# RADIO SOUNDING SCIENCE AT HIGH POWERS

J. L. Green[1], B. W. Reinisch[2], P. Song[2], S. F. Fung[1], R. F. Benson[1],
W. W. L. Taylor[1], J. F. Cooper[1], L. Garcia[1], T. Markus[1], D. L. Gallagher[3],
P. Gogineni[4]
[1]NASA/GSFC Greenbelt, MD, USA
[2]Center for Atmospheric Research, Univ. of Mass. Lowell, Lowell, MA, USA
[3]NASA/MSFC, Huntsville, AL, USA
[4]Remote Sensing Laboratory, University of Kansas, USA

## ABSTRACT

Future space missions like the Jupiter Icy Moons Orbiter (JIMO) planned to orbit Callisto, Ganymede, and Europa can fully utilize a variable power radio sounder instrument. Radio sounding at 1 kHz to 10 MHz at medium power levels (10 W to kW) will provide long-range magnetospheric sounding (several Jovian radii) like those first pioneered by the radio plasma imager instrument on IMAGE at low power (<10 W) and much shorter distances (<5 $R_E$). A radio sounder orbiting a Jovian icy moon would be able to globally measure time-variable electron densities in the moon ionosphere and the local magnetospheric environment. Near-spacecraft resonance and guided echoes respectively allow measurements of local field magnitude and local field line geometry, perturbed both by direct magnetospheric interactions and by induced components from subsurface oceans. JIMO would allow radio sounding transmissions at much higher powers (~10 kW) making subsurface sounding of the Jovian icy moons possible at frequencies above the ionosphere peak plasma frequency. Subsurface variations in dielectric properties, can be probed for detection of dense and solid-liquid phase boundaries associated with oceans and related structures in overlying ice crusts.

## Introduction

An advanced radio sounder instrument on missions to icy moons and other bodies in the solar system can provide critical and diverse measurements necessary for detection of subsurface oceans and for characterization of moon ionospheres, magnetosphere-moon interactions, and permanent or induced magnetic fields. This information is critical for fulfillment of Solar System Exploration requirements, including determination of whether life is possible on such bodies [1,2,3].

The first opportunity to fly a sounder instrument of this type is on the nuclear electric power and propulsion (NEPP) enabled Jupiter Icy Moons Orbiter (JIMO) mission. The JIMO scientific objectives include determining the presence and distribution of subsurface water in the icy moons and determining the nature of magnetosphere-moon interactions [4]. As illustrated in Figure 1, five fundamental scientific measurements can be made by an advanced radio sounder/wave instrument:

- **Subsurface sounding** of solid bodies, to survey ice stratigraphy underlying visible planetologic features and to detect the presence and location of regional lakes and global oceans.
- **Sounding of moon ionospheres**, to measure altitude profiles of electron

density below the spacecraft at points along its orbit.

• **Remote magnetospheric sounding**, to obtain electron density distributions along the magnetic field line through the spacecraft. Magnetospheric sounding would probe the Jupiter and Ganymede magnetospheres, and induced magnetic fields around Europa and Callisto from their subsurface oceans.

• **Local sounding**, to determine the magnetic field strength and the electron density at the spacecraft, even at times when propulsion system operations preclude direct field and plasma measurements.

• **Passive electric field observations,** to measure natural electromagnetic and electrostatic emissions.

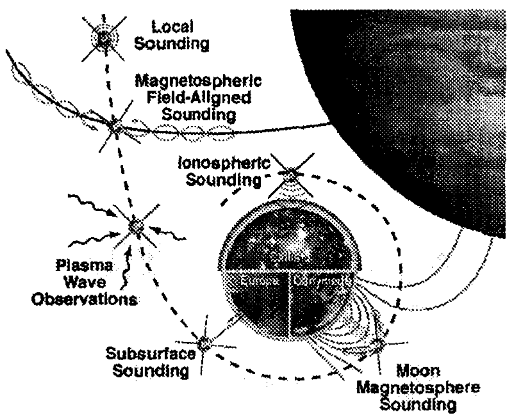


Fig. 1: Five critical measurements for JIMO and NEPP enabled missions.

