RPCMIP/RPCLAP Cross-Calibration Report

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RPCMIP/RPCLAP cross-calibrated science dataset on the ESA's Planetary Science Archive (PSA)

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Version 1.0	2019-03-29	First version of the cross-calibration report.
Version 1.1	2019-08-31	Updated version following 2019 final PSA review Section 2.4 updated (information on new cross-calibrated intervals added).

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List of Acronyms

ESA	European Space Agency
LAP	LAngmuir Probe
LDL	Long Debye Length
MIP	Mutual Impedance Probe
PSA	Planetary Science Archive
RD	Reference Document
RPC	Rosetta Plasma Consortium
SDL	Short Debye Length
TM	TeleMetry

Reference Documents

RD1	User Guide to the RPC-MIP Science Datasets in the ESA's Planetary Science Archive (PSA), RPC-MIP-UG-LPC2E, 2018
RD2	Rosetta RPC-LAP to Planetary Science Archive Interface Control Document, RO-IRFU-LAP-EAICD-1_13

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1. Introduction

This document describes the cross-calibration processing performed to derive high time resolution plasma density from the measurements of the RPC-MIP (Mutual Impedance Probe) and the RPC-LAP (Langmuir probe) instruments, two of the five instruments of the Rosetta Plasma Consortium (RPC) on board the orbiter of the ESA Rosetta mission.

RPC-MIP is an active electric sensor that measures the transfer impedance between a transmitter (monopole or dipole) and a receiving dipole. It operates in the [7-3500] kHz frequency range in different frequency bands and different frequency resolutions. In active mode (i.e. with its transmitter(s) on), it acquires electric spectra that can be analysed to determine some of the plasma bulk characteristics, among which the electron plasma density which is provided as a dataset in the ESA's Planetary Science Archive (https://archives.esac.esa.int/psa). A more detailed description of the RPC-MIP instrument and of the datasets available on the PSA can be found in Trotignon et al (2007) and in *RD1*.

RPC-LAP is a set of two Langmuir probes that can independently measure the electric current between the probe and the plasma (by applying a bias voltage) or the voltage of the probe with respect to the spacecraft (by applying a bias current). By applying bias voltages or currents, RPC-LAP is able to gather information regarding the electron and ion populations composing the plasma environment surrounding the Rosetta spacecraft as well as measure the Rosetta spacecraft electric floating potential. Its measurements are provided as a dataset in the ESA's Planetary Science Archive (https://www.cosmos.esa.int/web/psa/rosetta). A more detailed description of the RPC-LAP instrument and of the datasets available on the PSA can be found in Eriksson et al (2007) and in *RD2*.

On the one hand, RPC-MIP can access the plasma (electron) density under certain operating conditions (described in *RD1*) with limitations on the time resolution due to the TM allocation and on-board processing capabilities. On the other hand, RPC-LAP can monitor the temporal fluctuations of the spacecraft floating potential and/or the ion and electron currents collected by the biased probes with higher time resolution. By combining data from these two complementary instruments, the plasma density can be retrieved with a high cadence and has been made publicly available through the PSA. This document details the method used to obtain this combined RPCMIP/RPCLAP cross-calibrated plasma density dataset.

2. Inputs from RPC-MIP and RPC-LAP

2.1 Data from RPC-MIP

RPC-MIP provides reliable estimates of the plasma electron density with time resolution up to ~2.5 s and with limitations associated to operational constraints (details in section 4 and section 6.1 of *RD1*). In particular, the accessible range of plasma density values depends on operational parameters (in particular SDL or LDL mode) and RPCMIP cannot provide densities if the local plasma frequency, that directly depends on the plasma density itself, falls out of the frequency interval probed by the instrument. Plasma electron densities derived from the RPC-MIP measurements are available as a dedicated dataset on the PSA and are used as reference values during the RPCMIP/RPCLAP cross-calibrated plasma density derivation process, taking into account their associated uncertainty and quality values (*RD1*).

On the PSA, the RPC-MIP data used for cross-calibration is available as the L5 RO-C-RPCMIP-5 dataset.

2.2 Selection of RPC-MIP data

Time intervals with RPC-MIP in both SDL and LDL mode undergo the cross-calibration procedure and are provided to the PSA.

2.3 Data from RPC-LAP

Different measurements from RPC-LAP can be used to retrieve plasma density variations. In particular, ion current collected on the RPC-LAP probes and floating potentials measured by RPC-LAP probes are directly related to the plasma density and are therefore considered as inputs to the cross-calibration process (see *RD2* for more details on the measurement process). The dependency to the plasma density is taken into account through two different models, valid within certain assumptions described in section 4.3.1 and section 4.3.2.

The RPC-LAP instrument performs measurements from two spherical probes that can be operated independently, allowing simultaneous measurements that are used to validate the RPCMIP/RPCLAP plasma density cross-calibration process (as described in section 6).

On the PSA, the RPC-LAP data are available as L5 datasets as RO-C-RPCLAP-5.

