Calibration Report of the **WHISPER** Measurements in the Cluster Science Archive (CSA)

prepared by
the WHISPER team

Document Status Sheet

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List of Acronyms

BM	Burst Mode
CAA	Cluster Active Archive
CSA	Cluster Science Archive
DWP	Digital Wave Processing
EDI	Electron Drift Instrument
EFW	Electric Field and Wave
FFT	Fast Fourier Transform
FGM	Flux Gate Magnetometer
GPSM	Space Plasma and Magnetometry Group
HIA	Hot Ion Analyzer
ICD	Interface Control Document
ISS	Institute of Space Sciences
NM	Normal Mode
PEACE	Plasma Electron And Current Experiment
UG	User Guide
WEC	Wave Experiment Consortium
WHISPER	Waves of HIgh frequency and Sounder for Probing of Electron density by Relaxation

1 Introduction

The key WHISPER (Waves of High frequency and Sounder for Probing of Electron density by Relaxation) datasets include:

- electric field spectra in the 2–80 kHz frequency range
- the total electron density

The latter can be deduced from the characteristics of natural waves in NATURAL mode (i.e. when the transmitter is off) and/or from resonances triggered in the sounding mode.

A general description of WHISPER science products available at Cluster Science Archive (CSA) is given in the WHISPER User Guide (UG, CAA-EST-UG-WHI) while detailed information about the contents of all the datasets can be found in the WHISPER Interface Control Document (ICD, CAA-EST-ICD-WHI).

This document provides detailed information about calibration procedures, with a particular insight on the density derivation from electric field spectra.

2 Instrument Description

The WHISPER experiment results from a collaboration between experimenters organised within the context of the Wave Experiment Consortium, WEC, which includes five instruments (Pedersen et al., 1997; WEC Instrument User Manual, 2000). The WHISPER instrument (Décréau et al., 1993; 1997) consists basically of a receiver, a transmitter, and a wave spectrum analyser, associated with parts of two other WEC instruments: the sensors of the EFW (Electric Field and Wave) experiment and data processing functions of the DWP (Digital Wave Processing) experiment.

The WHISPER instrument provides two functions:

- the continuous survey of the natural plasma emissions in the 2-80 kHz frequency band
- the measurement of the total electron density of the plasma, (a) from the measurements of the relaxation sounder, an active radio frequency technique which aims at identifying the electron plasma frequency in the 4-82 kHz range, and/or (b) from natural plasma emissions

The WHISPER frequency range includes electrostatic and electromagnetic natural emissions of interest to the Cluster objectives, in particular in the vicinity of the plasma frequency from which the total electron density may be determined.

Two modes of operation are used alternatively:

- the NATURAL mode when the transmitter stays on stand-by
- the sounding mode during which the transmitter triggers plasma resonances prior to reception

In both cases, a pair of EFW sensors is used as a double-sphere electric dipole antenna, whose potential difference is band-pass filtered, digitised, multiplied by a windowing function, and finally analysed in frequency by an on-board FFT processor which computes a full frequency spectrum every 13.33 ms. It covers the full frequency band in 512 or 256 bins, with a frequency resolution of 162.8 Hz (F_{ech} / 1024 with the sampling frequency F_{ech} = 1 MHz / 6) in the 512-bin FFT option or 325.5 Hz in the 256-bin FFT option. The complex signal allows to derive the amplitude (modulus) of the potential difference at each bin. Phase information is not transmitted to ground. Furthermore, all frequency bins for amplitude are not transmitted to ground, bin selection depending on the operation mode. For example, in the standard sounding operation mode, 480 bins from 512 are transmitted covering the 2-80 kHz frequency range for NATURAL spectra and the 4-82 kHz frequency range for active spectra, respectively.

2.1 Natural mode

In NATURAL wave mode, one spectrum is acquired every 13.3 ms. Either 16 or 64 of on-board spectra are accumulated to smooth sporadic features and improve the signal to noise ratio. This results in accumulated spectra covering the 2-80 kHz frequency range with a time resolution of either 0.213 s or 0.851 s, respectively. For more details, see the UG and ICD.

2.2 Sounding mode

In sounding mode, the WHISPER instrument operates like a classical relaxation sounder. It uses the two long double sphere antennas of EFW to transmit and receive. The WHISPER transmitter sends, through the conductive outer braids of one of the antennas, a wave train during a very short time interval (1.024 ms or 0.512 ms) at a frequency chosen from one of the available on-board frequency tables (selected by telecommand). A few milliseconds after, the WHISPER radio receiver connected to two of the EFW spheres, is switched on. The received signal is subsequently listened and Fourier-analysed to construct a part of the ACTIVE spectrum, keeping only a few bins around the triggered frequency. The working frequency is then shifted according to the selected table and the process is repeated until the whole frequency range is covered. A complete ACTIVE spectrum covers the 4-82 kHz frequency range. One NATURAL spectrum is also acquired on-board with the same construction pattern (with acquisition just before transmission at the working frequency). Depending on the telemetry allocation, this NATURAL spectrum can be transmitted to ground and is referred as PASSIVE spectrum. For more details, see the UG and ICD.

3 Measurement Calibration Procedures

One appreciable advantage of WHISPER instrument, shared by most high-frequency wave instruments, is that calibration files are stable over the mission lifetime. Conversion of raw spectra to physical units can be performed at an early stage of data handling, immediately after telemetry decommutation.

The calibration procedure is still executed once per orbit, to check the instrument's health. During the mission lifetime, the calibration files have never needed any revision. We may note that amplitudes of waves from distant radio sources (type III solar bursts), as measured from the four different WHISPER instruments, are equal to within 1 dB, less than the experimental uncertainty which is estimated to be 2 dB. Furthermore, the conversion of bin number to frequency is well defined due to the high stability of the on-board oscillators, and does not evolve with time.

Conversion to physical units: A word of caution must be given concerning signal amplitudes. To convert the potential difference measured by the antenna to an electric field, a fixed effective antenna length of 88 m has been used, like all other WEC instruments. In reality, the Cluster antenna effective length depends on the plasma regime (i.e. Debye length). Scientific studies requiring precise signal amplitudes may need a better estimation of the antenna effective length (Béghin et al., 2005).

The used antenna length of 88 m corresponds to the physical tip-to-tip distance between the two probes forming the receiving antenna. This value is used as the default effective antenna length except:

- when the reception is performed on a ½ antenna, as a consequence of hardware issues affecting EFW probes. When one of the two EFW probes forming the receiving antenna is inoperative, the measurement is carried out between the remaining EFW probe and the satellite body, which has large dimension as compared to the probe, raising uncertainty in the electric distance between both parts. In that case, a 44 m antenna length (half of the nominal physical value) is used arbitrarily to convert measurements into an electric field and the user is advised to use provided amplitude values with caution. Note that there is no impact on the density values provided by WHISPER, as they are derived from the frequency values of recognized plasma signatures, as explained later. More information on the EFW probes failures and selected receiving antenna can be found in the WHISPER User Guide (CAA-EST-UG-WHI).
- during the commissioning phase, when antennas were deployed sequentially through successive dedicated sequences between September 2000 and November 2000. The corresponding length used for measurement conversion on the 4 satellites is given in the figure below:

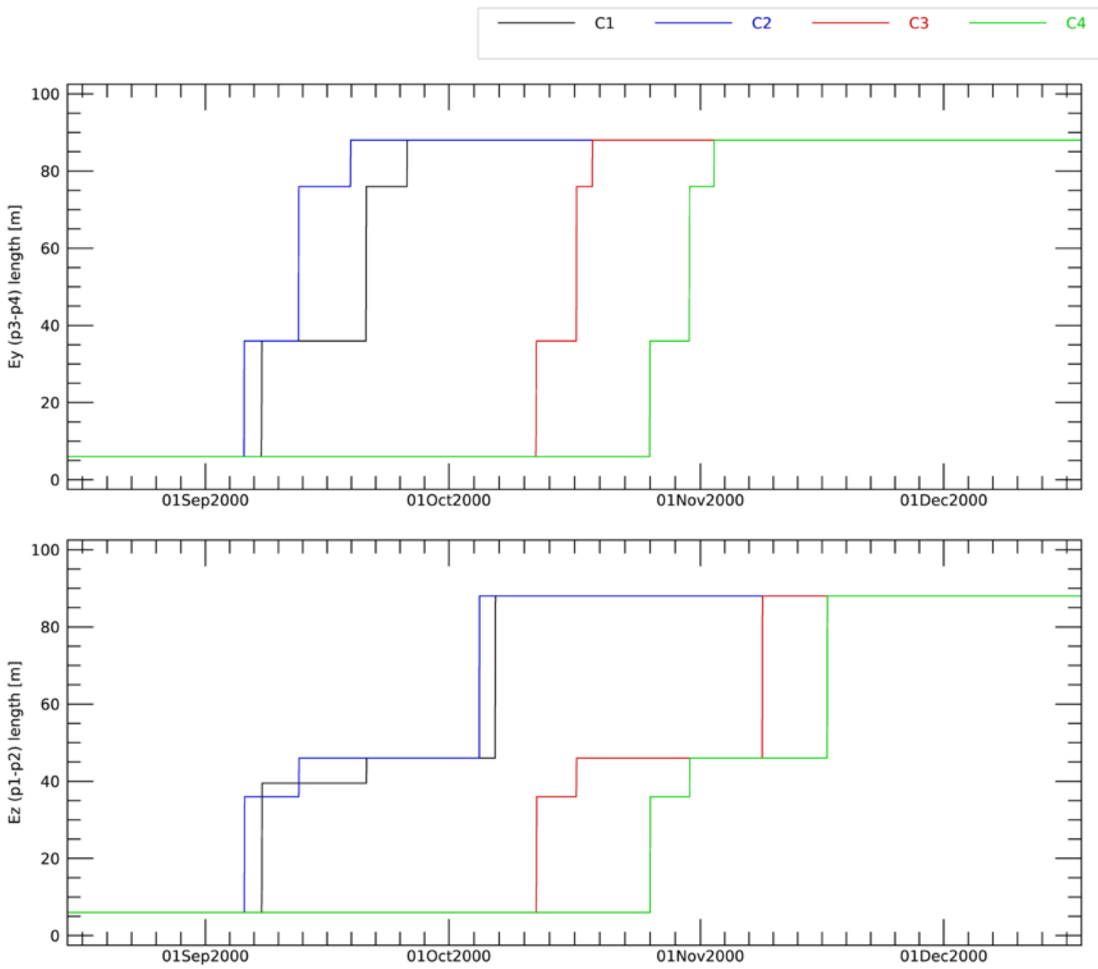

Figure 1: Antenna length used for measurements to electric field conversion during the commissioning phase, for the Ey antenna, formed by EFW probes 3 and 4 (top panel) and for the Ez antenna, formed by EFW probes 1 and 2 (bottom panel), for the 4 satellites (see legend at the top for the colour code). Note that the transitions between two successive antenna lengths are considered as instantaneous while in reality, their durations range from 5 to 25 minutes (the retained time corresponds to the end of the deployment sequence).