Radio sounders have been flown for decades in the near-Earth environment such as the ionospheric sounders on the Alouette/ISIS series of satellites, and most recently the magnetospheric sounder, Radio Plasma Imager (RPI) on the IMAGE spacecraft [5]. Because the space environment around the Jovian icy moons is different from that of Earth, major innovations will be needed for the successful operation of an advanced radio sounder at Jupiter [6]. This paper will concentrate on those improvements to radio sounding that can take advantage of the higher electric power, higher duty cycles, and data rates planned for on NEPP class missions. Current work on these improvements is being funded by NASA's High Capability Instruments for Planetary Exploration (HCIPE) program.

Frequency Range

To achieve all of the possible science objectives of JIMO and other NEPP-enabled missions, the sounder will operate over a large frequency range, 1 kHz – 50 MHz, to perform the different measurements listed above. For subsurface sounding, the sounder provides useful subsurface echoes only above the ionospheric peak plasma frequency. For ionospheric sounding it should operated over a frequency range of 90 khz to ~ 9 MHz based on the expected upper plasma density range for the Galilean moons, including Io, of $10^2$ - $10^6$ $cm^{-3}$ [7, 8, 9, 10, 11]. Much like the sounding in the Earth's magnetosphere, the frequency range for Jovian magnetospheric sounding (based on realistic spacecraft orbits) is 1 to ~ 800 kHz. This frequency range, which partly overlaps that for ionospheric sounding, allows echoes to be received from large distances both across and along field-lines in the Jovian magnetosphere and moon environments. The frequency range for local sounding is from 1 to ~ 900 kHz covering an *in situ* density range from much less than 0.1 up to $10^4$ $cm^{-3}$. This frequency range ensures that the expected high densities at low altitudes within the icy moons' ionospheres will be measured. Finally, nearly all of the natural plasma-wave emissions from the Jovian magnetosphere covers the same frequency range up to ~ 40 MHz [12].

## Subsurface Sounding

For subsurface sounding, reflections occur at stratigraphic boundary layers with sharp changes in the dielectric properties of the medium, e.g., at the interfaces between two different phases of water or between water and soil. Subsurface sounding data will yield information about internal structure and properties. Also, such data are sensitive to tidal deformation amplitudes of moon surfaces. Tidal deformation of up to 30 m for Europa is expected [13, 14]. The icy moons of Jupiter are of similar overall composition, but show different surface features as a result of different sub-surface processes. Each of these moons could have water under an icy crust, but its structure and thickness are unknown. For Europa, the ice crust thickness. has been estimated to be between 2 and 30 km. Many of the uncertainties are due to the largely unknown temperature gradients and different levels of water impurities across various subsurface layers. One of the most important potential processes for internal evolution is transport of heat by ice convection. If the ice is convecting, then surface ice should be no thicker than 20 km [15]. Convection leads to a sharp increase in temperature followed by a thick region of nearly constant temperature. If ice is not convecting, then an exponentially increasing temperature profile is expected. The crust is thought to be a low-density mixture of ice and rock in unknown proportions. Additionally, the ice crust could contain salt, similar to sea ice on the Earth. The exact amount of salt and how that amount changes with depth is also unknown.

Radars operating in the HF and VHF region of the EM spectrum have been used to sound thousands of meters through glacial ice [16,17] and a few meters of sea ice [18, 19]. Radar techniques have been widely used to obtain information about spatial variation of internal structure, thickness, bed roughness and basal conditions of polar ice sheets [16, 17, 20, 21]. Our current knowledge about Lake Vostok, a Europa ocean analog at kilometer depth in Antarctic ice, is primarily derived from radio sounding.

