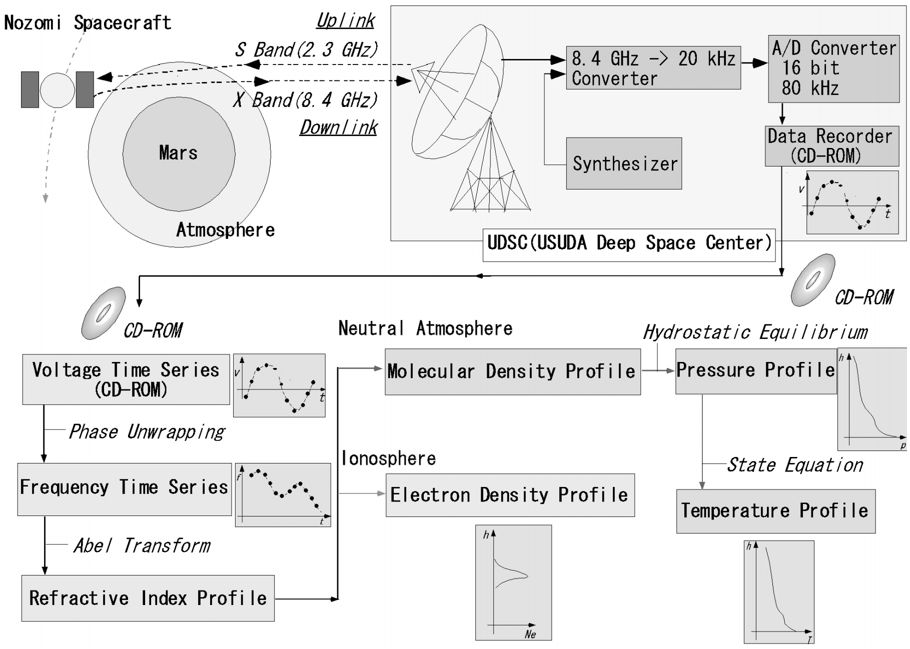

Figure 1. The data-recording system at UDSC, and the data-processing procedure for radio-occultation experiments.

In 1989, during the Neptune encounter of Voyager 2, ISAS cooperated with NASA in carrying out a radio-occultation experiment on Neptune's atmosphere. The radio occultation revealed the thermal structure of the neutral atmosphere, and the electron-density profile in the ionosphere [10]. The accuracy of the profiles was improved by coherently arraying the signals recorded simultaneously at different stations, including UDSC [11].

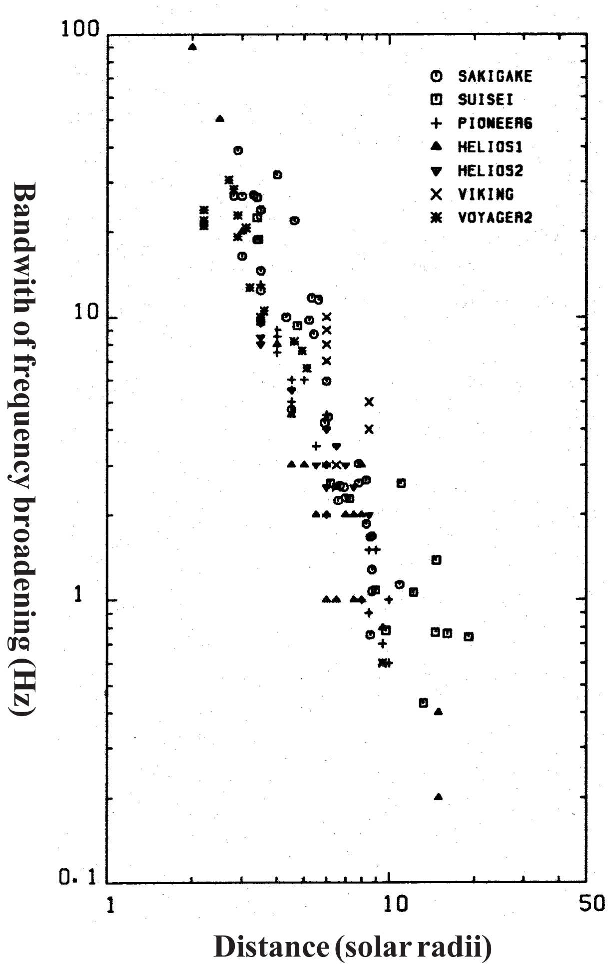

Figure 2. Frequency broadening observed during solar conjunctions using Sakigake and other interplanetary spacecraft, as a function of the distance from the center of the Sun to the ray path.

