Lessons Learned from Previous Space-Borne Sounders as a Guide to Future Sounder Development

Robert F. Benson¹, Mark L. Adrian¹, Manohar D. Deshpande², William M. Farrell³, Shing F. Fung¹, Vladimir A. Osherovich⁴, Robert F. Pfaff⁵, Douglas E. Rowland⁵

¹Code 673, NASA/Goddard Space Flight Center, Greenbelt, Maryland 20771 USA  
robert.f.benson@nasa.gov  
²Code 555 NASA/GSFC, Greenbelt, Maryland 20771 USA  
³Code 695, NASA/GSFC, Greenbelt, Maryland 20771 USA  
⁴Code 673, CUA/GSFC, Greenbelt, Maryland 20771 USA  
⁵Code 694, NASA/GSFC, Greenbelt, Maryland 20771 USA
OUTLINE

36 rocket, satellite and space-probe sounders from 7 countries since 1961

Space-borne radio sounding as the gold standard for \textit{in-situ} and remote electron-density ($N_e$) determinations even under low-density conditions such as $N_e < 1 \text{ cm}^{-3}$

Fundamental plasma processes and gradients in $N_e$ & $\mathbf{B}$ from sounder-stimulated plasma resonances and short-range echoes involving ion as well as electron motions

Importance of antenna orientation relative to $\mathbf{B}$ for the detection of plasma resonances

Importance of special plasma conditions for certain sounder-stimulated plasma phenomena such as field-aligned $N_e$ irregularities (FAI)

Nearly lossless propagation within $N_e$ wave ducts

Information on the terrain beneath the satellite from surface reflections

Summary
History of 36 space-borne sounders

1961: 3 US rockets tested antenna deployment and space-borne sounding concept

1962: first topside sounder satellite (Canadian built and US launched Alouette 1) survived unexpected artificial radiation belt created by high-altitude hydrogen-bomb test prior to launch and was operational for 10 years

1964 - 1994: 11 ionospheric topside sounder satellites built by 4 countries; Explorer XX, Alouette 2, ISIS 1, Cosmos 381, ISIS 2, ISS A & B, Intercosmos 19, EXOS C, Cosmos 1809 and CORONAS 1 (US, Canada, USSR, Japan)

1970 - 1995: 7 ionospheric sounding rockets built by 4 countries (France, US, Norway, Canada); 4 were dual payloads (2 each from Norway & Canada); wave propagation and plasma resonance investigations

1998: Orbital Complex on Mir Space Station

1977 - 2000: 10 magnetospheric sounding satellites built by 3 countries (GEOS 1, ISEE 1, GEOS 2, EXOS B, EXOS D, IMAGE and 4 Cluster satellites (France, Japan, US); all either of the relaxation type, or used mainly as relaxation sounders, except RPI on IMAGE

1990 - 2003: 3 extraterrestrial sounders; relaxation sounders at Jupiter (URAP/Ulysses) and Saturn (RPWS/Cassini) (US/France) and the ionospheric sounder and ground-penetrating radar (GPR) at Mars (MARSIS/Mars Express) (Italian/US)
ISIS-2 digital topside ionogram illustrating plasma resonances & echoes
Kashima, Japan, 23 May 1979 1023:41 UT, (18.5 N, 143.4 E, 1377 km)

Equivalent notation: $f_{ce} = f_H$, $f_{pe} = f_N$, $f_{uh} = f_T$
Space-borne radio sounding as the gold standard for $N_e$ measurements

ISIS X: dual launch of the Alouette-2 topside-sounder satellite and the Direct Measurements Explorer-A (DMEA) satellite (also known as Explorer XXXI)

Comparison of different DMEA probe techniques used the nearby Alouette-2 topside-sounder as the $N_e$ reference level
- Donley et al., Proc. IEEE., 57, 1078, 1969
- Wrenn and Smith, Proc. IEEE., 57, 1085, 1969

Comparison of DMEA and Alouette-2 cylindrical electrostatic probes indicated "no inherent incompatibility" between sounder and probe operations
- Brace and Findlay, Proc. IEEE., 57, 1057, 1969

DE-2 /ISIS-1 & ISIS-2 conjunction comparisons indicated topside $N_e(h)$ profiles typically accurate to within 30% even at greatest distance from sounder (near F peak)
- Hoegy and Benson, JGR, 93, 5947, 1988

Magnetospheric IMAGE/RPI $N_e$ values accurate to ~ 1% even when $N_e \sim 1 \text{ cm}^{-3}
- Benson et al., JGR, 108, A5, 1207, (SMP 16), 2003

Plasmaspheric loss & refilling, related to magnetic storm, based on IMAGE/RPI orbit-plane magnetospheric $N_e$ contours
- Reinisch et al., JGR, 109, A01202, 2004
Fundamental plasma processes and gradients in $N_e$ & $B$ from sounder-stimulated plasma resonances and short-range echoes

$f_{pe}$ & $f_{uh}$ resonances as oblique echoes due to gradients in $N_e$ & $B$ [McAfee, JGR, 1968]

Resonances and cutoffs self consistent to better than 1% [Warnock, Proc. IEEE, 1969]

$3f_{ce}$ resonance as oblique echoes due to gradients in $B$ [Muldrew, Radio Sci., 1972]

