

HF RADIO SOUNDING OF GEOSPACE PLASMAS

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ABSTRACT

Interferometric Doppler imaging has become an integral part in radio sounding of geospace plasmas. Doppler and angle of arrival measurements have become important tools of ionospheric HF radio science. The state of the art in HF sounding and automated ionogram interpretation for ground-based and space applications is reviewed in this paper.

INTRODUCTION

Radio sounding is a well-established technique that was first deployed in the 1920's for ionospheric sounding from the ground [1]. In recent years, advanced digital sounders were developed for ground-based observations that provide detailed information about the structure and dynamics of the bottomside ionosphere [2]. These modern sounders measure more than just the time of flight and amplitude of the echoes, they also determine the arrival angle, wave polarization, and Doppler frequency. Radio sounding relies on total reflection of radio waves from plasma structures that have plasma frequencies f_N equal to the radio frequencies f for the ordinary wave mode. It is, therefore, not possible on the ground to receive echoes reflected from the topside ionosphere –unlike the incoherent scatter radar echoes– or the magnetosphere since the ionospheric F2 layer prevents all transmitted waves with frequencies $f < foF2$ (the maximum plasma frequency) from propagating beyond the height of the F2 layer peak. The first topside ionospheric sounders [3], Alouette and ISIS [4, 5] recorded the amplitudes and echo delay times of ionospheric echoes as function of frequency in the same way it was done by the ground-based sounders of the time. The typical frequency range of the analog sounders was 0.1 to 20 MHz [6] corresponding to the plasma frequencies in the ionosphere. Recently, modern radio sounding techniques were applied to magnetospheric sounding with frequencies from 3 kHz to 3 MHz [7, 8], corresponding to electron densities of $N_e \approx 10^5$ to 10^{11} m^{-3} since $f_N/1Hz \approx 9 \sqrt{N_e/1m^{-3}}$. Modern topside ionospheric sounders that provide automatic ionograms scaling and electron density profiles are being prototyped but have not been flown yet.

PRINCIPLES OF RADIO SOUNDING

Remote sensing of space plasmas with radio waves was originally developed for ground-based ionospheric observations using different techniques: partial reflection (2-6 MHz), total reflection or radio sounding (0.1 –30 MHz), coherent scatter (10-100 MHz), and incoherent scatter (50-900 MHz). Hunsucker [9] gives a brief description of these different techniques. The discussion in this paper is limited to HF radio sounding of space plasmas. Electromagnetic waves propagate through a magnetoionic medium in the so-called free-space mode as long as $n^2 > 0$ where n is the index of refraction. Reflection occurs where $n = 0$ and the plasma density gradient is parallel to the wave normal [10]. Only waves with the so-called characteristic wave polarizations are solutions of Maxwell's equations [11]. The characteristic polarizations are generally right and left hand elliptical [12] with regard to the magnetic field direction. In ionospheric radio science, the left and right hand waves are usually referred to as ordinary and extraordinary waves. Solving dispersion relation for $n = 0$ gives the following three reflection conditions (cutoff frequencies):

$$\begin{aligned} X=1 & \quad \text{ordinary (O) wave} \\ X=1-Y & \quad \text{extraordinary (X) wave} \\ X=1+Y & \quad \text{Z-wave} \end{aligned} \tag{1}$$

$$\text{where } X = \left(\frac{f_N}{f} \right)^2, \quad Y = \frac{f_H}{f}, \quad f_N = \frac{1}{2\pi} \sqrt{\frac{N e^2}{m \epsilon_0}}, \quad f_H = \frac{e B_0}{2\pi m}.$$

N , e , and m are number density, charge, and mass of the electrons, ϵ_0 is the free space permittivity, and B_0 is the earth's magnetic field. The O and Z modes have left hand, and the X mode right hand polarization with respect to the magnetic field direction. Except at high latitudes, the Z mode is rarely observed from the ground and the two prevailing modes, O and X, can be identified by the sense of rotation of the \mathbf{E} field vector. Ionosondes typically scan through frequencies

from ~0.5 to 30 MHz transmitting narrow pulses into the vertical direction and measuring the echo delay time. The data can be displayed in form of an ionogram showing the echo delay as function of the sounding frequency. The echo delay t_d is usually expressed in terms of the virtual height $h' = 0.5 c t_d$ where c is the free space speed of light. The quiet daytime ionogram in Fig. 1 was recorded at Millstone Hill, Massachusetts (42°N) and shows echoes from the E, F1 and F2 layers. This ionogram is relatively easy to interpret since the ionosphere showed almost no irregularities –there is a traveling disturbance in the F1 region - and all the echoes were returned from overhead reflection points.