3. Future Missions

In the near future, radio-occultation experiments will be performed on missions to Mars, the moon, and Venus. These radio-occultation projects are briefly described below.

3.1 NOZOMI, a Mars Orbiter

The NOZOMI spacecraft was launched in 1998, and is scheduled to arrive at Mars in 2004. The primary objective of the mission is to reveal the interaction between the Martian ionosphere and the solar wind. Radio occultations of the Martian atmosphere are planned after the orbital injection of the spacecraft. The spacecraft was supplied with a dual S- and X-band frequency transmitter for performing radio-occultation experiments, aimed at observing the thermal structure of the neutral atmosphere and the electron-density profile of the ionosphere.

High-vertical-resolution profiles of temperature, obtained by radio occultation, are useful for meteorological study. The Viking radio occultation showed that during global dust storms, the thermal structure changes strongly near the surface [12]. More recently, the radio occultation experiments with Mars Global Surveyor (MGS) have given us many insights into the Martian atmosphere, such as the temporal variation of the radiative-convective boundary layer near the surface, distinctive meridional gradients of pressure at low altitudes, and the presence of atmospheric waves, such as gravity waves, planetary waves, and thermal tides [13, 14]. The MGS observations also indicated the influence of thermal tides on the variation of the height of the ionospheric peak [15], suggesting a close coupling between the neutral atmosphere and the ionosphere.

Among the unsolved problems of the Martian ionosphere is the source of nightside plasma. In contrast with the dayside ionosphere, which has been observed many times, the nightside ionosphere is not well characterized, due to sparse sampling [16, 17]. Since very few data are available, the ionization mechanism of the nightside ionosphere of Mars is still unsolved. Some hypotheses of the ionization were proposed from the point of view of electron precipitation [18, 19] and transport from the dayside [20]. It is expected that NOZOMI's radio-occultation measurement will provide new data to improve the understanding of the nightside ionosphere with the aid of simultaneous in-situ measurements.

Using the NOZOMI spacecraft, a radio-occultation experiment on the solar corona was performed from December, 2000, to January, 2001. During the observation period, the distance from the ray path to the solar surface ranged from 12 to 37 solar radii. Unfortunately, it was impossible to implement the dual S- and X-band frequency configuration, because only the X-band transmitter is working now, due to onboard trouble. Therefore, the two-way radio-propagation scheme was used: the S-band uplink was generated using the ultra-stable oscillator (the Allan variance is about 10^{-15}) at UDSC, and it was converted into the X-band downlink onboard the spacecraft. Examples of the phase fluctuation for 37, 26, and 12 solar radii are shown in Figure 3. The results of detailed analyses will be reported elsewhere in the near future.

3.2 SELENE, a Lunar Orbiter

The primary objectives of the SELENE mission, which is a joint space program of ISAS and NASDA, are to study the lunar origin, evolution, and environment. The radio-occultation experiment using the SELENE spacecraft, the launch of which are scheduled in 2005, aims to study the charged-particle regions near the lunar surface.

The first radio occultation of the moon was performed with the Pioneer 7 spacecraft, using dual-frequency (49.8 and 423.3 MHz) beacons [21]. At that time, no plasma cloud with an electron density greater than 4×10^7 m^{-3} was detected. On the other hand, the dual-frequency (0.9 and 3.7 GHz) occultation with the Russian spacecraft Luna 19 and 22 showed a total electron content of the order of 10^{14} m^{-2} at altitudes up to 10 km [22] above several regions