Receiver saturation: Overflows concern natural measurements and are signal samples exceeding the dynamical range of the analog-to-digital converter and are closely related to the operation mode of the WHISPER instrument. The overflow number is derived from the number of time samples above or below the converter limits during the acquisition time. As several gains are available on-board and the instrument automatically switches from high gain to low gain whenever too many overflows are encountered, the overflows influence on WHISPER measurements should be limited. However, the WHISPER dataset user should always consider checking the coded overflow rate in the CSA WHISPER product, as described in the WHISPER ICD. Overflow value is between 0 and 1 so that 0 means no overflow and 1 means full saturation. Figure 2 shows an example of a relative saturation due to overflows. Overflows are colour-coded in the upper bar, giving an idea of the saturation of the receiver. In this example, plasma signatures cannot be exploited when full saturation occurs, as indicated by the white colour. Note that time intervals where overflows can possibly affect measurements quality are listed in a dedicated caveat dataset (see the **C[i]_CQ_WHI_CAVEATS** dataset description in the WHISPER ICD).

Note:

➲ Overflow is derived from the number of time samples above or below converter's limits during the acquisition interval and not during the short pre-acquisition interval (although both intervals are placed within the 13.3 ms WHISPER basic time step). The pre-acquisition interval is meant to command a gain change (from the higher of two possible gains, to the lower one) when the instrument is commanded in 'automatic gain', in practice almost all the time.

Figure 2: Example of a WHISPER electric spectral power density spectrogram affected by overflows on C4 for October 02, 2001. The upper bar gives the colour-coded overflow rate.

4 Measurement Processing Procedures

4.1 Electric Spectral Power Density

Conversion from WHISPER measurements to electric spectral power density is straightforward and does need any specific processing. Nevertheless, interferences can sometimes be observed on WHISPER spectrograms. They have several origins, as described in the UG. They usually appear as continuous lines in the spectrograms at given frequencies. Figure 3 gives an example of EDI interferences perturbing WHISPER spectra.

Figure 3: Example of EDI perturbations for C3 on November 05, 2005. EDI interferences appear as horizontal harmonic lines with fundamental frequency depending on the EDI operation mode.

Interferences, when clearly identified, should always be removed. For instance, EDI interferences are automatically removed, as far as possible, in the density extraction process (see appendix **A.2**). Time periods affected by interferences are also listed in the **C[i]_CQ_WHI_CAVEATS** dataset, as described in the WHISPER ICD.

4.2 Electron Density

Most of the time, densities are extracted via a semi-automatic pipeline or by fully automatic pipelines for the most recent years. Occasionally, they are determined manually, in particular for cross-calibration studies, scientific analyses, or in specific magnetospheric regions. Note that the density determination can be relatively complicated in some regions (e.g. in the nightside magnetosphere) and cannot be performed on a routine basis over the whole orbit. It has to deal with different types of resonances and natural wave signatures (cut-offs) actually observed in the different encountered regions of the Earth's environment. Several algorithms have been developed to derive the total electron density from both ACTIVE and NATURAL spectra, with help from EFW spacecraft potential and FGM magnetic field measurements, and taking into account the encountered plasma regime: solar wind and magnetosheath, plasmasphere and cusp, and tail (Trotignon et al, 2006, 2010; Rauch et al, 2006).

On-ground analysis of the resonance pattern observed in ACTIVE sounding spectra, plus comparison with the associated NATURAL spectra when possible, allows the identification of characteristic frequencies of the surrounding plasma, in particular the upper hybrid frequency F_{uh}. The plasma frequency F_{pe} is derived from the upper hybrid frequency using the following relationship:

$$F_{pe}^2 = F_{uh}^2 - F_{ce}^2$$

where F_{ce} is the electron gyrofrequency, given by the magnetic field modulus B_0 derived from FGM CSA archive files, as $F_{ce}\,[Hz] = 28\,B_0\,[nT]$

Finally, the total electron density is given by:

$$N_e = F_{pe}^2/\alpha$$

where α is a constant $\alpha = e^2 / (4\pi^2 \varepsilon_o m) = 80.7\ kHz^2.cm^3$

In the solar wind and magnetosheath, the approximation $F_{pe} = F_{uh}$ can be considered as the magnetic field influence can be neglected. To unlink the production of WHISPER and FGM CSA datasets, such an approximation has been applied to process the solar wind and magnetosheath time intervals after January 2011.

The uncertainty on the density value is given by:

$$\Delta N_e = (2 / \alpha)\ Fpe\ .\ \Delta Fpe$$

ΔFpe is the uncertainty associated to the plasma frequency. Such an uncertainty is defined for each density determination algorithm (see Appendix A).

Depending on the plasma regime, an *ad-hoc* algorithm is applied to estimate the electron density from WHISPER ACTIVE and NATURAL measurements. The selected algorithm is identified by three parameters given for each density value in the **C[i]_CP_WHI_ELECTRON_DENSITY** CSA density product:

- *Computation_Method*: indicates the algorithm code (see table below).
- *Spectrum_Type*: indicates the type of spectrum ACTIVE (A) or NATURAL (N) from which the density is extracted.
- *External_Data*: indicates if an external data was used during the density derivation process. In practise, only E (for EFW) is used. See the algorithms description in Appendix A for more details.

Moreover, three parameters (*uncertainty*, *contrast*, *quality*) are given for each density value to characterize the accuracy of the density estimates (see UG, section 5.1.2).

The density determination rationale and algorithms have evolved all along the mission lifetime, from early manual investigations to modern machine learning techniques. The implementation of the latter techniques was made possible thanks to the production of a large number of densities derived and validated by semi- or fully- manual methods developed iteratively over the years, constituting a quite unique training dataset.

Three generations of algorithms have been developed and applied at different periods during the mission:

- 2001-2003 density files: the time line is decomposed into *a priori* identified plasma regimes and ACTIVE and NATURAL data were processed together (first ACTIVE, then NATURAL). Due to (1) uncertainties in the identification of plasma regimes and (2) boundary fluctuations, the manual validation process was excessively time consuming and a new processing pipeline had to be developed. The corresponding algorithm codes are 10, 20, 30 (see table below).

- post 2003 density files: the time line is decomposed manually into intervals corresponding to a plasma regime. For each interval, an operator defines a frequency search band that contains the plasma frequency signature of interest and selects the appropriate algorithm. ACTIVE and NATURAL data are then processed automatically and independently. Although the derivation pipeline is different than the previous one, the core algorithms applied to derive the density value from WHISPER spectra are very similar to the previous ones. The corresponding algorithm codes are 11, 12, 21 and 40 (see table below).

- post November 2019 density files: the time line is decomposed by fully automatic pipelines based on ANN (Artificial Neural Networks, see Gilet et al., 2021) according to the spectra characteristics, resulting in a typology-based spectra classification. The prevailing criterion to classify spectra is related to the presence or absence of multiple spectral characteristics and whether or not they are discriminated in frequency. A specialized algorithm is then applied to a typology to determine the electron density. This is done for 3 different types of spectra:
    - ACTIVE spectra with one strong resonance (typically encountered in the Solar Wind and Magnetosheath), corresponding to algorithm code 50
    - NATURAL spectra with a broad low-frequency plasma signature combined with multiple poorly frequency-discriminated signatures in the corresponding ACTIVE spectra (as generally encountered in the Tail and edge of the Plasmasphere), corresponding to algorithm code 51
    - NATURAL spectra with several plasma signatures combined with multiple frequency-discriminated signatures in the corresponding ACTIVE spectra (e.g. electron gyroharmonics, Bernstein's modes) typical for the core Plasmasphere when the magnetic field is high enough), corresponding to algorithm code 52

  Algorithms with codes 51 and 52 process NATURAL spectra to obtain an estimate of plasma frequency (directly related to electron density) at high temporal resolution. However, a systematic validation is also carried out on (quasi-)simultaneously acquired ACTIVE spectra, hence increasing the reliability of the process and avoiding to retain values based on non-local spectral signatures.

Note that even if the spectral characteristics are driven by the encountered plasma, **this classification does not always map magnetospheric regions** and cannot be used straightforwardly to determine magnetosphere boundaries.

