HF OBSERVATIONS IN THE AURORAL IONOSPHERE USING A DIGITAL IMPEDANCE PROBE

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ABSTRACT

A NASA sounding rocket launched in March, 2003 from Poker Flat, Alaska included an HF digital impedance probe to search for the upper hybrid frequency in order to determine absolute electron densities. The instrument was operated in both a *self* impedance mode and in a *mutual* impedance mode, and included a transmitter and receiver dipole, separated by 80 cm along a fiberglass tube extended along the spin axis of the payload in the forward direction. The transmitter stepped through 256 discrete frequencies between 0.1-5 MHz, which are each applied for 1 msec to the plasma, and provided measurements of the amplitude of the transmitted current as well as its phase. The receiver recorded the amplitude and phase of the received signal. In addition to the amplitude and phase of transmitted current and received voltage, which were determined on board the rocket, brief snippets of the applied voltage, the received voltage, and the transmitted current were telemetered for detailed analysis on the ground. In this paper, we analyse the amplitude and phase signals that were determined on board the rocket. We compare the plasma density derived from the plasma frequency determined from the impedance probe with that determined from the on-board Langmuir probe.

Key words: Ionosphere; impedance probe.

1. INTRODUCTION

A standard instrument to measure ionospheric plasma parameters is the Langmuir probe [1, 2]. Langmuir probes can be operated in a fixed-bias mode to deliver high-resolution relative density measurements, and in a sweep mode from which the absolute electron density, electron temperature, as well as the plasma and floating potentials can be determined. Measurements in both modes can be disturbed by surface contamination effects, which attenuate the collected current resulting in artificially lower densities [3, 4]. Instruments based on HF methods, such as Faraday rotation and impedance probes, however, are not influenced by surface contamination effects, and thus offer an alternative way to measure absolute electron densities. In many sounding rocket payloads both methods are often combined to provide high accuracy density from high frequency (HF) techniques with high temporal resolution fixed bias Langmuir probes [5].

2. IMPEDANCE PROBE

Impedance probes have been flown on several sounding rocket [6, 7] and satellite missions [8, 9]. A self-impedance probe makes use of the frequency dependent admittance of an antenna in a magnetised plasma. A minimum of admittance occurs at the upper hybrid frequency:

$$f_{uh} = \sqrt{f_{pe}^2 + f_{ce}^2} \tag{1}$$

When magnetic field strength and thus the electron cyclotron frequency

$$f_{ce}/\text{kHz} \approx 0.28 \cdot B/\text{nT} \tag{2}$$

is known, the electron plasma frequency

$$f_{pe}/\text{kHz} \approx \sqrt{80.6 \cdot N_e/\text{cm}^{-3}} \tag{3}$$

and thus the electron density can be determined.

A mutual impedance probe measures the current I that is driven through the transmitting antenna and the induced voltage U at the receiving antenna. The mutual impedance Z is given by the ration U to I and depends on the plasma parameters. The phase and amplitude of the frequency response can be used to derive the plasma parameters.

Although impedance probes do not suffer from surface contamination effects since they operate at high frequencies they do include error sources due to capacitance and other effects that influence the HF signal. We will not discuss these here.

Proc. '19th ESA Symposium on European Rocket and Balloon Programmes and Related Research, Bad Reichenhall, Germany, 7–11 June 2009 (ESA SP-671, September 2009)

3. JOULE-2003

Two instrumented sounding rockets where flown on March 27, 2003 from Poker Flat, Alaska (Fig. 1). NASA

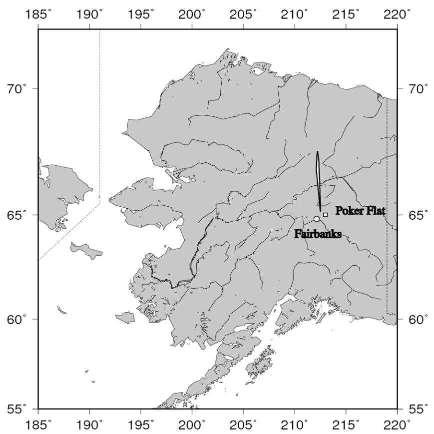

Figure 1. NASA 21.131 was launched from Poker Flat, Alaska to the north.

