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A Rocket Borne Experiment to Measure Plasma Densities in the *D*-Region

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Abstract. A description of two experiments is presented which, combined on the same rocket payload, can possibly provide the most accurate plasma density measurement in the lower ionosphere.

Key words: *D*-region – Winter anomaly – Plasma density – Faraday rotation – Differential absorption – Electrostatic probe.

1. Introduction

One of the most important parameters of any *D*-region study is the density of free, thermal electrons and ions. Not only is a considerable part of the solar energy converted at these altitudes used to create free electrons, the electron density in this region of the ionosphere also controls the radio wave absorption, hence also the anomalous HF absorption observed in Winter. The experiment consists of two independent instruments: A radio wave propagation method (Faraday rotation and differential absorption), and an electrostatic probe. The results of both instruments supplement each other yielding very accurate absolute densities of electrons, the probe, once normalised to the Faraday data, can provide good height resolution. Furthermore, an *in-situ* measurement has advantages when measuring under unstable conditions. In contrast to a propagation experiment, it is uninfluenced by changes of the plasma underneath, which could be interpreted as the effect of the height layer under consideration. The use of a probe in addition to a propagation experiment is therefore always adviseable whenever plasma densities are to be measured which are more or less constant (above ca. 100 km).

Hence, a propagation experiment alone should only be employed at heights of steadily increasing densities (*D*-region). A combination of both experiments was therefore flown on both B IV payloads (Nike Apache) with nominal apogees around 130 km.

2. Faraday Rotation and Differential Absorption

A magneto-plasma, such as the ionosphere, exhibits a dual, complex refractive index for left and right hand sense of circular polarisation, respectively. Both indices are functions of the electron density, N_e, the collision frequency, ν, the signal frequency, f, and the (Earth's) magnetic field, B. The refractive index ($\mu_0 + j\chi_0$) of the wave polarisation which also exists in absence of a magnetic field, is referred to as that of the ordinary wave (in the Northern hemisphere: left hand circular for frequencies above the gyro frequency, f_g). The other index ($\mu_x + j\chi_x$), controlling the other polarisation sense, is called the extraordinary and only exists in presence of a magnetic field (c.f. e.g. Budden, 1966). A linearly polarised HF wave transmitted from the ground to a rocket payload, can be considered as the superpositioning of a right and left hand circularly polarised wave. In absence of a magneto-plasma, the resulting polarisation will be a linear one parallel to the original polarisation, since both waves having the same velocities arrive simultaneously with the same amplitude at the receiving aerial (at the rocket payload). The difference in the real parts of the refractive indices leads to different arrival times of the two partial waves. Their superpositioning results in an elliptical polarisation whose major axis will be rotated by an angle, Ψ, against the original linear polarisation (Faraday rotation):

$$d\Psi = \frac{\pi f}{c} (\mu_0 - \mu_x) \, \mathrm{ds}, \quad \text{rad} \tag{1}$$

ds = element of the propagation path
c = velocity of light.

Similarly, from the difference of the imaginary parts of the two refractive indices, the differential absorption (DA) can be derived:

$$\mathrm{dDA} = \frac{2\pi f}{c} (\chi_0 - \chi_x) \, 20 \log e \, \mathrm{ds}, \quad \mathrm{dB}. \tag{2}$$

In the observed elliptical polarisation, the major axis, $A_{\max}$, is the sum, and the minor axis, $A_{\min}$, the difference between the two partial wave amplitudes (ordinary and extraordinary).
Hence, the differential absorption can be deduced from:

$$\mathrm{DA} = 20 \log \{(10^{M/20} - 1)/(10^{M/20} + 1)\}, \quad \mathrm{dB} \tag{3}$$

$$M = A_{\max}/A_{\min} \quad \text{modulation in dB.}$$

The most general formulation of the refractive indices is given by Sen and Wyller (1960). Particularly if investigations in presence of high collision frequencies are made (D-region), the rather complicated Sen and Wyller theory has to be employed. This is especially true for the computation of the collision frequency itself. The observed Faraday rotation and differential absorption, as well as the height to which a sounding frequency can yield usable data, are functions of that frequency.