Figure 2 shows an echogram collected by the University of Kansas coherent chirp-radar operating at peak transmit power of about 100 W. The data, collected with aircraft flying at a height of 500 m above the Greenland ice surface, show clear ice bed echoes and layering between 40 km and 130 km along the flight path. Ice bed echoes are masked by off-vertical clutter, signals scattered toward the radar by the rough ice surface, from the starting point to about 40 km along the flight path.

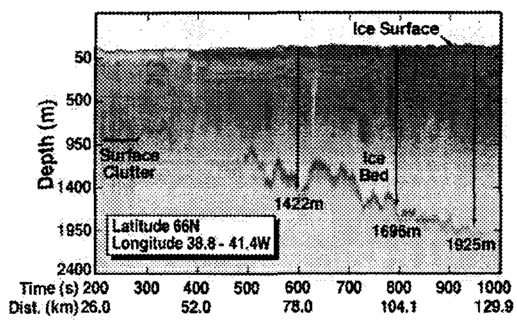


Fig. 2: A radar echogram of subsurface layers from Greenland.

Clutter can be an even more severe problem for an orbital radar because of the larger surface area in the field of view. Thus a JIMO sounder capable of subsurface echo detection must have a programmable waveform, high power, and signal processing capability to overcome this problem.

## Remote Ionospheric Sounding

Knowledge of the ionospheric structure of each moon is essential to correctly interpret subsurface sounding data as well as modeling magnetosphere-surface interactions. The ionosphere changes the propagation speed of the sounder pulses. In addition, the electron density distribution in the ionosphere allows us to infer the ionospheric composition and the ionization and recombination processes important to atmospheric evolution and surface chemistry.

Much of our understanding of the topside ionosphere (above the maximum electron density) was discovered using data from space-borne ionospheric sounders such as those on the Alouette/ISIS satellites. An example of a digital ISIS-2 topside ionogram is shown in Figure 3A. Figure 3B shows the electron density as a function of height as derived from echoes in panel A. This inversion process has been performed on a large number of such ionograms using an automated density inversion technique [22].

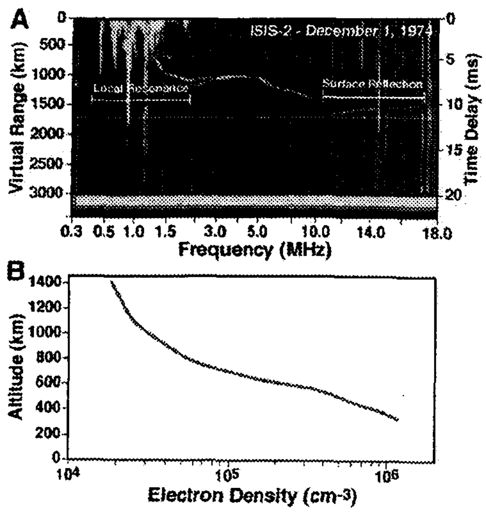


Fig. 3: A) shows an ISIS ionogram including reflections from the Earth's ocean surface and B) is the plasma density profiled derived from the ionospheric reflections.

In addition to the topside trace in the frequency range 1.25 to 10 MHz this example also shows the return trace from the ocean surface at 10 to 18 MHz. Therefore, ionospheric sounding provides the electron density distribution and information about the conducting layer below the ionosphere.

## Remote Magnetospheric Sounding

Magnetospheric sounding has been an invaluable technique for determining the electron plasma density distribution in the Earth's magnetosphere [23, 24] and will be essential for understanding plasma interactions between planetary moons and their magnetospheric environments.

The RPI on IMAGE is in an Earth polar orbit with an apogee altitude of ~7.2 $R_E$ (1 $R_E$ = 6371 km) and applies radio sounding techniques to measure electron plasma densities. Figure 4A shows an example of a plasmagram (analogous to an echogram or an ionogram) that displays measurements of echo amplitudes as functions of echo frequency and time delay (converted into virtual range by multiplying one half of the delay time by the speed of light). A complete scan of 114 logarithmically spaced frequencies takes about 2 minutes. The pulse width of 3.2 ms translates to a virtual range resolution of about 500 km.