36.206 was launched at 12:09:01 UTC and achieved an apogee of 193 km. NASA 21.131 was launched at 12:12:01 UTC and achieved an apogee of 199 km. The rockets were equipped with electric field detectors and two Langmuir probes comprised of a spehric swept sensor and a ring fixed-bias sensor (Fig. 2). In addition the 21.131 rocket carried a digital impedance probe (Fig. 2). We will show data only from the Joule rocket 21.131 here. Some measurements from the Langmuir probes have been presented in [10].

4. DIGITAL IMPEDANCE PROBE

A new impedance probe to accurately measure plasma density using a variety of phase detection schemes has been developed at the NASA / Goddard Spaceflight Center. Impedance probes do not suffer from payload charging effects as traditional Langmuir probes. The instrument uses a Direct Digital Synthesis (DDS) chip to generate a frequency sweep of 256 discrete frequencies between 100 kHz and 5 MHz of a duration of 1 ms each, which generally covers the expected range of plasma frequencies. The voltage and current transmitted by a short dipole antenna, as well as the voltage received by a second receiving dipole antenna spaced 80 cm away, are sampled in snippets with a 14-bit A/D converter at 8 MHz and telemetered to the ground.

The instrument has been flown on a sounding rocket, taking advantage of the high telemetry rate (8 Mbps) to study detailed waveforms. The instrument includes a low-telemetry mode suitable for satellites. The low-telemetry mode measures phase and gain between transmitted voltage and transmitted current, as well as between transmitted voltage and received voltage.

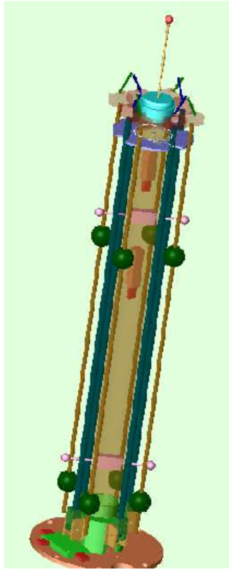

Figure 2. The payload of 21.131 consisted of a spherical (tip) and a ring (blue cylinder) Langmuir probe, an impedance probe with transmitter and receiver dipoles located just below the ring LP and near the base of the central tube, and E-field detectors (green spheres) mounted on folded booms shown here in the stowed configuration.

For this measurement, two different circuits were developed. A phase/gain meter IC (AD8302) determines phase and gain between two signals. Additional circuitry provides full 360 degree phase resolution. The alternative circuit uses a second DDS to synthesise a frequency a few kHz below the sweep frequency. This signal is mixed with the transmitted voltage and current, as well as the received voltage. The mixed signals are sampled at a 10 kHz and sent to the ground. Comparing the signals with the mixed signal of the transmitted voltage allows the determination of phase and gain of both the transmitted current and the received voltage. As this is carried

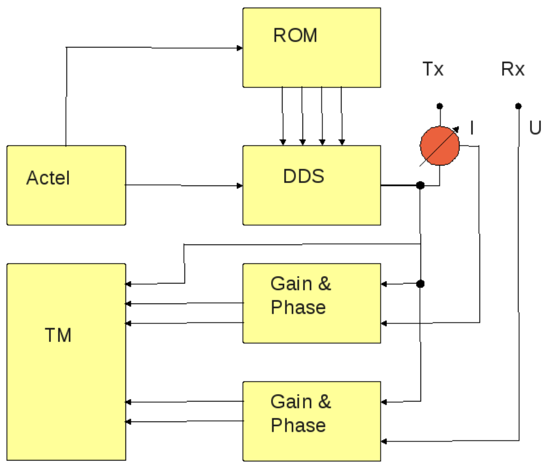

Figure 3. Schematic of Impedance probe design.

out as a function of frequency, the parallel resonance at the upper hybrid frequency is discerned, from which the plasma density may be easily calculated. The instrument was flown on a NASA sounding rocket from Poker Flat, Alaska in March, 2003. For this flight, the phase/gain meter IC circuit was chosen for the low telemetry mode. The output of this circuit directly provides phase and gain of the two signals, so that the performance of the instrument can be ascertained in a very straightforward way.