The different algorithms are given in the table below; the grey area means that the method is not applicable.

computation method	external data	Algorithm	
		Active Spectrum (A)	**Natural Spectrum (N)**
10	-	Max1 (see **A.1**)	LowCutoff1 (see **A.2**)
10	E	Max1 (see **A.1**)	LowCutoff 1_EFW (see **A.3**)
20	-	Max1 (see **A.1**)	
20	E		EFW_proxy (see **A.4**)
30	-	Plasmasphere (see **A.5**)	
30	E	Plasmasphere_EFW (see **A.6**)	
11	-	Max2 (see **A.7**)	LowCutoff2(see **A.9**)
11	E	Max2_EFW (see **A.8**)	LowCutoff2 _EFW (see **A.10**)
12	-		UpperCutoff (see **A.11**)
13	-	Max2 (see **A.7**)	
13	E	Max2_EFW (see **A.8**)	
21	-	Max2 (see **A.7**)	
--	-/E	Manual	Manual
21	E	Max2_EFW (see **A.8**)	EFW_proxy (see **A.4**)
40	E	Tail_Act (see **A.12**)	Tail_Nat (see **A.13**)
41	E	LowCutOff_Act (see **A.14**)	
50	-	ANN1_Act (see **A.15)**	
51	-		ANN2_Nat (see **A.16**)
52	-		ANN3_Nat (see **A.17**)

Details about density extraction algorithms are provided in Appendix A.

The two figures give examples of the result of the density derivation process:

Figure 4: Example of density values and NATURAL and ACTIVE spectrograms (from top to bottom) for C3 on August 19, 2003, corresponding to a plasmasphere crossing. Density values extracted from the ACTIVE WHISPER spectra are plotted as purple points whereas green line represents the density extracted from both ACTIVE and NATURAL measurements. In this interval two methods were used: *Max2* for ACTIVE and *UpperCutoff* for NATURAL.

Figure 5: Example of density values and NATURAL and ACTIVE spectrograms (from top to bottom) for C3 on March 17, 2005, corresponding to solar wind/magnetosheath transition. Density values extracted from the ACTIVE WHISPER spectra are plotted as purple points whereas green line represents the density extracted from both ACTIVE and NATURAL measurements. In this interval two methods were used: *Max2_EFW* for ACTIVE and *Proxy_EFW* for NATURAL.

5 Results of Cross-Calibration Activities

5.1 Electron density

WHISPER determines the total electron density from the propagation characteristics of radio waves in a region of space large as compared to the volume of the sheath surrounding the spacecraft. Consequently, the satellite potential and the plasma sheath have a negligible effect on the measured density.

The PEACE experiment measures the flux of thermal electrons (0-30 keV), where the effect of the positive spacecraft floating potential is significant for the cold electrons (below 10 eV); in particular the photoelectrons that exist below the floating spacecraft potential need to be removed before determining the electron density. It can happen that either cold electrons are removed at that stage or some of the photoelectrons contribute to the electron density measurement. On the other hand, the CIS instrument cannot detect cold ions whose energies are below spacecraft potential, as they do not reach its detectors. PEACE and CIS data are regularly calibrated against WHISPER derived densities, considered as absolute electron density estimates, especially in regions like the magnetosheath and the solar wind.

Density estimates from WBD and WHISPER have also been compared on selected events. In most cases, the cut-off frequencies determined from WBD and WHISPER NATURAL spectrograms are in a relatively good agreement despite the different frequency resolution of the two instruments. The slope of the cut-off observed by both instruments is indeed rather smooth and covers a 2 kHz frequency range which is much larger than the 0.163 kHz WHISPER frequency resolution, as illustrated in figure 6. The only difference seems to be related to the precise location of a cut-off frequency within the frequency band over which the gradient is observed. In the given example, the cut off frequency is determined by different techniques. One should note that there is a possibility that the cut-off is not local and then it would represent the density somewhere else. Usually the local cut-offs are steeper slopes in power spectrum.

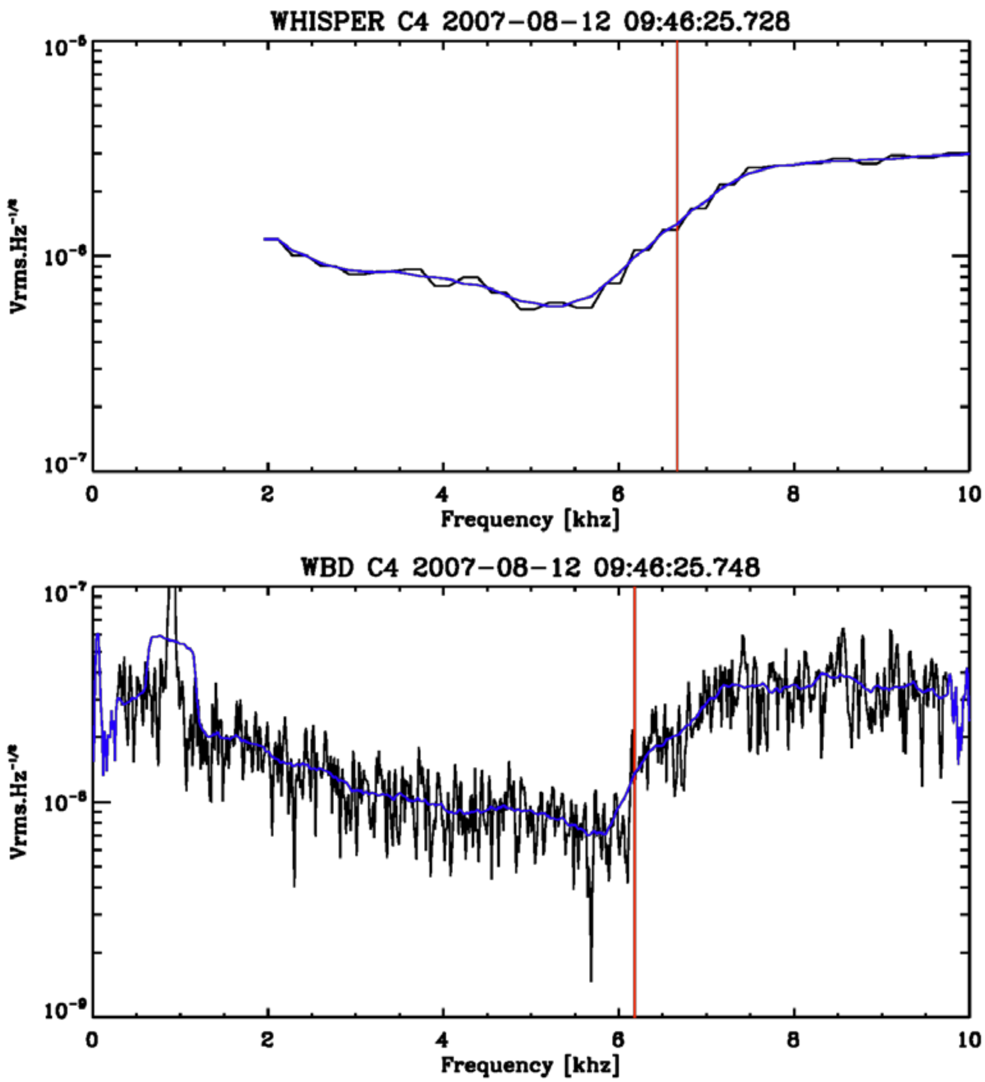

Figure 6: Example of cut-off frequency determination from NATURAL WHISPER (top) and WBD (bottom) spectrograms (from top to bottom) for C4 on August 12, 2007. Black and blue lines show respectively the measured spectrum and spectrum smoothed over frequencies. In the case of WHISPER, the spectrum is averaged (Décréau et al., 1993), hence its smoothed aspect, compared to the noisy individual spectrum measured by WBD. The red lines show the inferred locations of the cut-off on both instruments.

5.2 Total magnetic field

Among the different signatures observed by WHISPER in the plasmasphere, some are directly related to the magnetic field: the electron cyclotron frequency F_{ce} and its harmonics nF_{ce}. While they can sometimes be observed in NATURAL spectra, they are systematically clearly visible when triggered by the WHISPER sounding mode and can be exploited to derive the total magnetic field strength. An algorithm, based on a pattern recognition technique applied to spectrogram, has been developed (Rauch et al., 2006) to extract F_{ce} from WHISPER ACTIVE spectra in the plasmasphere region. It is based on the Radon transform technique, commonly used in image processing and has been validated on synthetic spectrograms. The presence of several harmonics enables to determine F_{ce} with a sub-pixel accuracy, i.e. less than 163 Hz, the highest WHISPER frequency resolution. The magnitude of the total magnitude field is then straightforwardly derived by $F_{ce}[Hz] = 28\ B_0[nT]$.

This technique has been applied to the first years of the mission (2001-2005), on manually selected plasmasphere crossings. Results have been used and validated through several WHISPER/EDI/FGM cross-calibration studies. Electron gyrofrequencies hence derived from the WHISPER instrument for this period have been made available to the CSA as a dedicated dataset.

6 Summary

The WHISPER instrument provides electric field power spectral density continuously on the 4 spacecraft over the mission lifetime. While most of the data processing is performed on board and the calibration of WHISPER measurements into physical quantity is straightforward, the electron density, a parameter of prime interest, has been derived on ground in a continuous manner during the mission using different strategies and ad-hoc algorithms that have evolved over time, but always associated to a careful validation phase aiming at providing a reliable high-quality dataset. More recent algorithms take advantage of modern AI techniques to automate the derivation process, but could only be implemented thanks to the mass of WHISPER densities determined by more conventional, or even manual, methods.

Details about the various density extraction algorithms are given in appendix to this document.

Specific studies have been conducted to compare WHISPER outputs to other CLUSTER products, for instance related to the magnetic field modulus determination in the plasmasphere and its comparison with FGM and EDI (electron gyrotime) measurements. Cross-calibration studies have been carried out to regularly compare electron density estimates from several CLUSTER instruments: WHISPER, PEACE, CIS-HIA, and CIS-CODIF, and have contributed significantly to raising the quality level of WHISPER products.