Figure 1 shows the dependence of Ψ and DA (per kilometre of height) as a function of frequency for a given set of parameters expected at 75 km for a

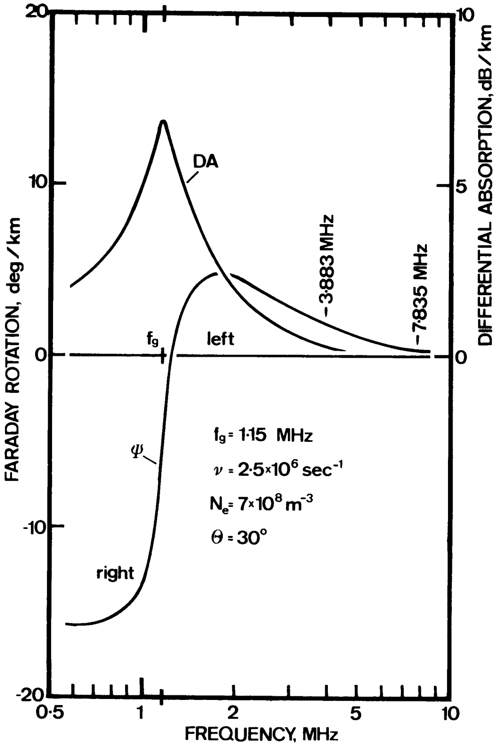

Fig. 1. Faraday rotation, Ψ, differential absorption, DA, (per kilometre) for a set of parameters expected at 75 km above "El Arenosillo" (Θ: angle between magnetic field and propagation direction)

launch from "El Arenosillo". The frequencies 3.883, 7.835 and 15.011 MHz were chosen to ensure that once a frequency is absorbed, a higher one will provide data. This figure also demonstrates that frequencies below the gyro frequency can yield useful data, particularly at lower altitudes (high collision frequencies). At the latitude of Southern Spain this would, however, mean a frequency of less than 1 MHz, which for practical purposes was not considered (interference with broadcast stations).

For each of the three sounding frequencies there was a transmitter of 500 to 800 W output feeding $\lambda/2$ aerials, $\lambda/4$ above ground radiating with linear polarisation. The payload side consists of a receiver for each frequency fed from a common, linearly polarised (dipole) aerial (2 spikes of app. 30 cm). The outputs, representing the momentary fieldstrengths measured by the scanning dipole (spinning rocket), are telemetered by analogue words.

3. Electrostatic Probe

A sphere inside a spherical grid (at rocket potential) is biased to collect charged particles of one polarity (here: positive ions). The bias is chosen high enough to safely repell the unwanted species even if the rocket potential changes during the flight, but low enough to avoid secondary emission on the inner sphere (22.5 *V*

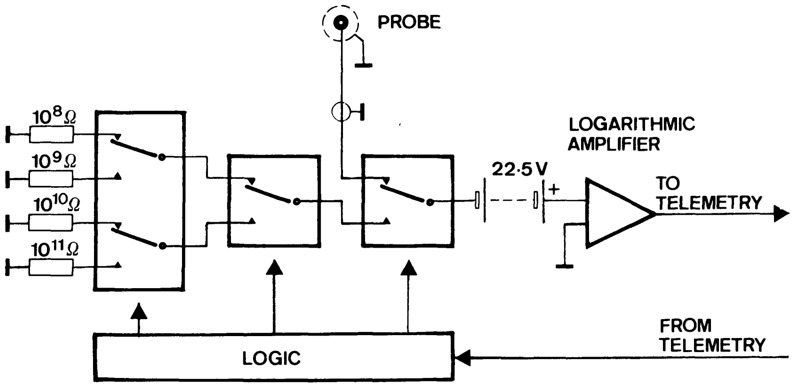

Fig. 2. Block diagramme of electrostatic probe

were chosen). The current thus detected is given by Sagalyn et al. (1963)

$$I = I_0 f(v_T, v) \tag{4}$$

where $I_0 = \pi r^2 eN v_T$ denotes the current to the stationary sphere (sphere radius, r, electron charge, e, density, N and the probe/rocket velocity, v).

$$v_T = \sqrt{8kT/\pi m} \tag{5}$$

describes the particles' thermal velocity (Boltzmann constant, k, temperature, T and species mass, m). Numerical values of D and E-region conditions and typical sounding rocket velocities (100 to 150 km apogee) show that for electrons the rocket velocity is negligible compared to the thermal velocity (stationary current I_0). In the case of ions, however, they can almost be considered as stationary, the probe simply samples a volume defined by the sphere's diameter and the rocket velocity vector (c.f. e.g. Folkestad, 1970).

Therefore, collecting positive ions makes the measurement much less dependent on a good ion temperature model. The mass of the dominant species also hardly influences the result for a large part of the flight. Since on the other hand, the rocket velocity must always be known accurately anyhow, the probe was biased to measure positive ions. The current thus collected by the deployable probe was amplified in a logarithmic amplifier whose input was switched to four calibration resistors ranging from 10^8 to $10^{11}\ \Omega$ (currents from 2×10^{-7} to 2×10^{-10} A, Fig. 2). Because of the different response times, the lower calibration currents were switched on longer than higher ones; to facilitate data processing the calibration cycle was controlled by the PCM telemetry (every 8160 frames or app. 8.4 s, Ulrich et al., 1976).