5. OBSERVATIONS: JOULE

5.1. Langmuir probe data

On this sounding rocket two Langmuir probes were flown. A spherical Langmuir probe (LP1) was operated in the sweep mode, to determine absolute electron densities and electron temperature, as well as in a fixed-bias mode between the sweeps. A second (ring) Langmuir probe (LP2) has only been operated in fixed-bias mode. From both Langmuir probes, electron density profiles have been determined [10]. The densities from both probes show a similar profile, but the absolute values disagree especially during the downleg due to contamination effects [11] (Fig. 4). Since the contamination is "short-circuited" during the sweeps, the data from the sweeps probe (LP1) is more reliable, and only these data are used in the following comparisons.

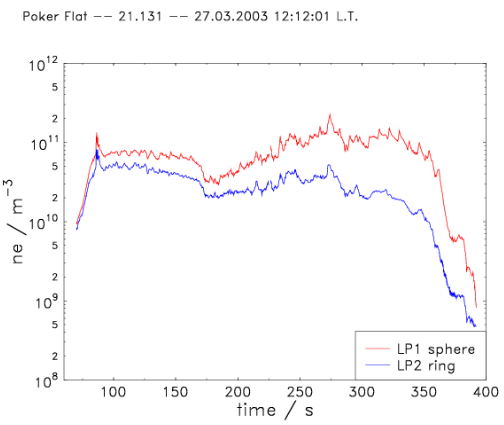

Figure 4. Electron density profile as determined by the spherical and ring Langmuir probes.

5.2. Impedance probe data

The digital impedance probe on this sounding rocket sampled snippets of the transmitted voltage and current, as well as the received voltage. Additionally, the gain and phase of the transmitted current and received voltage were determined on board. In this study we only use the gain and phase measurements which provide a wealth of data. The gain and phase of the received voltage show several resonances throughout the flight. The amplitude of the current measurements is rather low, preventing us from making accurate use of the phase data. However, the frequency dependent transmitted power can be calculated from the amplitudes of transmitted current and received voltage, the phase signal of the received voltage can be used for additional information. Figure 5 shows the time-dependent spectrum of the transmitted power for each sweep of the impedance probe during of the flight.

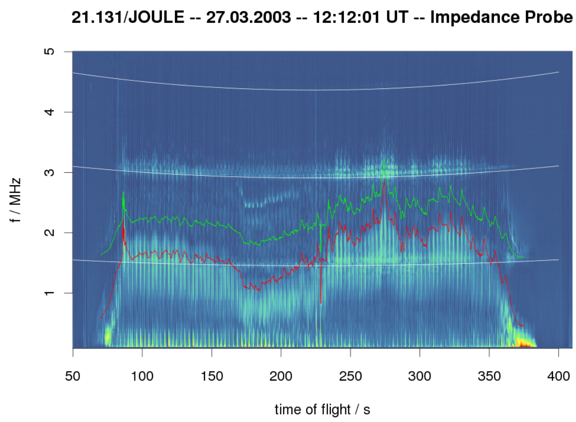

Figure 5. Time-dependent spectrum of all sweeps of the impedance probe during the flight of 21.131.

The shape of the broad band resonances between $\approx 1 - 2\,$MHz is very similar to the electron density as measured by the Langmuir probes shown in Figure 4. For comparison, the red line indicates the plasma frequency corresponding to the plasma density calculated from the LP1 data. The red line appears near the upper boundary of the broadband resonances. An additional feature which is clearly visible in the impedance probe data is the electron gyrofrequency f_{ce}. The white lines indicate the gyrofrequency and its harmonics as calculated from the magnetic field IGRF model. The strongest signals are measured at the gyrofrequency as well at its first harmonic, but the second harmonic is also visible in the data. With the electron plasma frequency and the electron gyro frequency known, the upper hybrid frequency can be calculated: This is shown as green line in this Figure. Since a minimum of admittance occurs at the upper hybrid frequency, this feature is not readily visible in this presentation.