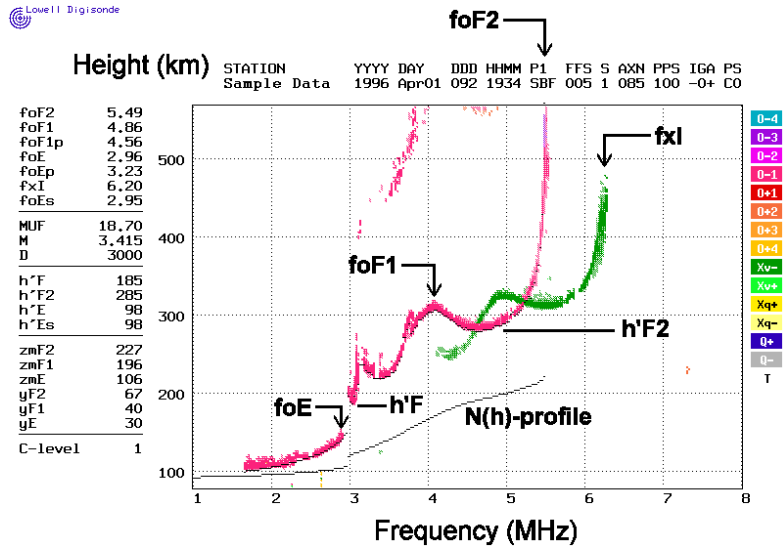


Fig. 1. Midday ionogram at Millstone Hill, MA displaying the O (red) and X (green) echo traces. Automatic scaling of the traces (black dashes at the leading edge of the traces) provides $h'(f)$, from which the electron density profile $N(h)$ is calculated. The corresponding plasma frequency profile is superimposed on the ionogram. A subset of the autoscaled characteristics is displayed on the left.

MODERN HF SOUNDERS

Modern sounders measure all echo parameters: echo delay time, amplitude, phase, Doppler frequency, wave polarization, and angle of arrival. Digital signal processing techniques have allowed reduced the radiated pulse power requirements to a few hundred watts from a few kilowatts in conventional ground-based ionosondes. These measurements make it possible to determine the structure and dynamics of the reflecting plasma, and they enable the automatic scaling of the ionograms and the calculation of the vertical electron density profiles in real time. Use of turnstile antennas determines the wave polarization, i.e., it identifies the ordinary (O) and extraordinary (X) wave components, and a properly spaced array of receiving antennas can determine the angle of arrival for ground-based observations. The array dimensions are comparable to the wavelength. Space-borne sounders require three orthogonal antennas for direction finding, and amplitude and phase measurements for each antenna signal [13]. Reinisch et al. [14] have described a simple way of finding the arrival angle by using the “quadrature vectors \mathbf{E}_i and \mathbf{E}_q ” obtained from the quadrature samples of the three orthogonal signal components. The vector product $\mathbf{E}_i \times \mathbf{E}_q$ is parallel to the wave normal, at least as long as the local plasma frequency is much smaller than the sounding frequency. These techniques produce correct arrival angles for a single arriving wave at frequency f . This is rarely the case, however, and echoes arrive simultaneously from different directions depending on the existing plasma structure. This creates complicated ionogram images with overlapping vertical and oblique O and X echoes as illustrated for a high altitude station in Fig. 2.

To correctly identify and interpret overlapping echoes in terms of plasma density and echo location it is necessary to measure the wave polarization (O or X), the arrival angle, and the Doppler shifts of the echoes together with the echo delay time, and not simply the echo amplitude (see the insert in Fig. 2). Fourier analysis of the signals at each range bin isolates the individual waves coming from different directions because of their different Doppler shifts:

$$d_j = \frac{1}{\pi} \mathbf{k}_j \cdot \mathbf{v} \tag{2}$$

Here \mathbf{k}_j is the wave vector, and \mathbf{v} is the velocity of the reflecting plasma. Applying interferometry to each spectral component determines the angles of arrival for the different echoes [15].