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Appendix A - Density determination algorithms

In this chapter, we will describe all semi-automatic or automatic algorithms used throughout the mission to extract the plasma frequency from WHISPER electric field spectrograms.

As stated in section 4.2, electron density value is derived from the determination of the plasma frequency F_{pe}, which is associated with plasma signatures (resonances or cut-offs) on WHISPER electric field spectrograms, depending on the plasma regime and the instrument mode (Natural/Sounding). The corresponding uncertainty on plasma density can be obtained via the formula given in section 4.2.

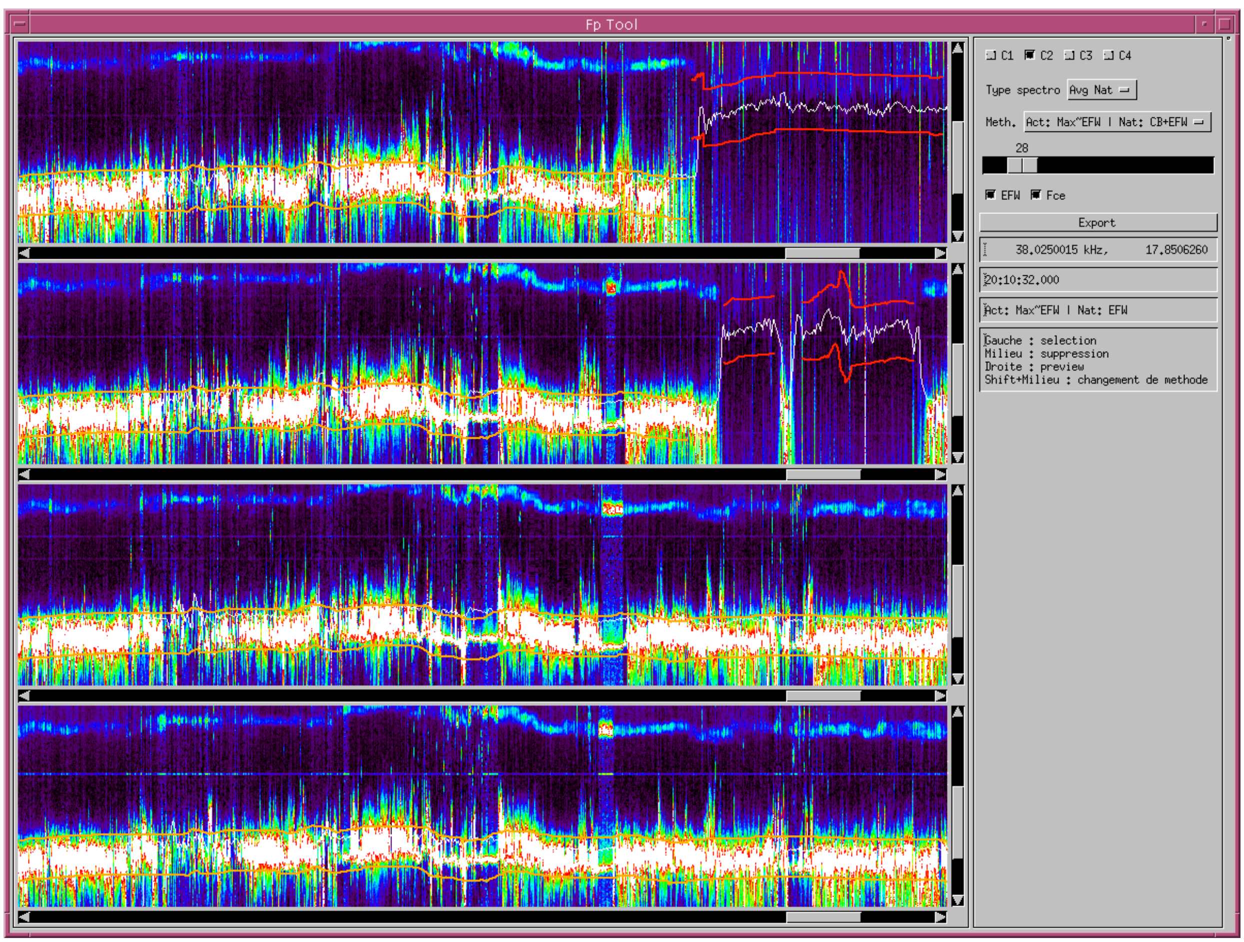

Figure A.1: Typical density processing session for semi-automatic methods. The toll shows the 4 WHISPER electric field spectrograms for the 4 spacecraft (the sliders allow scrolling through the whole spectrograms for 1 day). The orange and red bands are the search bands determined by the operator (the color indicates the algorithms that will be applied). The white line is the recalibrated EFW potential (the gyrofrequency can also be plotted). The right hand-side panel allows to control the spectrograms to process, select the current views (active, natural or average), select the algorithm to apply and parametrize the search band.

A.1 Max1 method (A10, A20)

This method applies to ACTIVE spectra for which the plasma frequency is characterized by a high resonance (typical from the Solar Wind and Magnetosheath).

Note:

➲ This method was used to determine densities from ACTIVE spectra during years 2001-2003. It has been superseded by less manual and time-consuming method.

Density value: For each spectrum, the resonance is extracted as follows:

- peaks extraction based on the magnitude (expressed in dB relatively to the spectrum minimum value)
- filtering: select the highest peak as the resonance only if A2/A1 < 0.8 where A1 is the magnitude of the highest peak and A2 is the magnitude of the second highest peak

Uncertainty: The uncertainty on plasma frequency is the frequency resolution of the WHISPER instrument (163 Hz) because the resonance peak is very narrow. If it is not, this method is not applied.

Contrast: The contrast is given by the local contrast of the resonance (signal-to-noise ratio): if p is the magnitude of the resonance (in dB, relatively to the minimum value of the spectrum) and m is the mean magnitude in a 20 frequency bin interval around the resonance but not including data at the resonance frequency (if f is the resonance frequency, this interval corresponds to $[f - 1.63\ kHz, f + 1.63\ kHz]-\{f\}]$, the contrast c is given by:

$$c = p/m - 1$$

The value is then truncated to 1 if it exceeds 1.

A.2 LowCutoff1 method (N10)

This method is used in combination with the Max1 method and deals with NATURAL spectra for which the plasma frequency is characterized by a low cut-off signature. As many cut-offs are usually observed in spectra, a search band is first applied, based on the predetermined ACTIVE plasma frequency.

Note:

➲ This method was used to determine densities from ACTIVE spectra during years 2001-2003. It has been superseded by less manual and time-consuming method.

Density value: The plasma frequency is extracted as follows:

- the search band is defined as a 30-frequency bin interval around f_{act} (a linear interpolation between every pair of successive ACTIVE values) i.e. [f_{act} - 4.89 kHz, f_{act} + 4.89 kHz]
- to reduce the effect of noise, each spectrum is preprocessed: each spectrum is processed by a morphological opening operator (10 frequency bins) and smoothed (running mean value) in frequency (20 frequency bins)
- a low cut-off is automatically extracted using a dedicated routine. This routine selects the steepest gradient in the search band and defines the lower and upper bounds of the low cut-off. The retained plasma frequency is the center of the low cut-off band.

Uncertainty: The uncertainty is the half-width of the low cut-off frequency band.

Contrast: The contrast is an indicator of the local contrast of the cut-off: if u is the mean magnitude (in dB, relatively to the minimum value of the spectrum) in the upper part of the cut-off band (from the plasma frequency to the upper bound), l the mean magnitude in the lower part of the cut-off (from the lower bound to the plasma frequency), and m the mean magnitude in the whole search band, the contrast c is given by:

$$c = (u - l) / m$$

The contrast factor is bounded between 0 and 1.

A.3 LowCutoff_EFW method (N10E)

This method is used in combination with the Max1 method and deals with NATURAL spectra for which the plasma frequency is characterized by a low cut-off signature. As many cut-offs are usually observed in spectra, a search band is first applied, based on the predetermined ACTIVE plasma frequency and the EFW spacecraft potential values.

Note:

- This method was used to determine densities from ACTIVE spectra during years 2001-2003. It has been superseded by less manual and time-consuming method.
- This method is very similar to LowCutoff (section A.2) but here ACTIVE resonances are used in combination with EFW spacecraft potential data to define the search band.

Density value: The plasma frequency is extracted as follows:

- the search band is defined as a 30-frequency bin interval around f_{EFW} (a proxy of the plasma frequency derived from the EFW spacecraft potential, see section **B.1**) i.e. [f_{EFW} - 4.89 kHz, f_{EFW} + 4.89 kHz]
- the preprocessing and cut-off extraction steps are similar to method 7.2.

Uncertainty: Similar to LowCutoff1 method (see A.2)

Contrast: Similar to LowCutoff1 method (see A.2)

A.4 EFW_proxy method (N20E, N21E)

This method is used in combination with one of the Max methods providing plasma frequency on ACTIVE spectra (Max1, Max2, Max2_EFW) and is used for when NATURAL plasma signatures on WHISPER data cannot be used for the density determination. Both the EFW spacecraft potential and ACTIVE WHISPER resonances are then exploited to give a proxy of the plasma frequency for NATURAL spectra.

Note:

- ➲ N20E is equivalent to N21E, the original algorithm code (20) has indeed been updated to 21 to be consistent with the new generation algorithms (post 2003).
- ➲ This method is very similar to LowCutoff (section A.2) but here ACTIVE resonances are used in combination with EFW spacecraft potential data.

The figure below gives a typical example of a use case, with a Natural spectrogram (top) with no clear signature and the corresponding ACTIVE spectrogram (bottom), with exploitable resonances. The search band (orange) and EFW spacecraft potential (white) have been overplotted.