In Fig. 6 and Fig. 7, we show the received power of two sweeps at 100 sec and 175 sec time of flight. The blue arrows indicate the electron gyro frequency and its harmonics as calculated from the IGRF. The red arrows indicate the electron plasma frequency as calculated from the spherical Langmuir probe, as well as the upper hybrid frequency calculated from these gyro and plasma frequencies. While the gyro frequency and its harmonics match the observations very well, the plasma frequencies as determined by the Langmuir probe are visibly offset

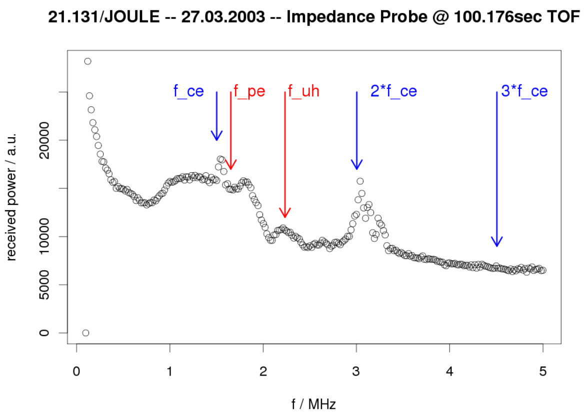

Figure 6. Received power as measured by the impedance probe at 100.176 s. The blue arrows indicate the electron gyro frequency as determined by the IGRF model. The red arrows indicate the electron plasma and upper hybrid frequency correspondng to the density determined by the Langmuir probe.

from the broad band resonance at the plasma frequency, for the sweep at 100 sec the plasma frequency appears to be a little larger, for the sweep at 175 sec the plasma frequency appears to be smaller than indicated by the Langmuir probe.

In addition to this, the data suggests several other resonances. Similar resonances have already been observed on other sounding rockets [12]. These Bernstein-modes waves (Qn resonances) where also seen by the HF peaks on the IMAGE satellite [13]. Benson [13] also identified Dn resonances in the IMAGE data. The cutoffs and resonances are given by the following equations:

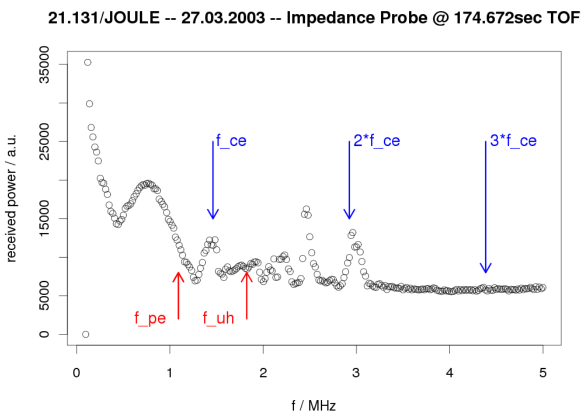

Figure 7. Received power as measured by the impedance probe at 174.672 s. The blue arrows indicate the electron gyro frequency as determined by the IGRF model. The red arrows indicate the electron plasma and upper hybrid frequency correspondng to the density determined by the Langmuir probe.

X mode cutoff:

$$f_x = (f_{ce}/2)\left(1 + \sqrt{4f_{pe}^2/f_{ce}^2}\right) \tag{4}$$

Z mode cutoff:

$$f_z = (f_{ce}/2)\left(-1 + \sqrt{4f_{pe}^2/f_{ce}^2}\right) \tag{5}$$

Qn resonances:

$$f_{Qn} \approx f_{ce}\left(n + \left(0.464/n^2\right)\left(f_{pe}^2/f_{ce}^2\right)\right) \tag{6}$$

Dn resonances:

$$F_{Dn} = 0.95\sqrt{f_{pe}f_{ce}}\sqrt{n} \tag{7}$$

$$F_{Dn}^{+} = \sqrt{f_{Dn}^2 + f_{ce}^2} \tag{8}$$

$$F_{Dn}^{-} = \sqrt{f_{Dn}^2 - f_{ce}^2} \tag{9}$$

We analyse the two sweeps again by determining the plasma and gyro frequencies from the impedance probe measurements. For the sweep at 100.176 s we determine a plasma frequency of $f_{pe} = 1.81$ MHz and a gyro frequency of $f_{ce} = 1.57$ MHz. For the sweep at 175.176 s we determine a plasma frequency of $f_{pe} = 0.80$ MHz and a gyro frequency of $f_{ce} = 1.48$ MHz. With these frequencies the additional cutoffs and resonances are calculated and show as green arrows in Fig. 8 and Fig. 9. Not only do the plasma, gyro and upper hybrid frequencies match the observations well, but also the additional resonances agree with the observed features in these two sweeps, supporting our determiantion of the plasma density.