2.4 Selection of RPC-LAP data

As a versatile instrument, RPC-LAP offers a large number of operational modes, resulting in independent measurements of different physical quantities on each probe. Among the different RPC-LAP operational macros, only a subpart leads to floating potential or ion current measurements. Hereafter is the list of RPC-LAP macros (identifying a specific operational mode of the RPC-LAP instrument, see section 2.3 of *RD2*) used as input to the cross-calibration process:

RPC-LAP macro	Measurements for Probe1		Measurements for Probe2		RPC-MIP mode
	Floating potential	Ion current	Floating potential	Ion current	
410	✓			✓	SDL
412	✓			✓	SDL
416	✓			✓	SDL
504	✓		✓		SDL
715	✓				LDL
716	✓				LDL
801	✓		✓		SDL
802	✓		✓		SDL
803		✓			LDL
805		✓			LDL
807		✓			LDL
816		✓			LDL
827		✓			SDL
914		✓		✓	SDL

In the table above, all input RPC-LAP macros are listed. However, due to prioritization rules and post-processing validation steps (described in section 5) some of them do not lead to cross-calibrated outputs. Note that some macros lead to measurements only for one RPC-LAP probe 1 (during the RPC-MIP LDL mode of operations, RPC-LAP probe 2 acts as the transmitter for mutual impedance measurements and cannot perform any measurements).

RPC-LAP measurements suffer some limitations related to the illumination conditions affecting the photoelectron currents collected on the probes whenever they are entering or leaving shadow. RPC-LAP inputs have thus been filtered in order to remove all periods containing shadow/daylight transitions.

3. Maneuvers filtering

Spacecraft maneuvers can create artefacts or affect the quality of RPC-LAP and/or RPC-MIP measurements (see *RD1* section 9.6 and *RD2* section 2.6.2), in particular Wheel Off-Loadings and orbit correction maneuvers. Therefore, time intervals containing such spacecraft maneuvers have been excluded from the cross-calibration procedure. No cross-calibrated plasma density is retrieved during these events.

4. Cross-calibration method

The procedure for the derivation of RPCMIP/RPCLAP cross-calibrated densities dataset is obtained through different steps, summarized in Figure 1.

First, RPC-MIP and RPC-LAP inputs are selected (see section 2), then filtered based on their quality and sampled on a common time scale (section 4.1 and 4.2). Then, according to a model describing the relation between the RPC-MIP and RPC-LAP observed quantities (sections 4.3.1 and 4.3.2), a best fitting model parameter estimation is conducted (section 4.3.4). The analysis is performed on time sliding windows with a 50% overlap between two consecutive windows (section 4.3.3). The best fitting model is applied to the full time resolution RPC-LAP input to obtain a single cross-calibrated density for each RPC-LAP measurement resulting in the final RPCMIP/RPLAP density (section 4.4.1), to which an uncertainty (section 4.4.2) and quality value (section 4.4.3) is associated.

While the best fitting procedure is performed over the full analysis window (under the assumption of certain parameters, as described later on in section 4.3), the next steps are performed over a succession of time intervals. The preliminary estimates obtained simultaneously from consecutive overlapping windows are compared and classified in 5 possible cases. Each case is associated with a specific derivation of final values of the RPCMIP/RPCLAP density, uncertainty and quality.