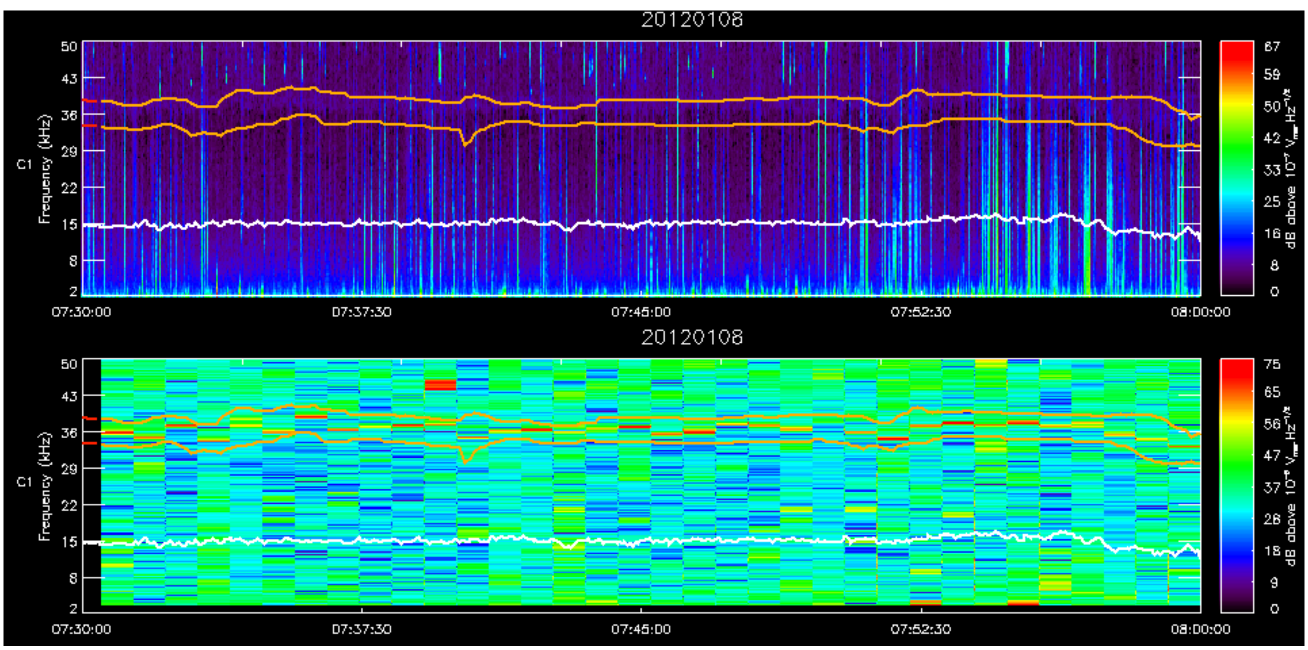

Figure A.2: Typical use case for EFW_proxy method.

Density value: The plasma frequency is extracted as follows:

- the proxy for plasma frequency is extracted from EFW spacecraft potential, as described in section **B.1**

- if no EFW potential data are available, no density will be provided for NATURAL spectra.

Uncertainty: The uncertainty is set to 0 (to indicate that the density is not extracted from the WHISPER spectrum).

Contrast: The contrast is set to -1 (to indicate that the density is not extracted from the WHISPER spectrum).

A.5 Plasmasphere method (A30)

This method applies to ACTIVE spectra in the Plasmasphere and relies on the fact that the ACTIVE spectra magnitudes are enhanced around the upper hybrid frequency.

Density value: The upper hybrid frequency is extracted as follows:

- preprocessing: a morphological top-hat operator is applied to each spectrum to enhance the resonance contrast
- smoothing: each spectrum is smoothed (low-pass Butterworth filter) and the frequency of the maximum magnitude is extracted
- filtering:
  - select the highest peak as the resonance only if A2/A1 < 0.8 where A1 is the magnitude of the highest peak and A2 is the magnitude of the second highest peak
  - keep only points such that the magnitude is at least 16 dB higher than the Natural level in a neighbourhood defined as [*t – 30 seconds, t + 30 seconds, f - 0.815 kHz, f + 0.815 kHz*], where *t* and *f* are the time and the frequency of the candidate resonance
- remaining peaks give the upper hybrid frequency estimates.

Uncertainty: The given uncertainty is the half-width at half-height of the smoothed peaks.

Contrast: Similar to Max1 method (section **A.1**)

A.6 Plasmasphere_EFW method (A30E)

This method is similar to method Plasmasphere (section **A.5**) in many ways but includes an additional step, based on EFW measurements, to increase time resolution.

Density value: The plasma frequency is extracted as follows:

- preprocessing: same as method **A.5**
- smoothing: same as method **A.5**
- filtering: the first two steps are as in method A.5, but in addition there are now two additional steps
  - EFW potential is used (if it behaves consistently), keeping only the peaks in the search band [$0.5 * f_{EFW}, 1.5 * f_{EFW}$] where f_{EFW} is the plasma frequency proxy (see section **B.1**)
  - to increase the time resolution, we reselect the peaks that were rejected by the magnitude condition relatively to the second highest magnitude but that lie in the search band around EFW
- remaining peaks give the upper hybrid frequency estimates

Uncertainty: Similar to Plasmasphere method (section **A.5**)

Contrast: The contrast is first determined similarly to Max1 method (section **A.1**), then corrected to take the quality of the EFW proxy into consideration, as follows:

$$c = (1 - \Delta) * c$$

where Δ is the relative distance between the peak frequency f and the *EFW recalibrated potential* f_{EFW}:

$$\Delta = 0.5 * | f_{EFW} - f | / f_{EFW}$$

A.7 Max2 method (A11, A13, A21)

This method applies to ACTIVE spectra for which the plasma frequency is characterized by a high resonance.

The figure below gives a typical example of this signature on an ACTIVE spectrogram with the selected search band (red) and a typical example of a spectrum with a resonance around 28kHz.

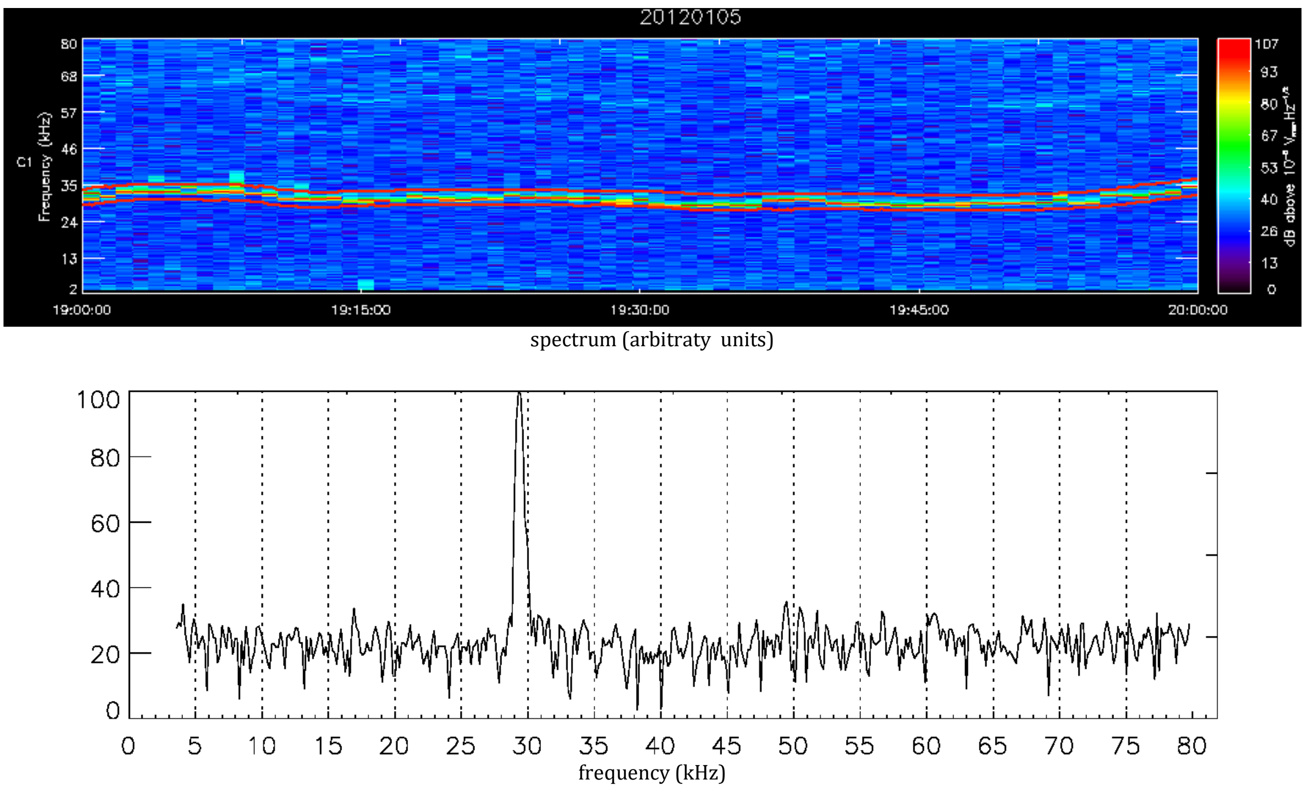

Figure A.3: Typical use case for Max2 method, with illustrative spectrogram (top) and spectrum (bottom).