4. Results

Due to interference from outside the payload, not all frequencies yielded data, electron densities could, however, be derived up to apogee from both B IV flights of the two salvoes. The raw data were processed to yield absorption and Faraday rotation by a correlation programme described by Torkar and Fried-

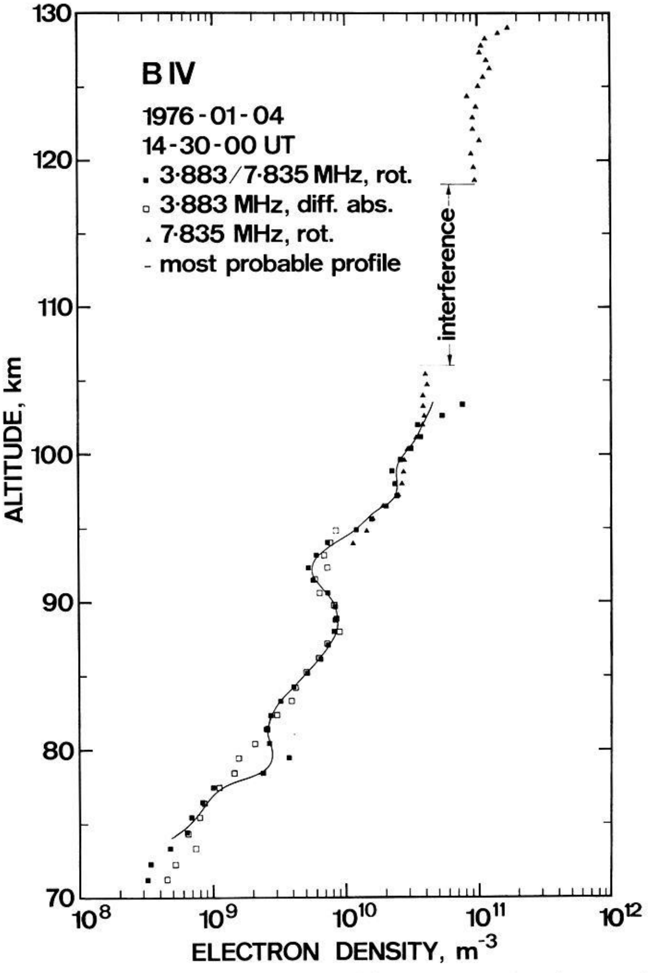

Fig. 3. Electron density profile derived from wave propagation experiment

rich (1976, the Earth's magnetic field model used is the one given by Chain et al. (1965) and the semiconductor integrals required in the Sen and Wyller formulation were computed according to Hara (1963). First the collision frequency, ν, was determined from the first B IV of January 4th, 1976. Best agreement between Faraday rotation (3.883/7.835 MHz) and differential absorption (3.883 MHz) was obtained with a height dependent proportionality factor, $K=\nu/p$, to the CIRA (1972), pressure, p, of the form:

$$K = 1.95 \times 10^5 \exp(0.0205 \times \mathrm{h}), \qquad \mathrm{m}^2/\mathrm{N\,s} \tag{6}$$

h in kilometres
p in $\mathrm{N/m}^2$

similar to a study by Mechtly (1974).