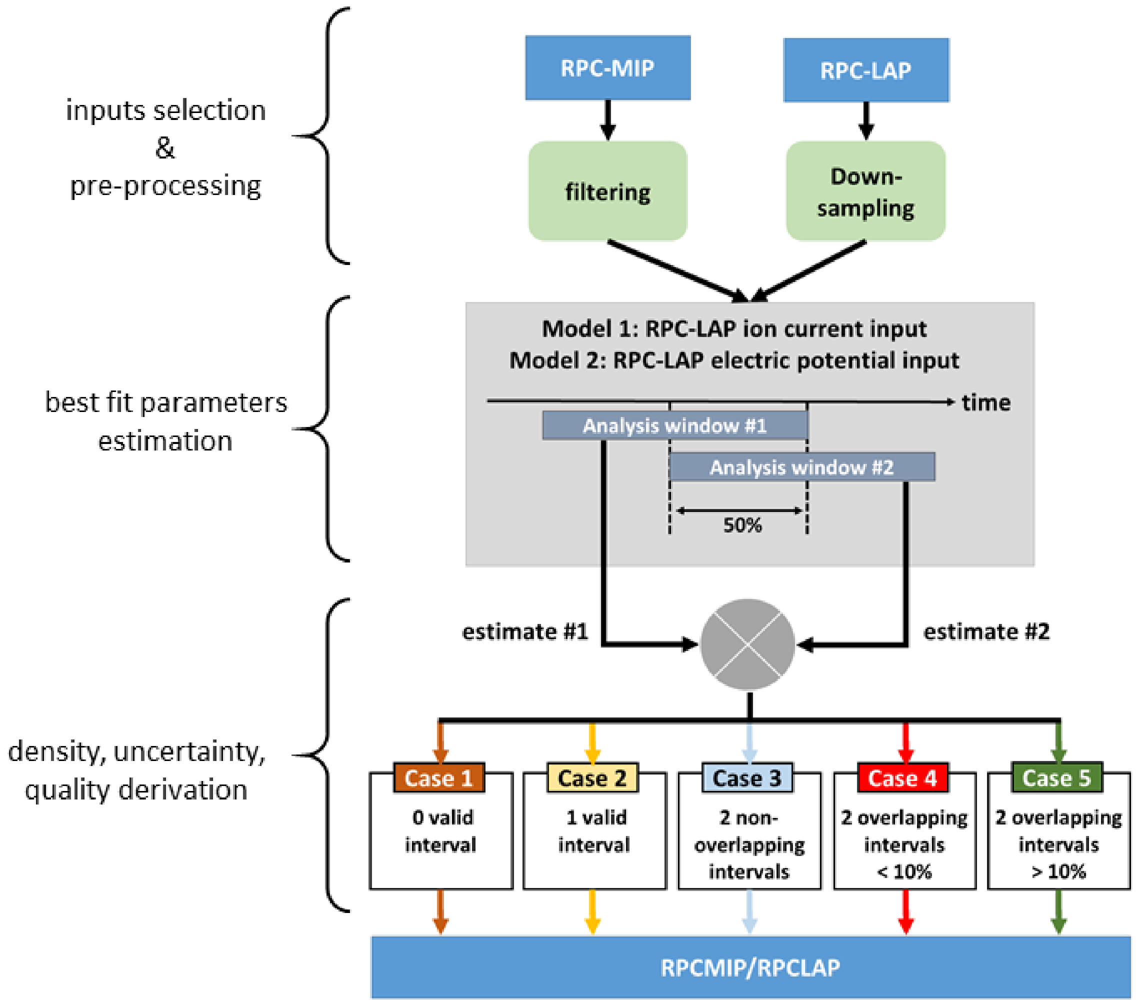

Figure 1: Overall cross-calibration procedure for the production of the RPCMIP/RPCLAP dataset.

4.1 Filtering of RPC-MIP input measurements based on their quality

Three quality values are associated to each RPC-MIP density used as input (*RD1*). From these qualities, a single joint quality is computed as the product between the "QUALITY_SNR" parameter (representing the local quality of the cut-off of the RPC-MIP power spectra, ranging from 0.1 to 1) and the "QUALITY_SPECTRUM" parameter (representing the spectrum complexity, ranging from 0.1 to 1). Lower quality RPC-MIP densities are then filtered out by applying a lower threshold on this joint quality, so that only high enough quality (i.e. reliable enough) RPC-MIP densities feed the cross-calibration as inputs. The value of the threshold is empirically set to 0.3.

The RPC-LAP data used in the cross-calibration are direct output from the analog-to-digital converters in the instrument, which only have been subject to calibration from telemetry units to volts or amperes (and, for the case of lower sampling frequency than 57.8 Hz, averaging). While any physical interpretation of these RPC-LAP parameters alone in terms of spacecraft potential or plasma density could have a large uncertainty, they are very accurate representations of the probe voltage w.r.t. the spacecraft ground or the current flowing from the probe to the plasma, which is what is used in the presented model (Eq. 1 and 3). This means that we do not consider any meaningful uncertainty associated with the input RPC-LAP data, and the quality value is therefore set to 1.

4.2 Time-alignment of RPC-MIP and RPC-LAP inputs

In order to base the cross-calibration procedure on RPC-MIP and RPC-LAP measurements acquired simultaneously, i.e. corresponding to the same plasma conditions, we select, in a first step of the cross-calibration procedure, a subset of RPC-LAP measurements acquired during the RPC-MIP measurements acquisition time.[1] Indeed, while RPC-LAP inputs are available with a high time resolution (up to 17 ms), each RPC-MIP input density is derived from one active MIP spectrum which is the result of several on-board spectrum acquisitions, averaged over periods that depend on operational parameters (up to 6 s). Moreover, the RPC-MIP on-board sequence also contains idle or passive measurements periods and RPC-MIP densities might not be derivable for each active spectrum, resulting in an irregularly, unevenly spaced time series. RPC-LAP input measurements therefore undergo a resampling step aiming at mimicking the actual RPC-MIP on-board data sampling: RPC-LAP measurements lying in RPC-MIP active acquisitions time intervals are averaged and RPC-LAP measurements lying in RPC-MIP not active acquisition periods (idle or passive measurements) are discarded. This results in an irregular gridding and in a drastic down-sampling of the RPC-LAP inputs, but corresponds to a realistic time alignment of RPC-LAP and RPC-MIP datasets. With this down-sampled data series, it is possible to perform the calibration procedure by analysing measurements obtained in exactly the same plasma conditions. Note however that the resulting cross-calibration procedure is then applied to the *entire* RPC-LAP input dataset in order to obtain density estimates and derive the final cross-calibrated densities.

[1] One could adopt a time-closest approach to align RPC-MIP values to RPC-LAP high cadence ones. Nevertheless, this approach was not considered optimal due to differences related to the on-board sampling of both instruments.

4.3 Fitting procedure

4.3.1 Cross-calibrated RPC-LAP ion current against RPC-MIP electron density

The theoretical relation between the electron density, inferred from RPC-MIP measurements, and the ion current, collected and measured from RPC-LAP is described below.