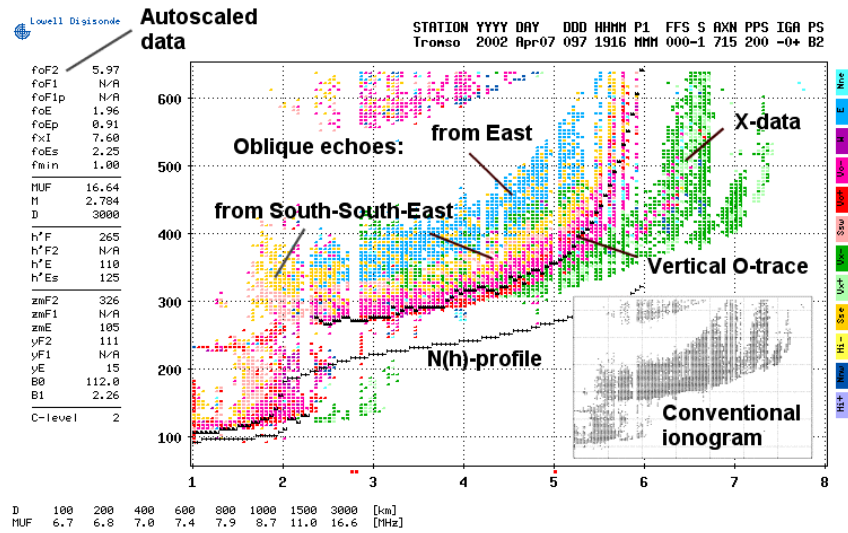


Fig. 2. Spread F ionogram at Tromso, Norway. Traces formed by echoes from the east, south-south-east, and overhead are clearly identified by the modern sounder. The autoscaled vertical O-trace (black dots) automatically generated the N(h) profile. The insert in the lower right corner shows the ionogram that conventional ionosonde would produce. The autoscaled characteristics on the left are reasonably accurate (Courtesy P. Cannon).

Fig.3 shows a sequence of low latitude ionograms from Boa Vista in Brazil just after sunset on 22 November 2002 during INPE’s COPEX campaign. The different colors give the directions from which the echoes are arriving.

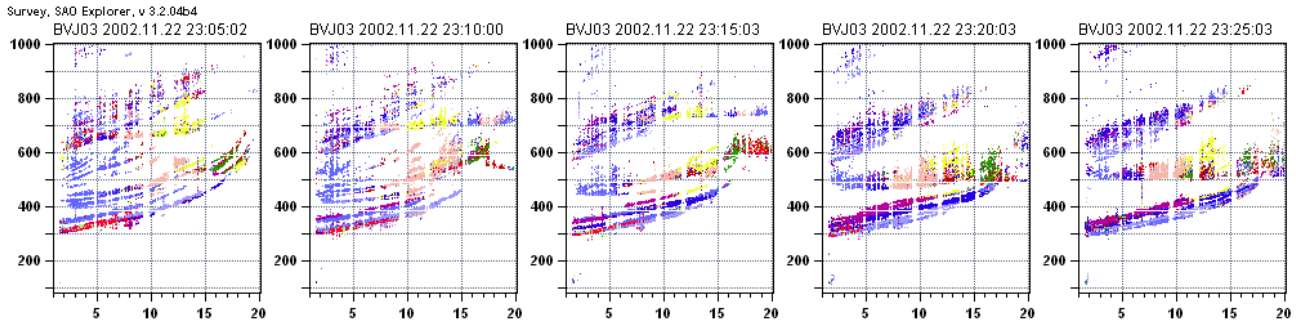


Fig. 3. Sequence of 5-min directional ionograms on 22 Nov 2003 at the Northern Equatorial Anomaly station in Boa Vista, Brazil. The red and green traces are the vertical echoes.

Information on the F layer horizontal structure at a given time is obtained from the echo skymap [2] that is similar to optical sky images. The skymaps [2] show the locations of the radio sources (reflection points), each source having its own line-of-site (LOS) velocity. The example in Fig.4 illustrates the conditions at 2229 LT during a spread F night at Jicamarca, Peru on 25 Mar 2003. Blue and red is used for positive and negative Doppler shifts, here clearly indicating a west to east drift of the plasma. The three dimensional velocity vector of the moving plasma is obtained from the set of LOS velocities [16]. The Digisonde at Jicamarca – like the 4 Brazilian Digisondes in Sao Luiz, Fortaleza, Cachoeira Paulista, and Sta. Maria, and the Digisonde at Tucuman, Argentina - calculates the velocity components in real time as illustrated in Fig. 5. The horizontal velocity components are given in magnetic coordinates.