Echoes at different frequencies that propagate in the same mode and direction form a distinct trace on a plasmagram. Figure 4A shows five such traces; indicating that only a limited number of modes and propagation directions can produce strong echo traces. The five traces in Figure 4A were actually produced by three modes, labeled X and Z in the figure (the Z involves coupling to the O mode), each propagating parallel (toward the northern hemisphere, labeled N) and anti-parallel (toward the southern hemisphere, labeled S) to the magnetic field direction [24]. The field-aligned electron density profiles in the two hemispheres, derived self-consistently from the five traces are shown in Figure 4B as one curve as a function of latitude. Using this electron density profile, traces are reproduced for the two Z traces and are shown as black curves in Figure 4A (along with the curves through the X traces used to derive the electron-density profile).

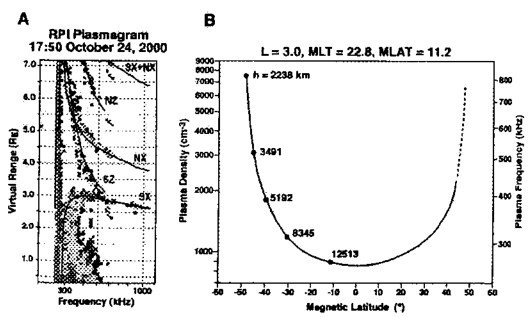


Fig. 4: The RPI plasmagram in A) show field-aligned echoes, which allow inversion of the data into a field-aligned plasma density profile, in B).

Multiple field-aligned density profiles obtained successively along the spacecraft track by RPI can be combined to produce a 2-dimensional density distribution along the field and along the IMAGE spacecraft track [25, 26, 27]. When the spacecraft revisits the same region periodically in different orbits, the plasma depletion and refilling and other dynamic processes can be investigated [28].

Analysis of radio sounder plasmagrams at a sufficient rate will locate transitions from closed (dipolar) to open field lines, very important for Ganymede and perhaps as well for complex time-varying fields around Europa and Callisto. Here we note that magnetometers accurately measure local vector magnetic fields but alone do not reveal remote field-line topology.

## Local Sounding

While radio sounding requires high transmitter power for long-range remote sensing, little power is needed to probe electron density and magnetic field intensity near the spacecraft location. Independent measurements of the *in situ* electron density and the magnetic field strength provided by a sounder are important for calibrations of the same quantities measured by other instruments. At times, the direct magnetometer and plasma spectrometer measurements may be limited by spacecraft propulsion system operations. A transmitting antenna immersed in a space plasma with electron density and magnetic field is capable of generating electrostatic as well as electromagnetic echoes. On topside ionograms, such as the one shown in Figure 2A, the former appear as prominent "stalactites" extending down from the zero virtual range base line. Because of their appearance, they have been referred to as resonances. They occur at the electron plasma frequency $f_{pe}$, the electron cyclotron frequency $f_{ce}$ and harmonics $nf_{ce}$, the upper-hybrid frequency $f_{uh} = (f_{pe}^2 + f_{ce}^2)^{1/2}$, and at other frequencies determined mainly by the ratio $f_{pe}/f_{ce}$. Since they correspond to waves that echo at small distances ($10^2$-to-$10^3$ meters in the ionosphere) from the spacecraft, and since their frequencies can be determined to within a few percent or less, they enable accurate determinations of the ambient electron density and magnetic-field strength that are not contaminated by spacecraft-plasma interactions. These accurate ambient values provide the starting point for the inversion of the long-range echoes into electron-density profiles [29].