The ion currents collected by RPC-LAP are obtained by biasing the probes at negative electric potentials, in order to maximize the collection of ions and the repulsion of electrons. In such cases the electron current contribution at the probe is assumed to be negligible. Assuming also a constant contribution of the secondary currents at the RPC-LAP probe, the current balance equation at the probe reduces to:

$$I_i - I_{sec} + I_{LAP} \cong 0$$

where I_i represents the ion current collected at the RPC-LAP probe, I_{sec} the sum of the secondary currents collected at the probe and I_{LAP} represents the current measured at the probe that keeps a fixed bias voltage. The photoelectron current, contributing to the secondary current term, should mainly change with the illumination condition of the RPC-LAP probes, since their bias voltage is fixed. Writing explicitly the ion density term, the current balance equation reads:

$$\frac{n_i}{slope} - I_{sec} + I_{LAP} = 0$$

where n_i represent the density of the ions collected at the RPC-LAP probe and $slope$ term is a function of the ion charge, RPC-LAP probe surface, the ion temperature, the ion velocity and the spacecraft potential. Assuming quasi-neutrality in the plasma surrounding the Rosetta spacecraft, the ion density is considered equal to the electron density, and both is hereafter referred as the plasma density n_{MIP}.

From the relation above, a linear relation holds between the RPC-MIP plasma density measurements and the RPC-LAP ion current measurements, that reads:

$$n_{MIP} = slope\ I_{LAP} + c \qquad \text{(Eq. 1)}$$

4.3.2 Cross-calibrated RPC-LAP floating potential against RPC-MIP electron density

The theoretical relation between the electron density, inferred from RPC-MIP measurements, and the spacecraft floating potential, inferred from RPC-LAP measurements, is described below.
Both the secondary particles currents collected by the Rosetta spacecraft are assumed to be negligible w.r.t. the more significant contribution of the photoelectron and primary ambient electron currents. For the moment we will ignore also the ambient primary ion current to the spacecraft, an assumption to be discussed later on. Under these hypotheses, the current balance equation at the Rosetta spacecraft reads:

$$I_e - I_{ph} \cong 0 \text{ (Eq. 2)}$$

where I_e and I_{ph} represent the electron current and the photoelectron current collected by the Rosetta spacecraft, respectively.

Due to large electron currents w.r.t. photoelectron currents collected at Rosetta, the spacecraft is usually negatively charged in the cometary plasma environment. During intervals of constant illumination conditions for the spacecraft, the varying negative potential of the spacecraft does not affect the photoelectron currents that therefore can be assumed as constant terms.

Under the previous assumptions, the current balance equation for the spacecraft reads:

$$n_e exp\left(-i_0 + \frac{V_{S/C}}{T'}\right) = I_{ph}$$

Where n_e represents the ambient electron density surrounding the Rosetta spacecraft-i_0 term is function of the electron charge, the electron temperature and the total collecting spacecraft surface, $V_{S/C}$ represents the spacecraft floating potential and T' is a function of the electron temperature, the electron charge and the Boltzmann constant.

The length of the booms over which the RPC-MIP and RPC-LAP instruments were mounted was proven insufficient (w.r.t. the Debye length at the s/c position) for placing the two plasma instruments outside the plasma sheath surrounding the main body of the Rosetta spacecraft. Therefore, the RPC-LAP floating potential measurement V_{LAP} is proportional to the spacecraft potential $V_{S/C}$ in a way that depend on such sheath effects *[Odelstad et al., 2017 MNRAS, Volume 469].*

Under the conditions described above, there is a linear relation between the logarithm of the plasma density (RPC-MIP measurements) and the spacecraft floating potential (RPC-LAP measurements), that reads:

$$\log \frac{n_{MIP}}{n_0} = \frac{V_{LAP}}{T} + i \quad \text{(Eq. 3)}$$

where n_{MIP} is the plasma density measured by RPC-MIP, n_0 is a density normalization term, V_{LAP} is the spacecraft potential measured by RPC-LAP. Returning to the assumption of negligible ion current, breaking this will add a term linearly depending on density and spacecraft potential to the right hand side of the current balance equation [Eq. 2], and therefore invalidate the strict mathematical form of Eq. 33333333333 as an exact representation. In practice, a logarithmic fit still works very well, particularly over the relatively short analysis time-intervals used in the cross-calibration procedure.

4.3.3 Windows analysis

The cross-calibration procedure is performed with RPC-MIP plasma density estimates and the selected RPC-LAP inputs (either ion current measurements or floating potential measurements), over moving time windows. The moving time window approach is shown in Figure 2. The boxes (green and blue) represent the sliding time windows where a fit is performed between RPC-MIP plasma densities and RPC-LAP ion currents or floating potential, following equations 1 or 3, respectively (section 4.3.1 and 4.3.2).
Each window has a fixed width of 20 minutes with a 10-minute overlap. The length of the analysis window has been arbitrarily set as a trade-off between (i) a small enough window to minimize the variation of the plasma conditions (plasma parameters other than the plasma density are assumed almost constant or at least to be smooth and monotonic functions of the density) surrounding/passing through the Rosetta spacecraft within each time window[2] and (ii) a large enough window to ensure a sufficient amount of points to perform a statistically significant best fitting procedure. Note that in case there is a too low amount of simultaneous RPC-MIP and RPC-LAP measurements within a 20-min time window, the fitting procedure is not performed over that time window. This limit is set to 10 simultaneous data points in each considered 20-min time window. A 50% overlap in two consecutive windows might result in two independent best fits over each 10 minutes half-window. In that case, these two independent best fits are used in the derivation of the cross-calibrated density (section 4.4.1).