Density value: The plasma frequency value is extracted from the resonances, following several steps:

- a search band is defined by an operator (width can be tuned)
- preprocessing: EDI interferences filtering (see section **B.2**)
- peaks extraction within the search band based on the magnitude (expressed in dB relatively to the spectrum minimum value)
- filtering:
    - o if F_{ce} available, keep only those peaks that are not near the electron gyrofrequency or its 12 first harmonics, i.e. points lying in the [$nF_{ce} - \Delta$, nF_{ce} +

$\Delta]_{n \in [1,12]}$ interval are discarded. nF_{ce} is one of the gyrofrequency harmonics and Δ is defined as

$$\Delta = max\ (0.1*nFce,\ 0.8125\ kHz)$$

- select the highest peak as the resonance only if A2/A1 < 0.85 where A1 is the magnitude of the highest peak and A2 is the magnitude of the second highest peak

Uncertainty:

- for algorithm codes A11 and A21: similar to Max1 method (section **A.1**).
- for algorithm code A13: the given uncertainty corresponds to the frequency search band manually selected by the operator. This is used in a limited number of cases, e. g. when the plasma frequency can be inferred by temporal continuity by the operator on less clear spectra (i. e. without a clear resonance), leading to an uncertainty greater than one instrument frequency bin.

Contrast: Similar to Max1 method (section **A.1**)

A.8 Max2_EFW method (A11E, A13E, A21E)

This method applies to ACTIVE spectra for which the plasma frequency is characterized by a high resonance, making use of the EFW spacecraft potential for validation.

The figure below gives a typical example of this signature on an ACTIVE spectrogram with the selected search band (yellow) and the EFW spacecraft potential (white) and a typical example of a spectrum with a resonance around 15kHz, collocated with electron gyrofrequency harmonics.

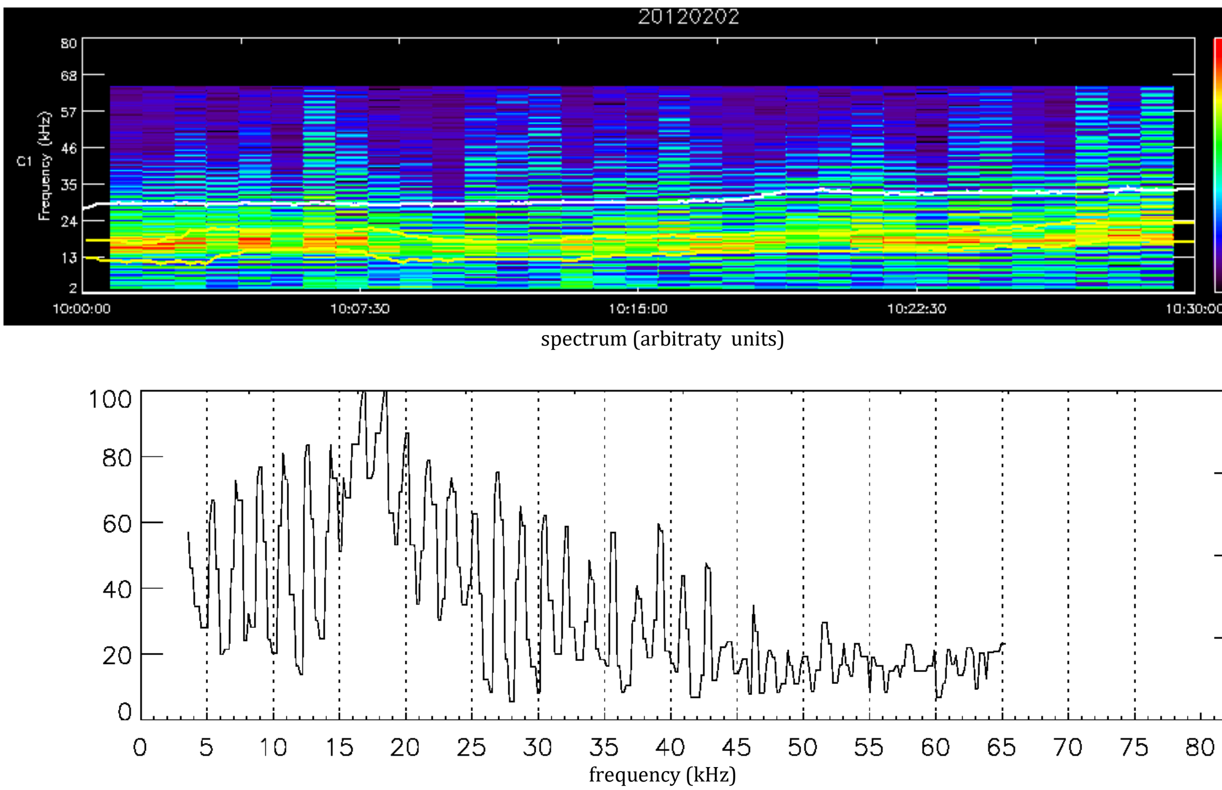

Figure A.4: Typical use case for Max2 method, with illustrative spectrogram (top) and spectrum (bottom).

Density value: This method is similar to Max2 method (section **A.7**) in many ways, but filtering is different because EFW spacecraft potential is used:

- search band, preprocessing (EDI), peaks extraction and use of F_{ce} are similar to Max2 method (section **A.7**)
- filtering:
    - select only the peaks whose temporal variations are close to those of the plasma frequency proxy from EFW spacecraft potential measurements:

- compute the plasma frequency proxy (see section **B.1**)
- in a 8 successive spectra window, only the peaks subset that matches most the variations of the proxy is kept. The criterion is to minimize the error of the linear fit of the series of selected peaks to proxy values at the same time (chi-square returned by the IDL linfit function)

Uncertainty:

- for algorithm codes A11 and A21: similar to Max1 method (section **A.1**).
- for algorithm code A13: the given uncertainty corresponds to the frequency search band manually selected by the operator. This is used in a limited number of cases, e. g. when the plasma frequency can be inferred by temporal continuity by the operator on less clear spectra (i. e. without a clear resonance), leading to an uncertainty greater than one instrument frequency bin.

Contrast: Similar to Max1 method (section **A.1**)

A.9 LowCutoff2 method (N11)

This method applies to NATURAL spectra for which the plasma frequency is characterized by a low cut-off signature (e.g. in the Solar Wind).

The figure below gives a typical example of this signature on a Natural spectrogram with the selected search band (orange) and a typical example of a spectrum with a cut-off around 40kHz.

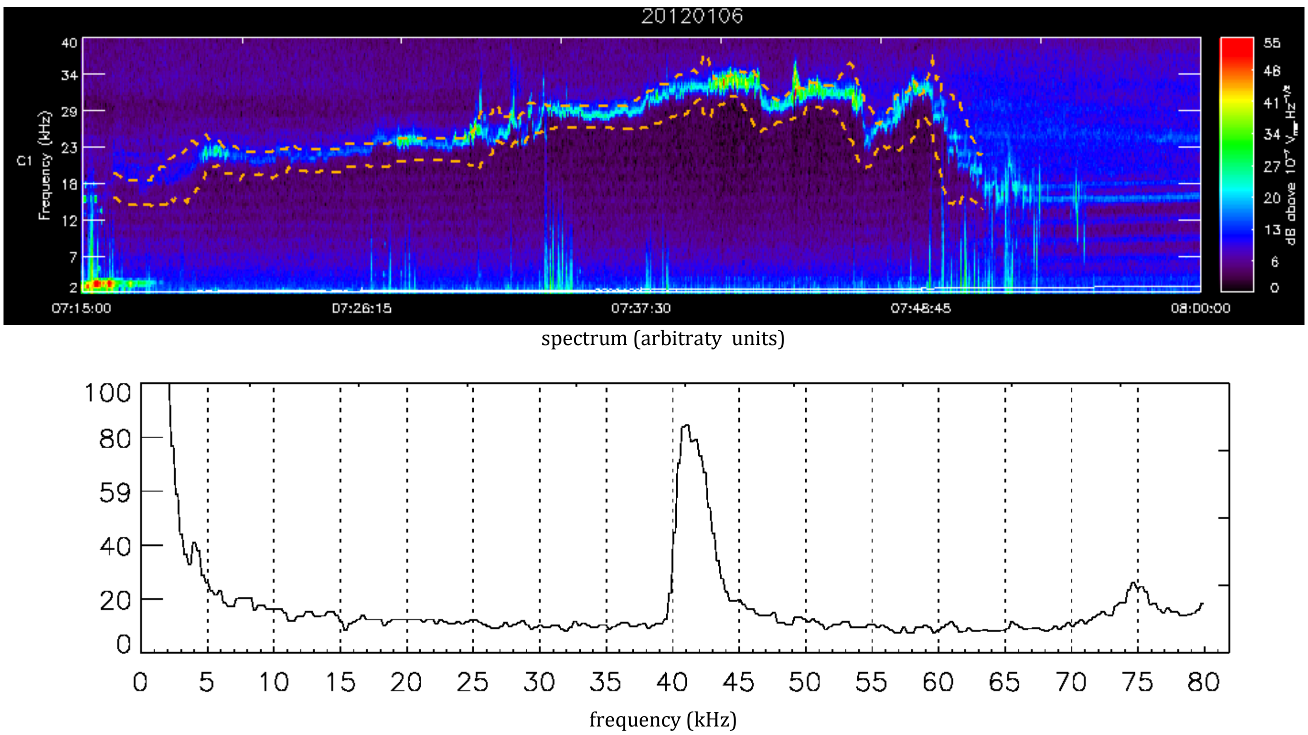

Figure A.5: Typical use case for LowCutoff2 method, with illustrative spectrogram (top) and spectrum (bottom).

Density value: Each Natural spectrum is processed in the following way:

- a search band is defined by an operator (width can be tuned)
- preprocessing: EDI interferences filtering (see section **B.2**)
- low cut-off extraction within the search band, similarly to section **A.2**
- plasma frequency values with a contrast < 0.2 are discarded

Uncertainty: Similar to LowCutoff method (section **A.2**)

Contrast: Similar to LowCutoff method (section **A.2**)

A.10 LowCutoff2_EFW method (N11E)

This method is used in combination with one of the Max methods providing plasma frequency on ACTIVE spectra (Max2, Max2_EFW) and applies to NATURAL spectra for which the plasma frequency is characterized by a low cut-off signature (e.g. in the Solar Wind), using EFW measurements to define a search band.