6. CONCLUSION

An instrumented sounding rocket has been flown into the auroral ionosphere that include two Langmuir probes (sphere and ring) and an impedance probe instrument. The spherical Langmuir probe was operated in fixed-bias mode and periodically also in sweep mode, whereas the ring probe was only operated in fixed bias mode. At first glance, the electron density calculated from the fixed-bias mode of the spherical probe agrees with the spectral features observed by the impedance probe. Two sweeps of the impedance probe have been analysed in detail, one where the plasma frequency is smaller than the gyro frequency, and one where the plasma frequency is larger than the gyrofrequency. The closer examination shows that at times the electron density (plasma frequency) observed by the impedance probe can be both slightly larger or smaller than that of the Langmuir probe. The electron cyclotron frequency as measured by the impedance probe, however, agrees very well with the magnetic field from the IGRF model. Besides the electron cyclotron

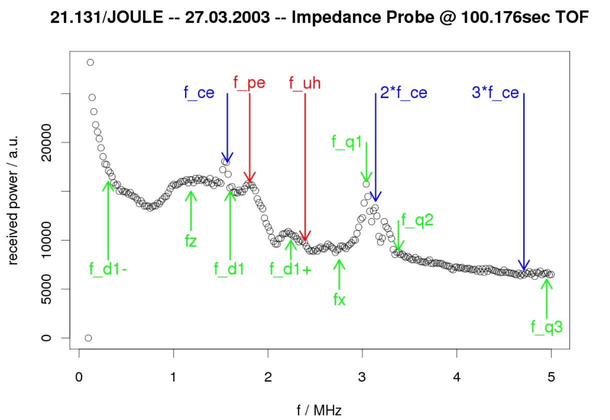

Figure 8. Data as in Fig. 6 but with the plasma, gyro and upper hybrid frequencies determined by the impedance probe data. Also shown are the Dn and Qn resonances as well as the X and Z mode cutoffs as green arrows.

and gyro frequencies and upper hybrid frequency, the impedance probes detects, mostly between the gyrofrequency and its first harmonic, several other resonances. For both, $f_{pe} < f_{ce}$ and $f_{pe} > f_{ce}$, many, if not all, of these resonances agree very well with the D and Q resonances as calculated from the electron plasma and gyro frequency as detected by the impedance probe.

ACKNOWLEDGEMENTS

Sven Bilen is gratefully acknowledged for fruitful discussions about sounding rocket instruments during the ESA PAC meeting in Bad Reichenhall.

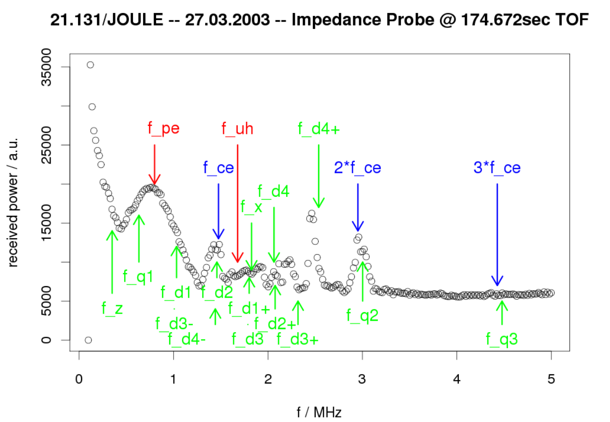

Figure 9. Data as in Fig. 7 but with the plasma, gyro and uper hybrid frequencies determined by the impedance probe data. Also shown are the Dn and Qn resonances as well as the X and Z mode cutoffs as green arrows.

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