### Natural Plasma Waves

For completeness, although high power is not needed to observe the natural wave environment, radio sounders can easily perform this type of measurement. All planetary magnetospheres produce a number of plasma wave emissions, but Jupiter produces the most complex planetary radio spectrum in the solar system. Jupiter's magnetosphere is filled with electromagnetic radiation from a few mHz to 10s of MHz and higher. Each Jovian radio component tends to have its own occurrence rate, distribution and morphology, and thus seems to have a separate origin [12].

Plasma waves found naturally in the Jovian magnetosphere are of interest because: 1) their activities and propagation contain important information about the dynamical processes (e.g., plasma instabilities) and plasma environment (e.g., electron density and magnetic field strength) in the planetary magnetosphere, and 2) their measurements provide ground truth for analyzing active radio sounding measurements. In addition, natural emissions are a significant background for active sounding operations. The sounder operation above ~ 40 MHz nominal frequency chosen for the pre-JIMO Europa Orbiter mission design was selected to minimize natural background emission on average, but sweep-frequency monitoring in moon orbit could reduce this constraint. As done on the IMAGE/RPI instrument a passive measurement between any of the above sounding sequences can be done quickly and provides routine measurement of the natural plasma waves [30].

### Resolution of Subsurface Structures

Subsurface sounding data with spatial sampling required to define vertical stratigraphy at depth resolution of about 200 m (1 μs pulse-width) and horizontal area resolution of about 5 $km^2$ or better (assuming a spacecraft altitude at a few 100 km) can be achieved. The minimum pulse width of 1 μs limits the resolution for the separation of consecutive depth layers. The return echo path is approximately confined to a plane perpendicular to the spacecraft track. Resolution of a few hundred meters in the along-track direction can be obtained by filtering of Doppler-shifted echoes. The resolution in the cross-track direction can be several km, depending on frequency, spacecraft altitude, and pulse length.

The horizontal resolution along the spacecraft track depends on the measurement rate; i.e., the time between repetitive measurements. The measurement rate depends on the length of each listening phase (the target range of interest) and the number of frequencies in each scan (combination of the frequency resolution and the frequency range). The spatial resolution for the sounder is determined by the digital sampling rate which is also limited by the telemetry data rate. The higher NEPP-enabled data rate allows for a substantial increase in the measurement rate. A high data rate is also required for subsurface sounding. In this mode, the sampling rate is 250 ns for a depth resolution of about 200 meters. Assuming 20 km of subsurface coverage, the data rate can be as high as 2 Mb/s. For a lower limit, with a reduced frequency resolution or spatial resolution along the satellite track, a nominal 0.5 Mb/s data rate in the subsurface sounding mode can be used.

For magnetospheric sounding, the strongest echoes propagate along the field [24, 31, 32]. The choice of the adjustable pulse width in the 1 μs to 3.2 ms range depends on the scale size of the sampled region, i.e. 500 km resolution is sufficient for sounding along Jovian magnetospheric field lines, while kilometer resolution is needed for moon magnetic field regions, e.g., for Ganymede's magnetosphere.

## High Power Requirements

Three measurement objectives that require high-power transmissions are (1) subsurface sounding, to produce detectable subsurface echoes, (2) ionospheric sounding for the detection of remote low electron densities, and (3) magnetospheric sounding, to cover large the spatial scales of the Jovian magnetosphere. Table 1 summarizes the power requirements of the 4 sounder science objectives.

| Science Objectives | Sounder Power Required (W) |
|---|---|
| Subsurface sounding | 10,000 |
| Magnetospheric sounding | 10-10,000 |
| Ionospheric Sounding | 100 - 500 |
| Local Resonances | 10 |

Table 1: Sounder Power Requirements

For subsurface sounding, using the simulation described in [33] and applied to subsurface sounding at Jupiter's icy moons for 10 kW of transmitted power at 10 MHz, a signal is detectable for a depth of 10 km for 1% impurities and more than 20 km for 0% impurities [6].