The figure below gives a typical example of this signature on a Natural spectrogram, with the selected search band (orange) and EFW spacecraft potential (white) and a typical example of a spectrum with a cut-off around 15kHz.

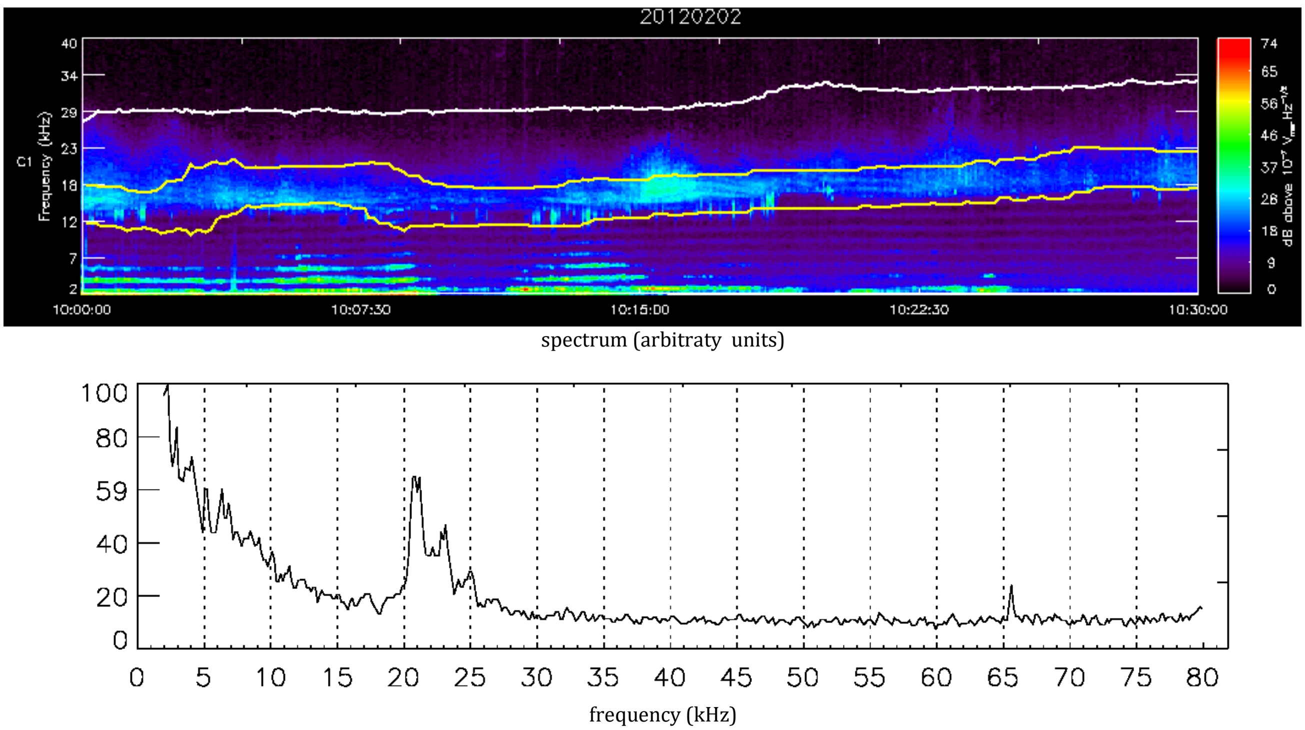

Figure A.6: Typical use case for LowCutoff2_EFW method, with illustrative spectrogram (top) and spectrum (bottom).

Density value: Each Natural spectrum is processed in the following way:

- the search band is given by the proxy extracted from EFW spacecraft potential and WHISPER ACTIVE plasma frequencies (see section **B.1**)
- preprocessing: EDI interferences filtering (see section **B.2**)
- low cut-off extraction: similar to section **A.3**
- plasma frequency values with a contrast < 0.2 are discarded

Uncertainty: Similar to LowCutoff method (section **A.2**)

Contrast: Similar to LowCutoff method (section **A.2**)

A.11 UpperCutoff method (N12)

This method applies to NATURAL spectra for which the plasma frequency is characterized by an upper cut-off signature (e.g. in Plasmasphere).

The figure below gives a typical example of this signature on an ACTIVE spectrogram, with the selected search band (white dots) and the upper cut-off estimates (black crosses). EFW spacecraft potential (white line) has been overplotted to illustrate the god agreement with the result, in terms of temporal variations. The other white line corresponds to the electron gyrofrequency from FGM.

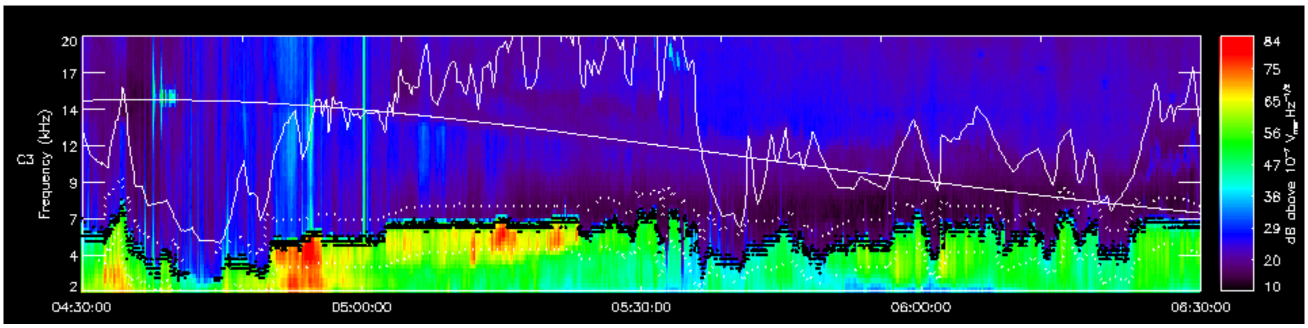

Figure A.7: Typical use case for UpperCutoff2_EFW method (illustrative spectrogram).

Density value: Each Natural spectrum is processed in the following way:

- a search band is defined by an operator (width can be tuned)
- preprocessing: EDI interferences filtering (see section **B.2**)
- upper cut-off extraction within the search band, similarly to LowCutoff1 (section **A.2**)
- plasma frequency values with a contrast < 0.2 are discarded

Uncertainty: Similar to LowCutoff1 (section **A.2**)

Contrast: Similar to LowCutoff1 (section **A.2**), with upper and lower bounds inverted.

A.12 Tail_Act method (A40E)

In the Earth's magnetic tail regions, the plasma frequency (and hence the electron density from which it is directly derived) is very low, and most often below 4 kHz, the lowest frequency covered by WHISPER in sounding modes. When a dense thermal electron population is present (with a plasma frequency higher than 4 kHz), plenty of strong resonances may be observed at the electron cyclotron frequency and its harmonics, the plasma frequency, the upper-hybrid frequency, and Bernstein's resonances. As the magnetic field is also very low, all these resonances are unfortunately too close together to be unambiguously distinguished. The way to solve this problem is to take advantage of the higher spectral energy density above the plasma frequency.

The figure below gives a typical example of this signature on an ACTIVE spectrogram and a typical example of a spectrum with an active low cut-off around 13kHz.

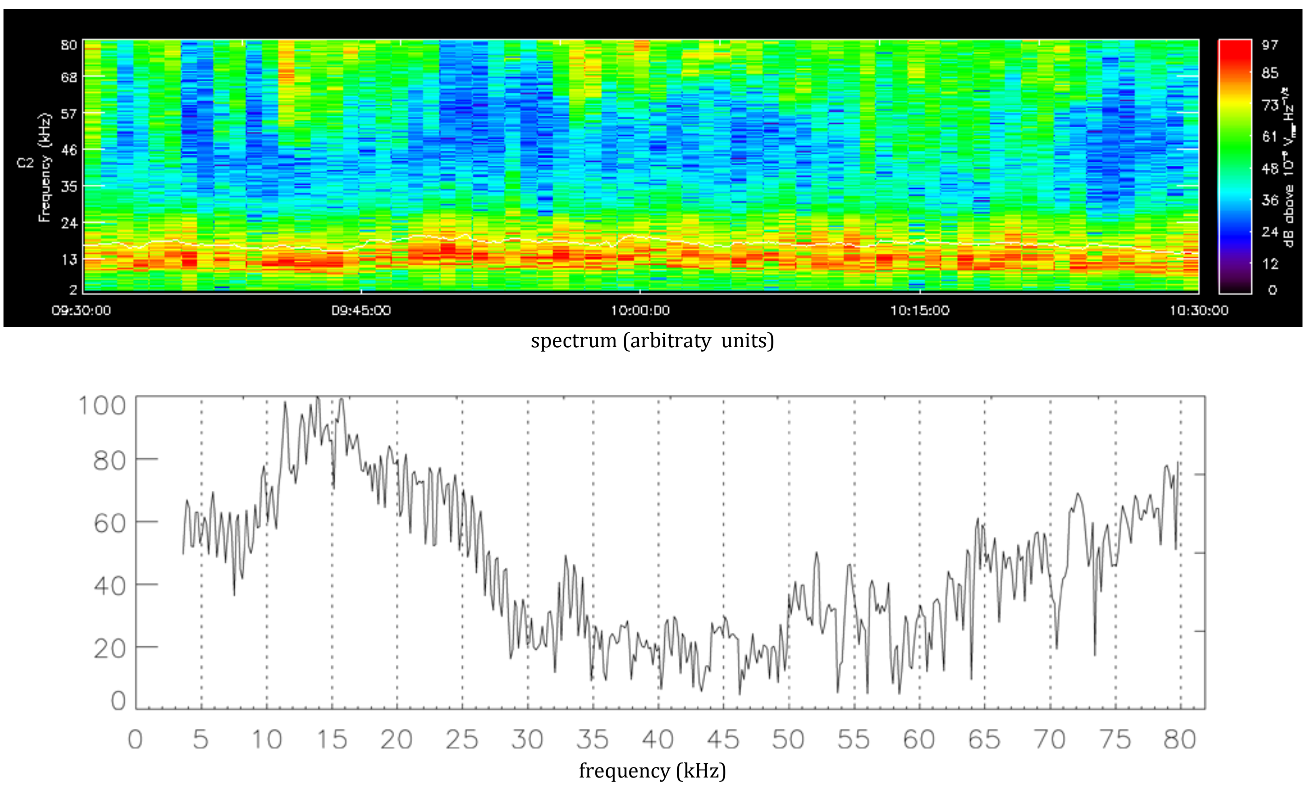

Figure A.8: Typical use case for Tail_Act method, with illustrative spectrogram (top) and spectrum (bottom).