[2] Note, however, that in case of fast ion velocity or electron temperature variations, this assumption does not hold anymore and the resulting cross-calibrated densities fluctuations should not be overinterpreted by the user. It is necessary to come back to lower level products (LAP sweeps or MIP spectra) in order to properly interpret the data in such cases.

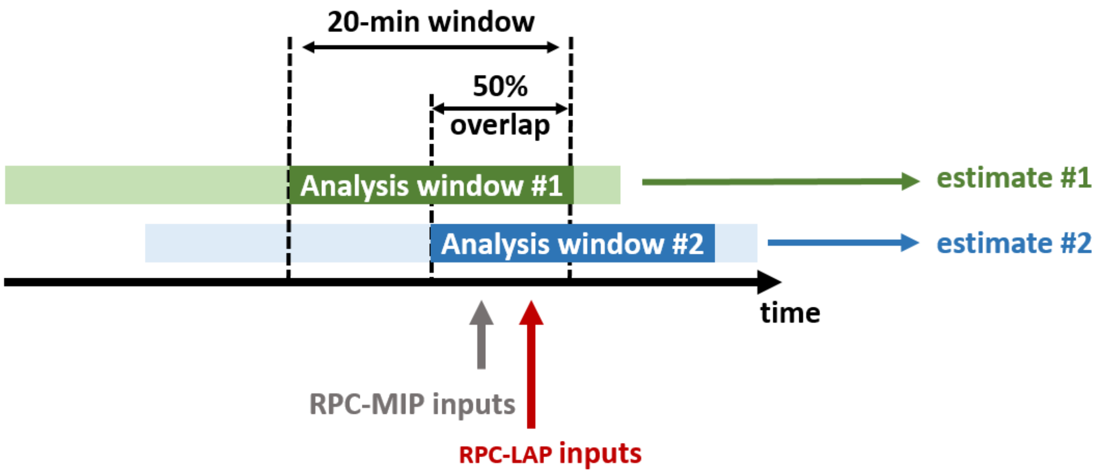

Figure 2: **Example of sliding window approach.** The green and blue boxes represent two analysis windows, each of 20 minutes time width and with an advancement step in time of half the window size. From each sliding windows, preliminary density estimates are obtained from RPC-MIP and RPC-LAP inputs. Due to the 50% overlap between sliding windows, two density estimates are, a priori, available for each RPC-LAP input measurement.

4.3.4 Fitting method

For each cross-calibration analysis time window, depending on the considered RPC-LAP input, one of the two analytical models described in sections 4.3.1 and 4.3.2 is applied (namely equations 1 and 3). An empirical relation between the input RPC-LAP floating potential/ion current measurements and RPC-MIP plasma densities is obtained by best fitting the analytical model parameters (namely $slope$ and c for ion current measurements, T and i for floating potential measurements) over each considered time window.

Note that the following conditions are assumed to hold over time scales of 20 minutes, corresponding to the analysis window time width (section 4.3.3):

- isothermal electrons or constant ion velocity,
- constant illumination conditions at the RPC-LAP probes.

Although the first two hypotheses are to be carefully kept in mind by the user (indeed, in case of highly dynamic plasma parameters, the first two conditions are more likely to fail), the last hypothesis is ensured by the data selection procedure (section 3). Nonetheless, on the one hand the cross-calibration procedure, adapting on average the RPCMIP/RPCLAP densities to the RPC-MIP densities (fitting process, section 4.3.4), and on the other hand the computed uncertainties (section 4.4.2) enable the cross-calibrated densities to follow the real plasma density variations with good approximation.

In order to optimize the cross-calibration procedure, a minimum quality for the RPC-MIP input plasma densities is imposed (section 4.1), as well as a minimum amount of 10 simultaneous data points in each considered time window. Note that if such conditions are not met, the fit in the corresponding window is discarded (section 4.3.3).

The fitting method applied during the cross-calibration procedure is the Weighted Orthogonal Distance Regression. The software package of reference is the ODRPACK python library, based on ANSI Fortran77 subroutines for fitting a model to data. In particular, this method is based on the minimization of the weighted orthogonal distance, as explained below. If y_i and x_i are two corresponding input measurements (namely the RPC-MIP plasma density and the RPC-LAP ion current or floating potential), their relation can be expressed as:

$$y_i = f(x_i + \delta_i, \beta) - \epsilon_i$$

where ϵ_i represents the error on the y_i measurement, δ_i represents the error on the x_i measurement, and f a β parametric model imposed between the input data. The function f and parameters β describing the model are discussed in section 4.3.1 4.1 and section 4.3.2.