The power used for the Earth's ionospheric sounding by the ISIS satellites was 400 watts. This power was generated by solar cells. For missions to distant planets, even this amount of power would not be available from solar cells and therefore would be considered high power.

The required transmitter power in Table 1 is much higher than that of the IMAGE/RPI instrument used in the terrestrial magnetosphere. RPI transmits 10 W and receives good ducted echoes within ~5 $R_E$, which is about 1/6 to 1/2 the size of the dayside terrestrial magnetosphere. The Jovian magnetosphere is much larger. The same proportion of the Jovian magnetosphere, 25~50 $R_J$, is a factor of 60~120 in distance over the terrestrial counterpart. If the signal power decreases with $1/r^2$ (specular reflection), a transmitter of 30~120 kW would be required. Since the terrestrial observations have revealed field-aligned propagation [24, 31, 32], where the echo power drops more slowly with distance than $1/r^2$, a transmitter power of 30 W to 10 kW should be adequate for Jovian magnetospheric duct sounding.

## Conclusion

Future NEPP missions will have a large power sources for propulsion, science instruments, and data telemetry. A radio sounder can be fully powered by the new nuclear power source in missions like JIMO that will orbit Callisto, Ganymede, and Europa. A radio sounder orbiting a Jovian icy moon would be able to measure the electron density in: 1) the local environment (using up to 10 W), 2) the ionosphere (using a few 100 W), 3) in the magnetosphere (10 W to 10 kW). These measurements would provide information on the Jovian magnetospheric background, the magnetospheric influences on the moon's ionospheres, and distortions of magnetic field-line geometry from model predictions. JIMO would also allow radio sounding transmissions at much higher powers (~10 kW) making subsurface sounding of the Jovian icy moons possible at frequencies above the ionosphere peak plasma frequency from ~5 MHz to 50 MHz. Such sounding would allow subsurface variations in dielectric properties to be investigated allowing for the detection of dense and solid-liquid phase boundaries associated with oceans and related structures in overlying ice crusts.

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## References

[1] Office of Space Sciences, The Solar System Exploration Roadmap, NASA JPL, 400-1077, May, 2003.

[2] Cooper, J. F., et al., Europa exploration: Science and mission priorities, *The Future of Solar System Exploration, 2003 - 2013, Community Contributions to the NRC Solar System Exploration Decadal Survey, ASP Conf. Ser. 272*, 217-252, 2002.

[3] Belton, M. J. S., et al., New Frontiers in the Solar System: An integrated exploration strategy, Solar System Exploration Survey, Space Studies Board, Division on Engineering and Physical Sciences, National Academies Press, Washington, D.C., 2003.

[4] Science Forum, Jupiter Icy Moons Orbiter: Objectives, Investigations, Measurements, July 23, 2003.

[5] Reinisch, B.W., et al., The Radio Plasma Imager investigation on the IMAGE spacecraft, *Space Science Reviews*, *91*, 319-359, 2000.

[6] Green, J. L., et al., Radio sounding techniques for the Galilean icy moons and their Jovian magnetospheric environment, Submitted to *Icarus*, August 2004.

[7] Hinson, et al., Galileo radio occultation of Io's ionosphere and plasma wake, *J. Geophys. Res.*, *103*, 29343-29357, 1998.

[8] Kliore, A. J., et al., The ionosphere of Europa from Galileo radio occultations, *Science*, 277, 355, 1997.

[9] Kliore, A. J., Satellite atmospheres and magnetospheres, *Highlights of Astronomy*, Vol. 11B, International Astronomical Union, 1065-1069, 1998.

[10] Kliore, A. J., et al., Ionosphere of Callisto from Galileo radio occultation observations, *J. Geophys. Res.*, *107*, 1407, 10.1029/2002JA009365, 2002.

[11] Eviatar, A., et al., The ionosphere of Ganymede, *Planet. Sp. Sci.*, *49*, 327-336, 2001.