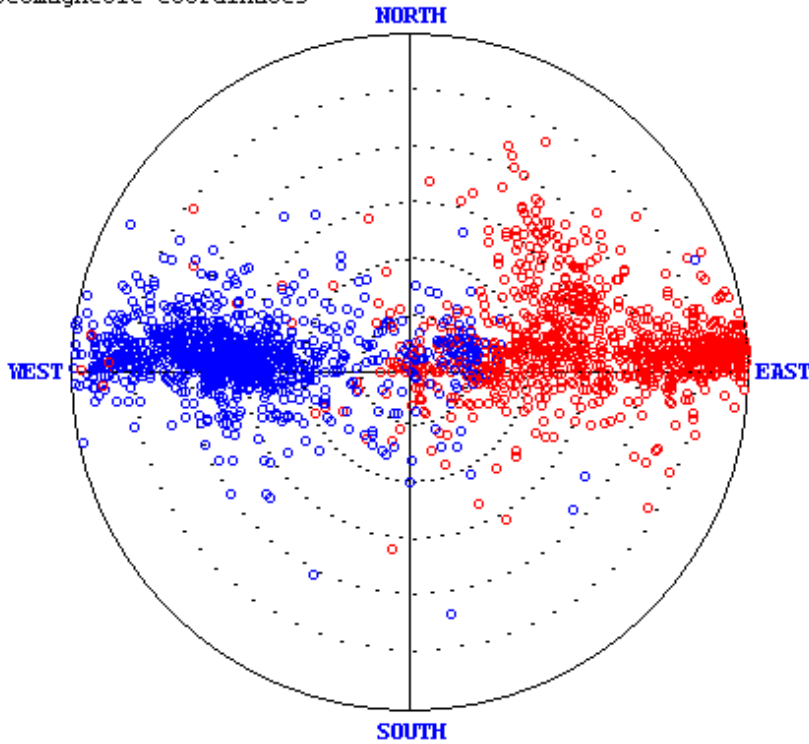
The radio plasma imager (RPI) on IMAGE [17] has for the first time applied modern sounding techniques to spaceborne sounding. The magnetospheric measurements are recorded in the form of plasmagrams [7], as illustrated in Fig. 6, where the virtual ranges are given in units of Earth radii, R_E .



STATION NAME Jicamarca
YYYY DATE 2003 Mar25
DDD HMM AXN PPS IG 084 0329 417 125 -8

Min Freq, kHz 3900
Max Freq, kHz 5390
Freq Step, kHz 500
Min Height, km 215
Max Height, km 320
Height Res, km 5.0
Gain, No 0
Case SNR, dB 4
Line SNR, dB 4
Max. Zenith 30
MPA, dB 19
Max. Amp, dB 64
Doppler Res, Hz .122
CIT, sec 8
Total Sources 2370