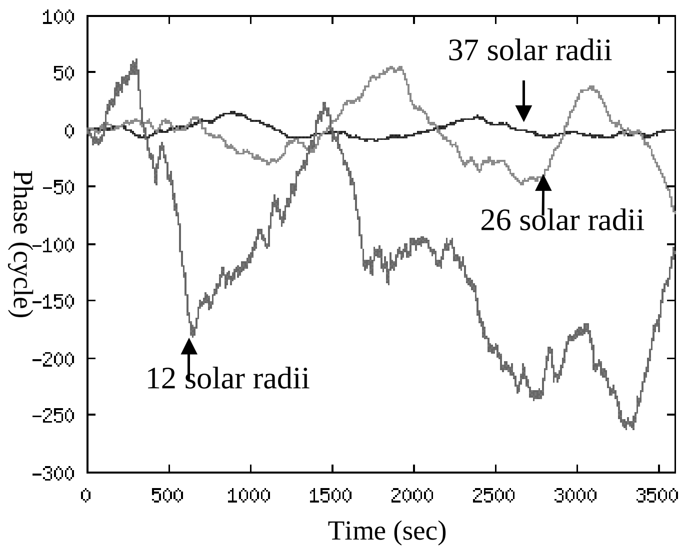

Figure 3. A part of the time series of the phase fluctuation in the two-way signal (S-band uplink and X-band downlink) observed during a solar conjunction using the NOZOMI spacecraft. The numerals indicate the distance between the solar surface and the ray path.

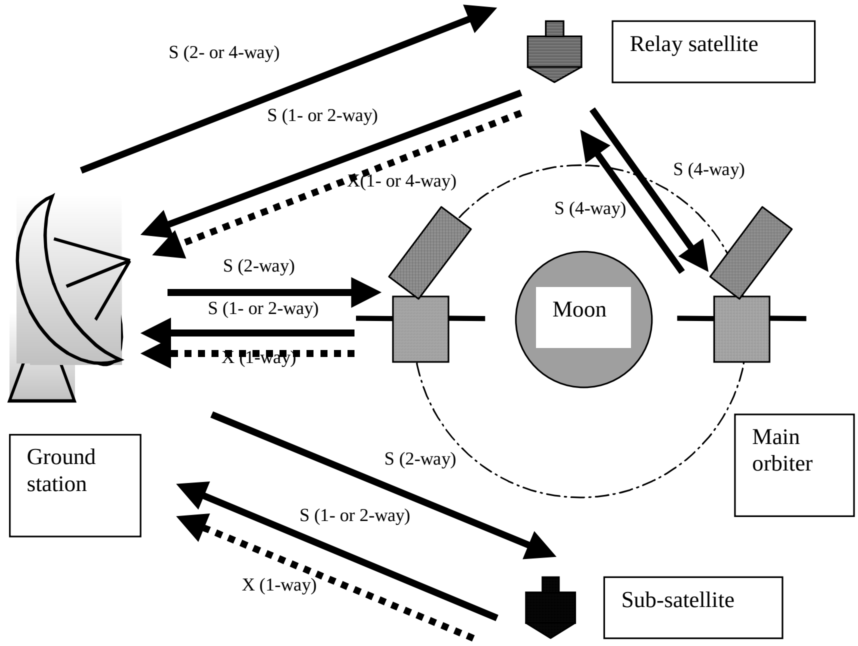

Figure 4. A schematic of the radio-communication system of the SELENE mission. The solid and broken arrows indicate the S and X bands, respectively. The relay satellite has an oscillator for a VLBI experiment, and a transponder for four-way communication. The sub-satellite has an oscillator for VLBI, and a transponder for two-way. The relay satellite and sub-satellite can emit S and X bands simultaneously in one-way mode

of the lunar surface, corresponding to an electron density of $\sim 10^9$ m^{-3} for the case of spherical symmetry. During the Lunar Prospector mission, "an intriguing magnetic anomaly on the moon's surface has been found that can stand off the solar wind, thus creating the smallest known magnetosphere, magnetosheath and bow shock system in the Solar System" [23]. Maybe the next step will be the discovery of "local mini-ionospheres" near the moon's surface.

The radio-communication system of the SELENE mission, shown in Figure 4, provides various possibilities for conducting radio occultation. The mission is composed of a main orbiter, a relay satellite, and a sub-satellite for a VLBI (very long baseline interferometry) experiment. Radio occultation will basically be performed using the coherent S- and X-band downlink from the main orbiter. Other suitable configurations, using the relay and sub-satellites for the detection of the charged particle layer, are now being planned.