The goal of the fitting method is to find the best-fitting β parameters (namely $slope$ and c regarding ion current measurements, T and i regarding floating potential measurements) by minimizing the sum:

$$\sum \left(w_{\epsilon_i} {\epsilon_i}^2 + w_{\delta_i} {\delta_i}^2 \right)$$

where w_{ϵ_i} represents the weight of the y_i measurement and w_{δ_i} represents the weight of the x_i measurement. Considering weights allow to correct for uncertain detections or different instrument precisions. In order to set the weight w_{ϵ_i}, the error ϵ_i is assumed to be of the order of their uncertainties of the RPC-MIP densities. In order to set the weight w_{δ_i}, the error δ_i is assumed to be of the order of the uncertainty of the RPC-LAP measurements. However, as such RPC-LAP measurements uncertainty is not assessed, a relative 10% uncertainty assumed (for both the RPC-LAP spacecraft potential and the ion current measurements).

4.4 Derivation of the final parameters

4.4.1 RPCMIP/RPCLAP plasma density derivation

The output of the fitting procedure (namely $slope$ and c for ion current measurements, T and i for floating potential measurements from section 4.3.1 and 4.3.2, respectively) together with the corresponding model (section 4.3.1 or 4.3.2) is then applied to the entire RPC-LAP (ion current or floating potential) time series over the corresponding time window, leading to a density estimate at each RPC-LAP measurement time and for each considered time window. The error propagation from the fit (described in the following subsections) is used to associate an uncertainty to each density estimate and obtain a valid density interval (n +/- Δn).

Because of the 50% overlap in two consecutive windows, up to two independent density estimates at a same time might result from the cross-calibration procedure. This implies that 5 different cases occur to define the final cross-calibrated density and associated uncertainty and quality values. The definition of the cross-calibrated density is detailed in this section, while the definition of the associated uncertainty and quality values are detailed in sections 4.4.2 and 4.4.3 respectively.

The five different cases are the following:

- case 1: no valid estimated density ranges,
- case 2: only 1 valid estimated range,
- case 3: 2 valid estimated ranges that do not overlap,
- case 4: 2 valid estimated ranges that overlap by less than 10%,
- case 5: 2 valid estimated ranges that overlap by more than 10%.

Indeed, when performing the cross-calibration procedure, some windows may be discarded because of a low (< 10) amount of simultaneous input points with sufficient quality. When it happens for two consecutive sliding windows, then no valid cross-calibrated density estimate is computed (case1) during the overlapping 10-min time interval. In case only one between a series of sliding windows is discarded, then there is a 20-minute time interval (corresponding to the discarded window) during which only one density estimate is computed at each RPC-LAP time measurement (case2). If the cross-calibration procedure is performed over two consecutive windows, for each overlapping 10-min time interval, two density estimates are computed at each RPC-LAP time measurement resulting in three other different cases (case3, case4, case5). Such simultaneous estimated density ranges can either be disjointed (case3), overlapping by less than 10% of the final density estimate (case4) or overlapping by more than 10% (case5). To summarize:

- In case1 no cross-calibrated densities are provided.
- In case2 the provided density corresponds to the preliminary estimated density obtained from the single valid cross-calibration window.
- In case3 the two simultaneous density intervals are disjointed. The corresponding final density estimate is the average value between the maximum and minimum values of the two density intervals.
- In case4 and case5 the two simultaneous density intervals overlap and the corresponding final density is the mean value of the common density interval.

4.4.2 Uncertainties derivation

The final uncertainties, enclosed in the RPCMIP/RPCLAP dataset, are obtained by propagating the fit errors and depending on the overlapping case between density estimates.

For each fitting window, a root mean squared error is derived and is taken as the preliminary uncertainty for the densities. This root mean squared error is obtained as follows:

$$\Delta_{rms} = \frac{\sqrt{\Delta_i^2}}{n}$$

where Δ_i^2 is the squared sum of the differences between the RPC-MIP density and the model output at the corresponding RPC-LAP measurement., Δ_{rms} is given as the preliminary uncertainty associated to each density estimate (identical for all density estimates from the same cross-calibration window).