Density value: Densities in the tail are processed on a case by case basis. This is because tail density processing requires human intervention and scientific expertise. Each ACTIVE spectrum is first smoothed (a Butterworth filter is applied) and the cut-off that is observed close to the plasma frequency is used to determine the electron density (Masson et al., 2010). The value is compared to density proxies extracted from EFW, PEACE and CIS for validation.

Uncertainty: Similar to LowCutoff1 (section **A.2**)

Contrast: Similar to LowCutoff1 (section **A.2**)

A.13 Tail_Nat method (N40E)

As already mentioned in section **A.12**, in the Earth's magnetic tail regions, the plasma frequency (and hence the electron density from which it is directly derived) is very low. Natural cut-offs can be observed above the lowest frequency of the WHISPER Natural mode (2 kHz). NATURAL spectra are processed in the tail if and only if resonances are also observed on ACTIVE spectra. However, only cases with clear and exploitable natural signatures will be processed.

Density value: Densities in the tail are processed on a case by case basis. This is because tail density processing requires human intervention and scientific expertise. The first step is to select a search band that contains the cut-off of interest. This is a manual step that can be done only when ACTIVE and NATURAL signatures agree. Each NATURAL spectrum is then smoothed (boxcar average over Δ/2, where Δ is the search band width) and the extracted low cut-off is used to determine the electron density. In the tail region, the cut-off is related to the so called 'z-mode' and occurs very close to the plasma frequency, due to the low value of the electron cyclotron frequency. The z-mode cut-off is given by the formula:

$$F_z = 0.5\ [\ -F_{ce} + (F_{ce}^{2} + 4\ F_{pe}^{2})\ ½\ ]$$

In the tail region, relative values of F_{ce} and Fp_e lead to the following approximation:

$$F_{pe} \sim F_z + 0.5\ F_{ce}$$

Uncertainty: Similar to LowCutoff1 (section **A.2**)

Contrast: Similar to LowCutoff1 (section **A.2**)

A.14 LowCutOff_Act method (A41E)

This method applies to ACTIVE spectra for which the plasma frequency is characterized by a low cut-off. Typical spectrogram and spectrum are given in section **A.12**.

Note:

➲ The purpose of this method is similar to (A40E), but it has been developed later to allow a semi-automatic density extraction instead of a case-by-case basis. Human intervention is still needed, but a lot reduced. It is used in the same magnetospheric regions as described in A.12.

Density value: Each ACTIVE spectrum is processed in the following way:

- a search band is defined by an operator (as thin as possible around the cut-off)
- preprocessing: a 3 frequency-bins morphological operator (closing followed by opening) plus smoothing is applied to each spectrum to limit the influence of electron gyrofrequency harmonics
- low cut-off extraction (defined as 2/3 of the cut-off range), the value is accepted only of it lies in the operator defined search band
- filtering with respect to EFW spacecraft potential variations, as described in **A.8**

Uncertainty: Similar to LowCutoff1 (section **A.2**)

Contrast: Similar to LowCutoff1 (section **A.2**)

A.15 ANN1_Act method (A50)

This method applies to ACTIVE spectra for which the plasma frequency is characterized by a high resonance (e.g. in Magnetosheath and Solar Wind regions). Typical examples of such WHISPER measurements are shown in **A.7**. Fully automatic algorithms have been implemented to select these kinds of spectra and to derive the electron density. They are based on artificial neural networks; trained with several years of validated WHISPER data.

Density value: The plasma frequency value is extracted from ACTIVE spectra by a specific ANN algorithm trained on a validated WHISPER dataset. This dataset contains ACTIVE spectra randomly selected from 2002 to 2017 (all spacecraft) and corresponding plasma frequencies extracted with first- and second-generation algorithms.

- input: ACTIVE spectra in dB relatively to the spectrum minimum value.
- output: The ANN algorithm determines a probability for each frequency bin. The highest probability bin is selected as the plasma frequency, provided that the probability is higher than 0.4.
- more details can be found in (Gilet et al., 2021)

Uncertainty: The uncertainty on plasma frequency is set to 4 frequency bins (ΔFpe = 0.652 kHz). The corresponding uncertainty for electron density is given by

$$\Delta N_e = (2 / \alpha)\ Fpe\ .\ \Delta Fpe$$

Contrast: Similar to Max1 method (section **A.1**).
Plasma frequency values with a contrast < 0.6 are discarded.

A.16 ANN2_Nat method (N51)

This method applies to NATURAL spectra generally encountered in the Tail or in the edge of Plasmasphere where a broad low-frequency signature is visible, in combination with multiple poorly frequency-discriminated signatures in the corresponding ACTIVE spectra. Fully automatic algorithms have been implemented to select these kinds of spectra and to derive the electron density. They are based on artificial neural networks; trained with several years of validated WHISPER data.

Density value: The plasma frequency value is extracted from NATURAL spectra by a specific ANN algorithm trained on a validated WHISPER dataset. During the extraction process, the following steps are applied:

- a smoothing method based on Savitzky-Golay filter is applied on dB-converted Natural spectra
- a cut-off search algorithm is applied to each spectrum to retrieve the likely position of the plasma frequency, fp1
- the fp1 line is filtered with respect to cut-off quality, time continuity and interference frequencies to reconstruct a proper search baseline
- a cut-off search algorithm is applied around the search baseline to retrieve plasma frequency values

Uncertainty: The uncertainty on plasma frequency is arbitrarily set to 10 frequency bins, i.e. ΔFpe = 1.629 kHz, to account for the cut-off width (typically of this order). The corresponding uncertainty for electron density is given by

$$\Delta N_e = (2 / \alpha)\ Fpe\ .\ \Delta Fpe$$

Contrast: Similar to LowCutoff1 (section **A.2**)

A.17 ANN2_Nat method (N52)

This method applies to NATURAL spectra generally observed in the core Plasmasphere when the magnetic field magnitude is high-enough, where several frequency-discriminated plasma signatures are observed (e.g. electron gyroharmonics, Bernstein's modes) on both NATURAL and ACTIVE spectra. Fully automatic algorithms have been implemented to select these kinds of spectra and to derive the electron density. They are based on artificial neural networks; trained with several years of validated WHISPER data.

Density value: The plasma frequency value is extracted from NATURAL spectra by a specific ANN algorithm trained on a validated WHISPER dataset. During the extraction process, the following steps are applied:

- a cut-off search algorithm is applied to the Natural spectrum spectrum to retrieve the likely position of the plasma frequency, fp1
- the fp1 line is filtered with respect to cut-off quality, time continuity and interference frequencies to reconstruct a proper search baseline
- a cut-off search algorithm is applied around the search baseline to retrieve plasma frequency values

Uncertainty: The uncertainty on plasma frequency is arbitrarily set to 10 frequency bins, i.e. ΔFpe = 1.629 kHz, to take into account the cut-off width. The corresponding uncertainty for electron density is given by

$$\Delta N_e = (2 / \alpha)\ Fpe\ .\ \Delta Fpe$$

Contrast: Similar to LowCutoff1 (section **A.2**)

Appendix B - External data processing

B.1 Plasma frequency proxy from EFW spacecraft potential

EFW spacecraft potential (V_{sc}) measurements can be used to derive a proxy of the plasma frequency. The relationship between the electron density and spacecraft potential is not simple as the spacecraft potential depends on the energy distribution of electrons and the satellite photoelectron distribution (Pedersen et al., 2008).

Nevertheless, spacecraft potential and plasma frequency temporal variations are highly correlated and the WHISPER density processing can be significantly improved by using a plasma frequency *estimate from the EFW potential*, defined as follows:

- for high densities or low values of V_{sc}, a rough approximation of the plasma frequency is given by the empirical formula:

$$f = 9\ (\ 200 * (-V_{sc})^{-1.85}\ )^{½}$$

- between each pair of consecutive ACTIVE plasma frequencies (as determined by one of the methods described above), the *f* curve is linearly stretched (*shearing* technique) to match the ACTIVE frequencies;
- the obtained curve can be interpolated to the times of WHISPER NATURAL spectra to give the plasma frequency estimate (proxy) from the *EFW potential* f_{EFW}.

In appendix A, f_{EFW} is used for different purposes:

- to define a search band for NATURAL cut-off extraction,
- as a proxy of the plasma frequency when WHISPER NATURAL electric field spectra cannot be used for the density estimate.

B.2 EDI interferences filtering

EDI interferences are characterized by horizontal harmonic lines observed on WHISPER spectrograms (see section **4.1**). They can easily be recognized and removed since the Code Repetition Frequency dataset from EDI (given in the EDI CSA product **C[i]_CP_EDI_CRF**) gives the time of emissions, the fundamental excited frequency and the potential extent of the perturbation. The corresponding values (fundamental and harmonics) are removed from WHISPER spectra and interpolated in the density determination process. Note that they are not removed in WHISPER electric power spectral density available at CSA.