3.3 Planet-C, a Venus Orbiter

The Planet-C mission, which has recently been officially approved as an ISAS project, is devoted to studies of Venus. The spacecraft should be driven into orbit around Venus in 2009. The primary objective of the mission is to investigate the atmospheric dynamics of Venus, using optical remote sensing and radio occultation. The radio-occultation technique has been utilized to study the thermal structure of the Venusian atmosphere [24]. Recently, radio occultation has also revealed the vertical distribution of sulfuric-acid vapor [25], and the presence of internal gravity waves [26]. The Planet-C mission will provide new information on the three-dimensional structure of Venusian meteorology, by combining the high-vertical-resolution profiles taken by radio occultation and the high-spatial-resolution imagestaken by onboard optical instruments.

The radio communication system of Planet-C will use X band in both the uplink and the downlink. The X-band signals can also be employed for occultation measurements of the solar corona in the range of impact parameter below five solar radii, in an attempt to get information on the parameters of the solar wind, in particular, on the characteristic scale of magnetohydrodynamic turbulence. Those results would be useful in solving the problem of the origin of the solar-wind plasma irregularities: generation by the Alfvén waves propagating from the transition-layer base, or generation by local instabilities [27].

4. Concluding Remarks

Past and future projects of radio occultation in Japan have been described. The projects cover the exploration of planetary atmospheres, the solar wind, and their interaction. The long history of radio occultation has shown the importance of the method, its advantages and disadvantages. The method is regarded as a powerful tool for space investigations in future missions, especially for exploring regions unattainable by other means.

The potential for space programs of Japan is seriously limited by the locations of the deep-space tracking antennas. To increase the opportunities in space research, several deep-space tracking antennas located at different longitudes are required. International collaboration in radio science is strongly needed.

5. Acknowledgement

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6. References

1. G. Fjeldbo and V. R. Eshleman, "The Bistatic Radar-Occultation Method for the Study of Planetary Atmospheres," *J. Geophys. Res.*, **70**, 1965, pp. 3217-3225.

2. R.A. Phinney and D. L. Anderson, "On the Radio Occultation Method for Studying Planetary Atmospheres," *J. Geophys. Res.*, **73**, 1968, pp. 1819-1827.

3. G. Fjeldbo, A. J. Kliore, and V. R. Eshleman, "The Neutral Atmosphere of Venus as Studied with the Mariner V Radio Occultation Experiments," *Astron. J.*, **76**, 1971, pp. 123-140.

4. D.P. Hinson, J. D. Twicken, and E. T. Karayel, "Jupiter's Ionosphere: New Results from Voyager 2 Radio Occultation Measurements," *J. Geophys. Res.*, **103**, 1998, pp. 9505-9520.

5. M.E. Gorbunov, A. S. Gurvich, and L. Kornblueh, "Comparative Analysis of Radioholographic Methods of Processing Radio Occultation Data," *Radio Science*, **35**, 2000, pp. 1025-1034.

6. R. Woo, F.-C. Yang, K. W. Yip, and W. B. Kendall, "Measurements of Large-Scale Density Fluctuations in the Solar Wind using Dual-Frequency Phase Scintillations," *Astrophys. J.*, **210**, 1976, pp. 568-574.

7. R. Woo and J. W. Armstrong, "Spacecraft Radio Scattering Observations of the Power Spectrum of Electron Density Fluctuations in the Solar Wind," *J. Geophys. Res.*, **84**, 1979, pp. 7288-7296.

8. M. K. Bird, "Coronal Investigations with Occulted Spacecraft Signals," *Space Sci. Reviews*, **33**, 1982, pp. 99-126.

9. K. Hirao and T. Itoh, "Project Overview and Highlights of Suisei and Sakigake," *Adv. Space Res.*, **5**, 1985, pp. 55-64.

10. G.F. Lindal, "The Atmosphere of Neptune: An Analysis of Radio Occultation Data Acquired with Voyager 2," *Astron. J.*, **103**, 1992, pp. 967-982.

11. E. Mizuno, N. Kawashima, T. Takano, and P. A. Rosen, "Voyager Radio Science: Observations and Analysis of Neptune's Atmosphere," *IEICE Trans. Commun.*, **E75-B**, 1992, pp. 665-672.

12. G.F. Lindal, H. B. Hotz, D. N. Sweetnam, Z. Shippony, J. P. Brenkle, G. V. Hartsell, R. T. Spear, and W. H. Michael, Jr., "Viking Radio Occultation Measurements of the Atmosphere and Topography of Mars: Data Acquired During 1 Martian Year of Tracking," *J. Geophys. Res.*, **84**, 1979, pp. 8443-8456.