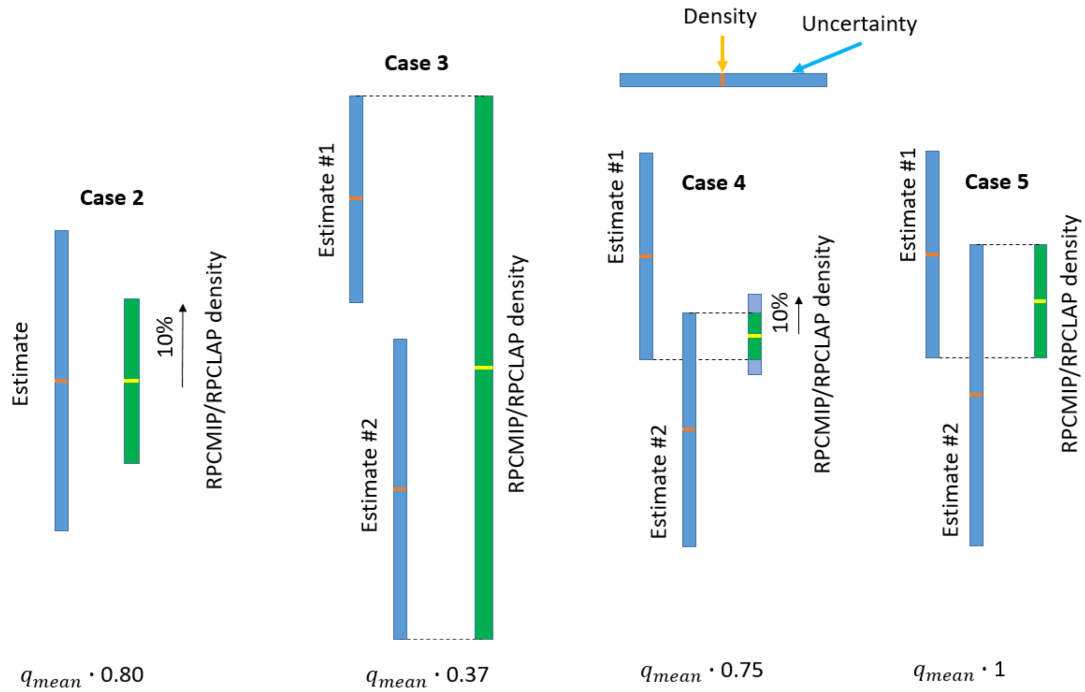

Figure 3: **Possible overlapping cases when comparing estimates from two consecutive analysis windows.** Each bar represents a density interval, where the box at the center and the boxes on the sides represent respectively the density values and the density uncertainties (image on top right side).

Figure 3 represents the possible situations when comparing simultaneous estimates obtained from two valid consecutive analysis windows:

- case 2: only one preliminary density estimate,
- case 3: density intervals are disjointed,
- case 4: intervals overlap with a common part lower than 10% of the final density value,
- case 5: intervals overlap with a common part greater or equal than 10% of the final density value.

The final value of density is derived as described in section 4.4.1. Possible uncertainties are summarized as follows:

- In case 2, when only one valid half cross-calibration window is available, no comparison between preliminary density estimates is possible. The corresponding uncertainty is imposed as 10% of the density estimate.
- In case 3 the uncertainty is computed as half the width of the total density interval ranging from the minimum value to the maximum value of the densities given by both intervals.
- In case 4 the value of the uncertainty is fixed to 10% of the derived density value. The empirical 10% value was found by imposing continuity on the cross-calibrated densities obtained from the two RPC-LAP input measurements.
- In case 5 the uncertainty is computed as half the width of the common overlapping density interval.

4.4.3 Quality values derivation

A normalized quality index is also provided for each cross-calibrated density. Possible values are defined to range from 0.1 to 1, where 0.1 and 1 represent the worst and best trust factor, respectively.

Below is described the procedure used to compute such quality indexes.

First, a preliminary quality index is computed for each analysis window. It corresponds to the ratio between the amount of RPC-MIP densities actually used to perform the fit w.r.t. the maximum theoretical number of RPC-MIP densities in a cross-calibration window in Normal Mode (*RD1*). When Burst Mode RPC-MIP data are used as input, the corresponding ratio can be higher than 1 and, in this case, the corresponding quality is set to 1. This preliminary quality is identical for all density estimates within the analysis window.

Second, for each overlapping half-window, a quality value, identical for each density estimate, is computed as the average value of the 2 preliminary values coming from the two full windows.

Third, a correction factor, independent for each density estimate and depending on the overlapping case, is estimated and applied to obtain the final quality value.

The final quality for each RPCMIP/RPCLAP cross-calibrated plasma density, q_i, is then given by:

$$q_i = k\frac{q_{w_j} + q_{w_{j+1}}}{2}$$

where k represents the correction factor, q_{w_j} and $q_{w_{j+1}}$ represent respectively the global qualities in the j-th and j+1-th windows. The k correction parameter is set as 0.80, 0.37, 0.75 and 1 for case 2, 3, 4 and 5, respectively.

The user is strongly encouraged to always consider these quality indexes and their potential impact on data analysis (in particular when averaging or conducting statistical studies).

4.4.4 Time uncertainty derivation

The time uncertainties of the estimates provided in the RPCMIP/RPCLAP dataset are derived from the RPC-LAP inputs. Each of the RPC-LAP measurements with a resolution of 57.8 Hz is obtained by an on-board average of the signal over windows centred at RPC-LAP time stamps (see *RD2*). The times of the cross-calibrated densities correspond to the RPC-LAP measurements. The associated time uncertainty is here defined as half the delay between two consecutive RPC-LAP measurements, corresponding to 8.5 ms in Burst mode.

5. A posteriori RPC-LAP inputs selection

RPCMIP/RPCLAP cross-calibrated densities can be obtained from two RPC-LAP inputs that are available simultaneously when the two RPC-LAP probes are operated simultaneously in the operational modes of interest for the cross-calibration described in this document. A prioritization of the RPC-LAP inputs to the cross-calibration procedure is therefore required and used. Comparison studies have been conducted to define the prioritization between different RPC-LAP inputs, or eventually to discard some of them. Some of these comparisons and the resulting prioritization scheme is described in the following.