Figure 3 shows the electron density profile derived from the same flight using

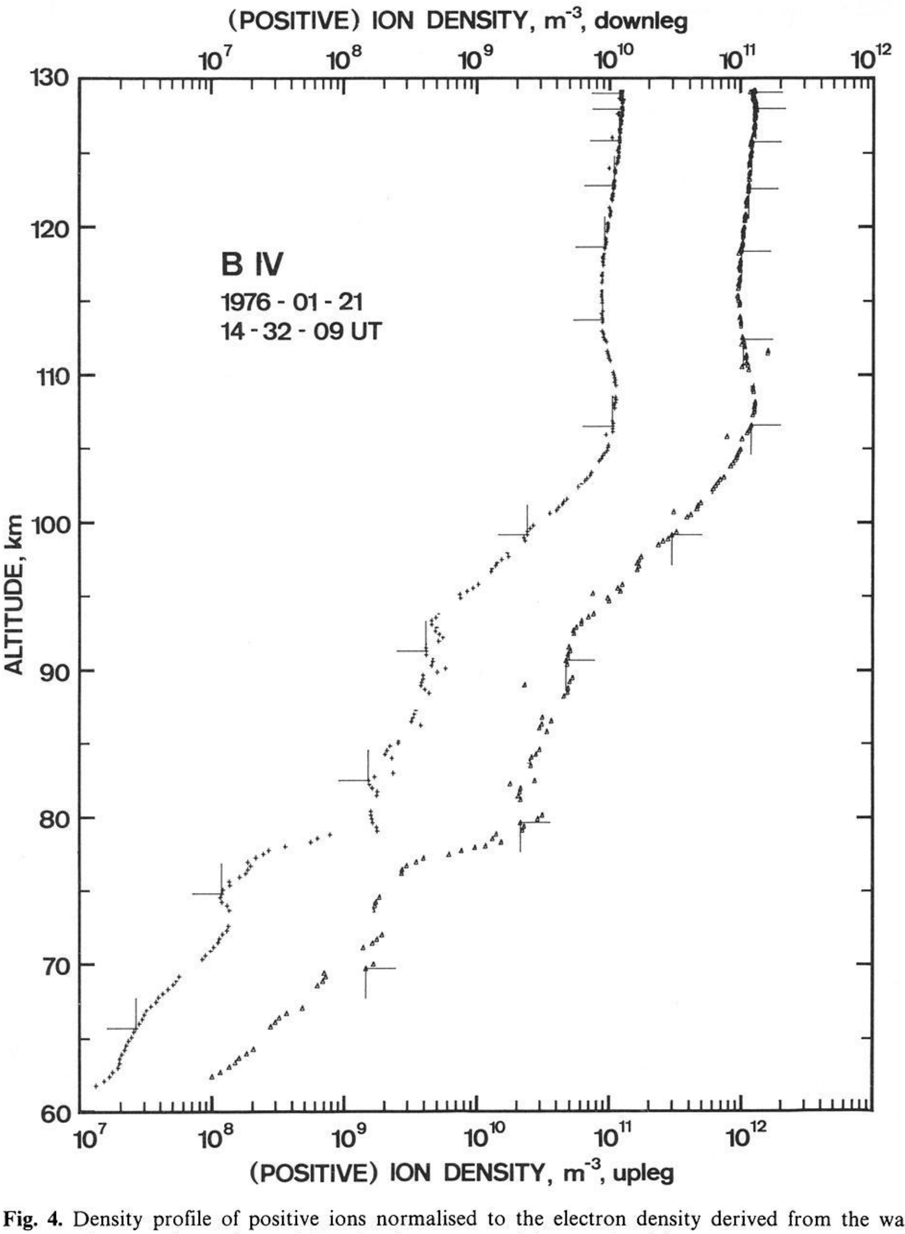

Fig. 4. Density profile of positive ions normalised to the electron density derived from the wave propagation experiment (up and downleg data separated by one decade)

the collision model of Equation (6). The line labelled "most probable profile" was obtained by simulating Faraday rotation and differential absorption until best agreement with the raw data was achieved as described by Friedrich and Jacobsen (1975). The data gap around 110 km which also appeared on the flight of the second B IV (January 21st, 1976) is due to interference from an unwanted transmitter, disappearing above that height and also be seen on the downleg.

Unfortunately, due to mechanical reasons, only the probe of the second B IV deployed and provided data. Because of the supersonic velocity of the rocket, the probe which stands out some 30 cm to the side of the payload will move in and out of the shock cone. The current thus spin-modulated, can be considered to represent the true, unperturbed value whenever the probe is outside the shock front (maximum of the current observed in each spin period). The position of this maximum relative to an aspect sensor should only change slowly during the flight with the angle of attack to the payload. In the data reduction, the rocket rotation sectors where the maxima occur are first plotted versus flight time. Only from this (smoothed) angular range of some $\pm 20°$ the averaged values are considered to represent the "true" ion densities. The current values obtained by this method (one per spin period) are then converted to ion density using Equation (4) by Sagalyn et al. (1963), with an ion temperature profile similar to CIRA (1972) neutral temperatures and ion mass, m, of 16 and 32 which show only a few percent difference in the result. Figure 4 shows the profile of the density of positive ions, above 80 km normalised to the electron density derived by the wave propagation experiment. This procedure is justified, since the mass spectrometer on the same payload measured the last negative ions much below that altitude (Arnold, private communication).

The gaps in the profile are at the times of the mass spectrometer's neutral gas mode which interferred with the measurement, the angles indicate in-flight calibration. The good agreement between up and downleg demonstrates that:

- The computed trajectory is correct.
- The plasma density remained stable during the flight.
- The assumption of the maximum current observed in a spin period representing the true value is a realistic one.

5. Conclusions

It seems fair to say that the combination of the two described instruments is ideal for the measurements in the *D* and *E*-region. For rocket flights outside the auroral zone where commercial radio stations are heavily absorbed, perhaps more than three sounding frequencies should be employed since one cannot predict all interference from other stations by monitoring the frequencies on the ground.

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