13. D.P. Hinson, R. A. Simpson, J. D. Twicken, G. L. Tyler, and F. M. Flasar, "Initial Results from Radio Occultation Measurements with Mars Global Surveyor," *J. Geophys. Res.*, **104**, 1999, pp. 26,997-27,012.

14. D.P. Hinson, G. L. Tyler, J. L. Hollingsworth, and R. J. Wilson, "Radio Occultation Measurements of Forced Atmospheric Waves on Mars," *J. Geophys. Res.*, **106**, 2001, pp. 1463-1480.

15. S.W. Bougher, S. Engel, D. P. Hinson, and J. M. Forbes, "Mars Global Surveyor Radio Science Electron Density Profiles: Neutral Atmosphere Implications," *Geophys. Res. Lett.*, **28**, 2001, pp. 3091-3094.

16. N.A. Savich, V. A. Samovol, M. B. Vasilyev, A. S. Vyshlov, L. N. Samoznaev, A. I. Sidorenko, and D. Ya. Shtern, "The Nighttime Ionosphere of Mars from Mars-4 and Mars-5 Radio Occultation Dual-Frequency Measurements," *NASA-SP*, **397**, 1976, pp. 41-46.

17. M.H.G. Zhang, J. G. Luhmann, and A. J. Kliore, "An Observational Study of the Nightside Ionospheres of Mars and Venus with Radio Occultation Methods," *J. Geophys. Res.*, **95**, 1990, pp. 17,095-17,102.

18. M.I. Verigin, K. I. Gringauz, N. M. Shutte, S. A. Haider, K. Szego, P. Kiraly, A. F. Nagy, and T. I. Gombosi, "On the Possible Source of the Ionization in the Nighttime Martian Ionosphere 1. Phobos 2 HARP Electron Spectrometer Measurements," *J. Geophys. Res.*, **96**, 1991, pp. 19,307-19,313.

19. S.A. Haider, J. Kim, A. F. Nagy, C. N. Keller, M. I. Verigin, K. I. Gringauz, N. M. Shutte, K. Szego, and P. Kiraly, "Calculated Ionization Rates, Ion Densities, and Airglow Emission Rates due to Precipitating Electrons in the Nightside Ionosphere of Mars," *J. Geophys. Res.*, **97**, 1992, pp. 10,637-10,641.

20. J.L. Fox, J. F. Brannon, and H. S. Porter, "Upper Limits to the Nightside Ionosphere of Mars," *Geophys. Res. Let.*, **20**, 13, 1993, pp. 1391-1394.

21. J.C. Pomalaza-Diaz, "Measurements of the Lunar Ionosphere by Occultations of the Pioneer 7 Spacecraft," Stanford Electronics Laboratory Scientific Report No. SU-SEL-67-095, 1967.

22. A.S. Vyshlov, "Preliminary Results of Circumlunar Plasma Research by the Luna 22 Spacecraft," *Space Res.*, **XVI**, 1976, pp. 945-949.

23. G.S. Hubbard, S. A. Cox., M. A. Smith, T. A. Dougherty, and L. Chu-Thielbar, "Lunar Prospector: Continuing Mission Results," 50th International Astronautical Congress, 1999, pp. 2-9.

24. M. Newman, G. Schubert, A. J. Kliore and I. R. Patel, "Zonal Winds in the Middle Atmosphere of Venus from Pioneer Venus Radio Occultation Data," *J. Atmos. Sci.*, **41**, 1984, pp. 1901-1913.

25. J.M. Jenkins, P. G. Steffes, D. P. Hinson, J. D. Twicken, and G. L. Tyler, "Radio Occultation Studies of the Venus Atmosphere with the Magellan Spacecraft: 2. Results from the October 1991 Experiments," *Icarus*, **110**, 1994, pp. 79-94.

26. D.P. Hinson and J. M. Jenkins, "Magellan Radio Occultation Measurements of Atmospheric Waves on Venus," *Icarus*, **114**, 1995, pp. 310-327.

27. I.V. Chashei, "On the Characteristic Scale of Magnetohydrodynamic Turbulence in the Solar-Environment Plasma," *Solar System Res.*, **32**, 1998, pp. 316-322.