Geomagnetic coordinates



Max Zenith: 30.0 deg

Zenith Grid Step: 5.0 deg

Positive Doppler
Negative Doppler

Fig. 4. Digisonde skymap at 2229 LT in Jicamarca on 25 Mar 2003



Jicamarca 25 March 2003

Digisonde F-region drift

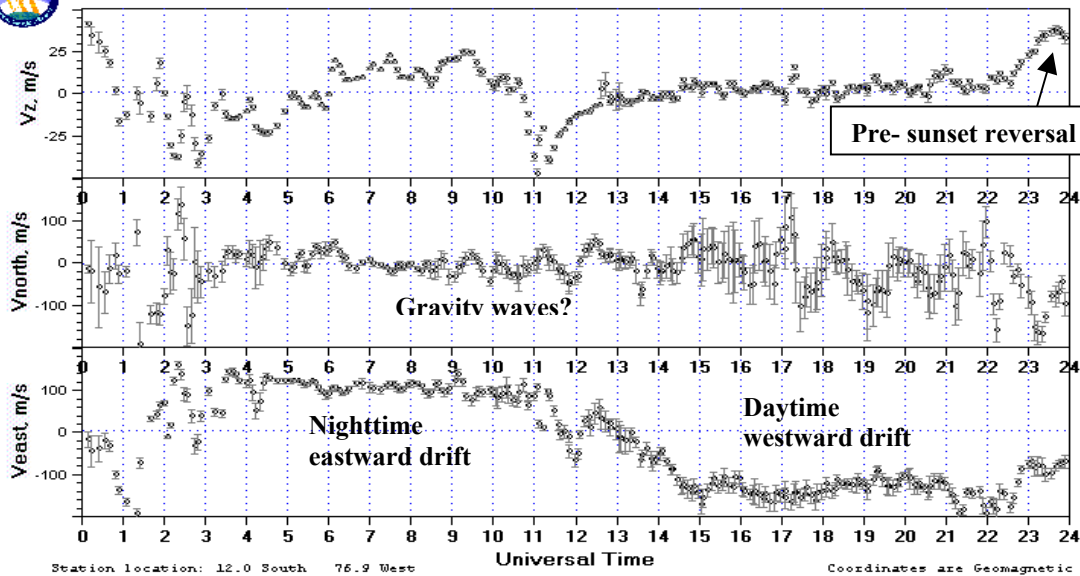


Fig. 5. The three drift velocity components at Jicamarca on March 25 2003. The horizontal components are plotted in geomagnetic coordinates.

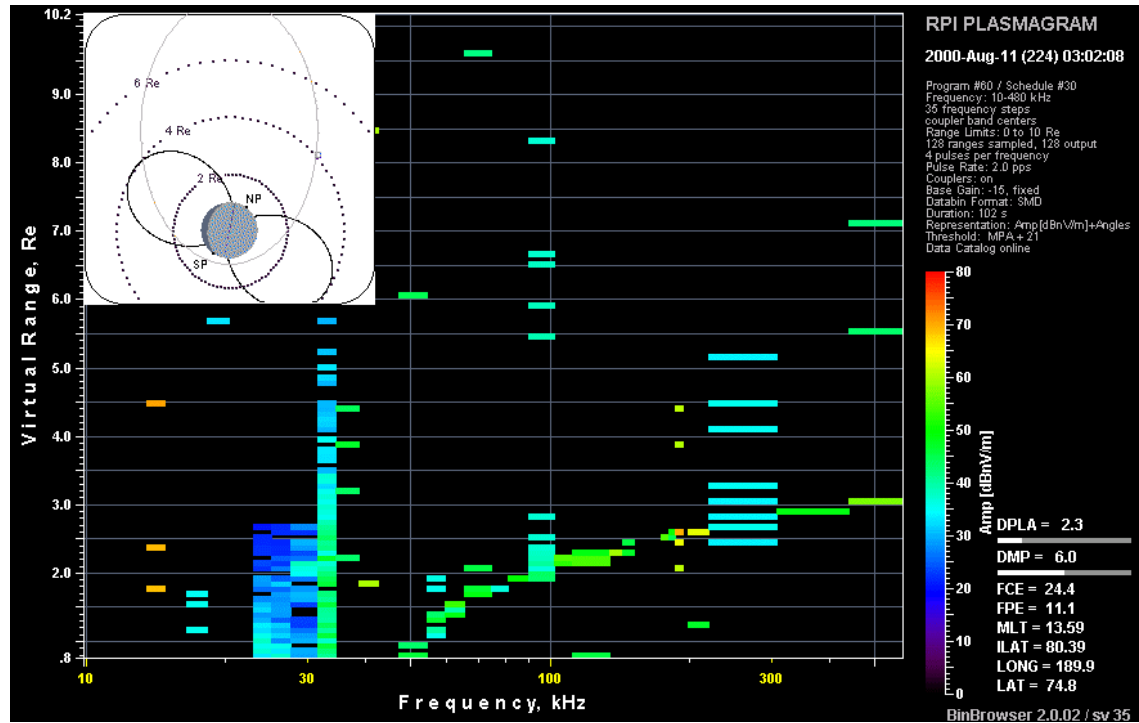


Fig.6. RPI plasmagram scanning from 30 to 600 kHz with virtual ranges up to 10 R_E . An X trace from the polar cap region extends from 50 to 600 kHz. RPI transmits less than 10 W of pulse power.

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