[12] Carr, T. D., et al., Phenomenology of magnetospheric radio emissions, in

*Physics of Jovian Magnetosphere*, Cambridge University Press, 1983.
[13] Yoder, C. F., and W. L. Sjogren, Tides on Europa, Europa Ocean Conference, San Juan Capistrano Inst., San Juan Capistrano, Calif., 1996.
[14] Moore, W. B. and G. Schubert, The tidal response of Europa, *Icarus*, *147*, 317-319, 2000.
[15] Moore, J.C., Models of Radar Absorption in Europan Ice, *Icarus 147*, 292-300, 2000.
[16] Bogorodskiy, V. V., et al., *Radioglaciology*, D. Reidel, 254, 1985.
[17] Gogineni, S., T. et al., Improved coherent radar depth sounder, *J. Glaciol.*, *44* (148), 659-669, 1998.
[18] Kovacs, A. and R.M. Morey, Electromagnetic measurements of multiyear sea ice using impulse radar, *Cold Regions Science and Technology*, *12*, 67-93, 1986.
[19] Okamoto, K., et al., Step-frequency radar for the measurement of sea ice thickness, Memoirs of National Institute of Polar Research, *45*, 56-65, 1986.
[20] Arcone, S. A., et al, Short-pulse radar wavelet recovery and resolution of dielectric contrasts within englacial and basal and ice of Matanuska Glacier, Alaska, *J. Glaciol.*, *41*, 68-86, 1995.
[21] Fujita, S., et al., Nature of radio echo layering in the Antarctic ice sheet detected by a two-frequency experiment, *J. Geophys. Res.*, *104*(B6), 13013, 1999.
[22] Huang, X., et al., Electron density profiles of the topside ionosphere, *Ann. Geophys.*, *45*(1), 125-130, 2002.
[23] Reinisch, B. W., et al., First Results from the Radio Plasma Imager on IMAGE, *Geophys. Res. Lett.*, *28*, 1167-1170, 2001.
[24] Reinisch, B.W., et al., Plasma Density Distribution Along the Magnetospheric Field: RPI Observations from IMAGE, *Geophys. Res. Lett.*, *28*, 24, 4521-4524, 2001.
[25] Nsumei, P. A., et al., Electron density distribution over the northern polar region deduced from IMAGE/RPI sounding, *J. Geophys. Res.*, *108*(A2), 10.1029/2002JA009616, 2003.
[26] Song, P., et al., Magnetospheric active wave experiments, *Frontiers of Magnetospheric Plasma Physics*, in press, 2004.
[27] Huang, X., et al., Developing an empirical model of the plasmasphere using IMAGE/RPI data, *Adv. Space Res.*, *33* (6), 829-832, 2004.
[28] Reinisch, B. W., et al., Plasmaspheric mass loss and refilling as a result of a magnetostorm, *J. Geophys. Res.*, *109*, A01202, doi:10.1029/2003 JA009948, 2004.
[29] Benson, R. F., et al., Classification of IMAGE/RPI-stimulated plasma resonances for the accurate determination of magnetospheric electron-density and magnetic field values, *J. Geophys. Res.*, *108*(A5), 1207, doi:10.1029/2002JA009589, 2003.
[30] Green, J. L., et al., On the origin of kilometric continuum, *J. Geophys. Res.*, *107(A7)*, 10.1029/2001JA000193, 2002.
[31] Fung, S. F., et al., Guided echoes in the magnetosphere: Observations by Radio Plasma Imager on IMAGE, *Geophys. Res. Lett.*, *30*(11), 1589, doi:10.1029/2002GL016531, 2003.
[32] Fung, S. F., and J. L. Green, Modeling of field-aligned radio echoes in the plasmasphere, Submitted to *J. Geophys. Res.*, June 2004.
[33] Leuschen, C., S. et al., Simulation of a surface-penetrating radar for Mars exploration, *J. Geophys. Res.*, *108*(E4), 8035, doi:10.1029/2002JE001875, 2003.