$(T_e)_{||}$ and $(T_e)_{\perp}$ from fringe patterns of $f_{pe}$ & $f_{uh}$ resonances [Warnock et al., JGR, 1970]

Stimulated plasma instability & nonliner phenomena, $f_{pe}/f_{ce}$ importance, new plasma wave mode [Oya, Phys. Fluids, 1971; Benson, Radio Sci., 1982; Osherovich, JGR, 1987]


Active wave determination of high-latitude ionospheric duct parameters [James, JGR, 2000]

Slow z-mode radiation from sounder-accelerated electrons [James, JGR, 2004]

Poynting vector interpretation of fce resonance [Muldrew, Radio Sci., 2006]
D1+ resonance antenna spin modulation on fixed- & swept-frequency

Optimal spin phase, calculated D1 & D1+ designated by *, D1, and +, respectively

**Optimal spin phase** coincides with 1.0 MHz (= FF) during frequency sweep.

**FF** = fixed freq.
Importance of special plasma conditions for certain sounder-stimulated plasma phenomena such as field-aligned $N_e$ irregularities (FAI)

Consecutive Alouette-2 ionograms showing Z-mode diffuse echoes when $f_N/f_H \approx n$ (for $n = 5$)

Attributed to sounder-stimulated FAI under these special plasma conditions

Benson, JASTP, 59, 2281, 1997
IMAGE/RPI example of nearly lossless propagation within hemisphere-to-hemisphere $N_e$ wave ducts forming multiple epsilon echo signatures

31 Aug 2002, 1850:28 UT (11.1 MLAT, 2:28 MLT, $L = 1.57$)

$S$ = short echo path (within local hemisphere)

$L$ = long echo path (extends to conjugate hemisphere)

Z-mode epsilons

- $3L + 3S$
- $3L + 2S$
- $2L + 3S$
- $2L + 2S \& 2S + 2L$
- $2L + S$
- $L + 2S$
- $L + S \& S + L$
- $L$

X-mode epsilons

- $2L + 3S$
- $2L + 2S \& 2S + 2L$
- $2L + S$
- $3L + 3S$
- $3L + 2S$
- $2L + 3S$
- $2L + 2S \& 2S + 2L$
- $2L + S$
Surface reflections also observed from Mars by the MARSIS sounder on Mars Express
ISIS-2 pass illustrating variations in surface reflection intensity
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Series prepared by K. Atkins
Surface-echo strengths from all ISIS-2 ionograms inspected

Work of N. Kurtz

- lake or Ross Ice Shelf boundary
- no echo
- questionable echo
- weak echo
- medium-strength echo
- strong echo
Peaceful coexistence with other in-situ & remote-measuring instruments demonstrated

Correct spectral identification of resonances and cutoffs yields accurate determinations of ambient $|B|$ (few tenths %) and $N_e$ (few %)

- auto detection of $|B|$ is almost always reliable
- auto detection of $N_e$ is seldom reliable but is feasible with correct spectral identification of all sounder-stimulated features

Additional parameters extracted from plasma resonances
- $N_e$ and $|B|$ gradients from accurate (< 1%) resonances and cutoffs
- $(T_e)_{||}$, from $f_{pe}$ resonance beat frequency as function of delay time
- $(T_e)_{\perp}$, from $f_{uh}$ resonance beat frequency as function of delay time
- $f_e(v)$ information from Qn resonances

Unexplained sounder-stimulated spectral features
- $D_{NT}$ resonance (observed between $f_{pe}$ and $f_{uh}$ mainly when $f_{pe}/f_{ce} < 1$)
- some prominent resonances below the $f_{ce}$ resonance
- resonance observed in the IMAGE/RPI data slightly above the $f_{ce}$ resonance
- Qn companion resonances and some diffuse resonances
- FAI stimulated when $f_{pe}/f_{ce} \approx n$
Summary (2 of 2)

Proper spectral identification requires understanding of sounder-stimulated resonances (from electrostatic wave echoes) and sounder-stimulated plasma emissions:
- high frequency resolution (wideband receiver output desired)
- combined fixed/swept-frequency operation
- accurate antenna-orientation information
- variable transmitter power
- science-quality magnetometer

Importance of $N_e$ field-aligned irregularities (FAI) in interpreting long-range sounding scattering from plasma patches and plasmapause and magnetopause
- long-range ducting (essentially lossless propagation)

Aids to automatic inversion of sounder echo traces to $N_e$ profiles
- direction-of-arrival determinations
- echo wave-polarization determinations

Possible to extract terrain information from surface reflections
- from conventional pulse modulation sounding
- detailed information using FM (chirp sounding) as a ground-penetrating radar
  as used in one mode of MARSIS on Mars Express
Abstract

Many nations have launched radio sounders in geospace over more than 4 decades and there have been sounders on space-probes and in orbit around other planets. Here we will summarize some of the lessons learned from these accomplishments by analyzing data from radio sounders on the Alouette and ISIS satellites and the OEDIPUS and other rockets in the terrestrial ionosphere, the IMAGE satellite in the terrestrial magnetosphere, the Ulysses space probe in Jupiter's Io plasma torus and the MARSIS satellite in orbit around Mars. Knowledge of these results should enable the optimum design of a future sounder.