An example of comparison between the cross-calibrated densities obtained with identical operational modes (leading to ion current measurements) from RPC-LAP probe1 and probe2 is shown in Figure 4. The top panel represents the comparison between the RPC-MIP plasma density and the RPCMIP/RPCLAP cross-calibrated density (derived from RPC-LAP probe1 measurements), both converted in plasma frequency. The background represents the normalized RPC-MIP calibrated active power spectra. Black star and light-grey shaded area represent the RPC-MIP plasma frequency detections and associated uncertainties, respectively. White points represent the cross-calibrated RPCMIP/RPCLAP plasma frequency obtained from RPC-LAP probe1 ion current measurements. The middle panel represent the comparison between simultaneous cross-calibrated densities, derived from simultaneous ion-current measurements on RPC-LAP probes. Blue and orange points represent the cross-calibrated densities derived from RPC-LAP probe1 and probe2, respectively. The bottom panel represents the final quality associated to each RPCMIP/RPCLAP cross-calibrated density (described in section 4.4.3), with the same color code as in the middle panel: blue points refer to cross-calibrated outputs from probe1, while orange dotted line refers to cross-calibration outputs from probe2.

From Figure 4 a good general agreement between RPC-MIP measurements (black stars) and RPCMIP/RPCLAP cross-calibrated outputs from probe1 (blue points) is observed. The same cannot be stated for the RPCMIP/RPCLAP outputs from probe 2, that do not capture the

plasma frequency variations properly. This can be explain by the two following reasons. First, RPC-LAP probe1 is mounted on the boom facing the comet nucleus and located in the close vicinity of RPC-MIP. Assuming a plasma flow from the nucleus, probe1 has therefore access to a plasma not much altered by interactions with the spacecraft, while the plasma around RPC-LAP probe2 can be expected to be more perturbed by e.g. wake effects of the plasma flow around the spacecraft. Second, probe2 shows signs of contamination effects and (at least from May 2016) an unknown perturbation current (RD2), which may further alter the correlation.
The time interval considered in Figure 4 corresponds to 5 minutes (25% of the sliding window size). Such time resolution allows the dynamics of the RPCMIP/RPCLAP densities to be followed while comparing with RPC-MIP estimates. The figure illustrate the increase in time resolution from RPC-MIP densities to RPCMIP/RPCLAP densities, which is one of the main goals of the cross-calibration process.

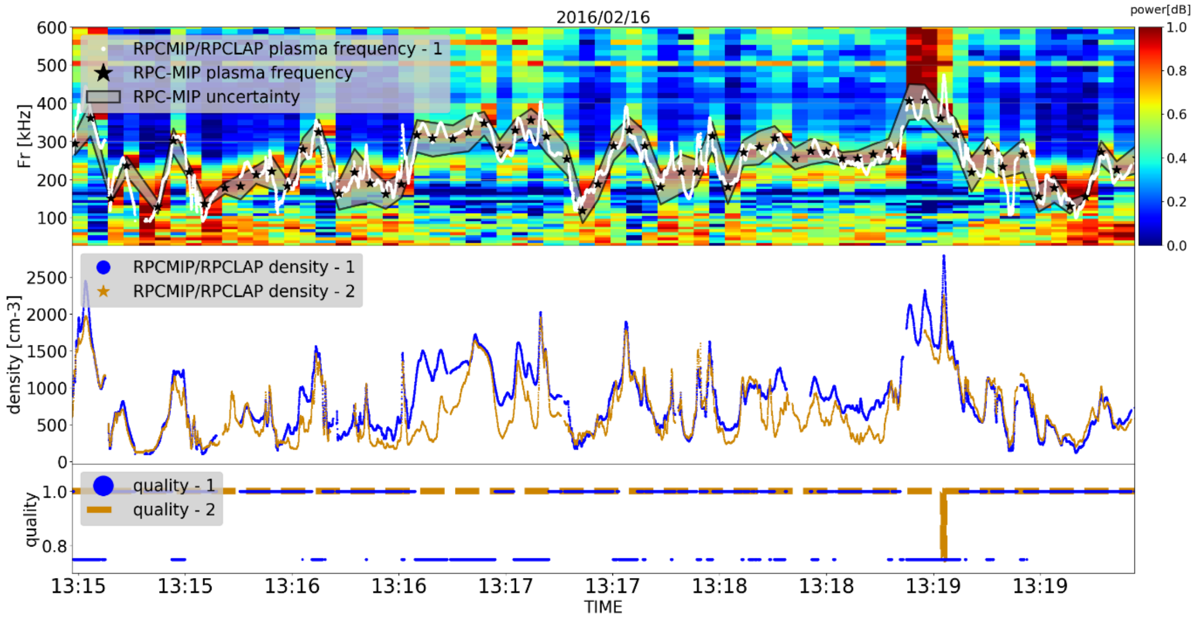

Figure 4: **Comparison between cross-calibrated outputs from identical input measurements (ion current) on probe1 and probe2.** Top panel. The background shows the color-coded normalized spectra from RPC-MIP measurements, w.r.t. time (x-axis) and frequency (y-axis). Black stars represent the RPC-MIP plasma frequency detections, together with the associated uncertainty (the light-grey shaded area). White points represent the cross-calibrated outputs (converted to plasma frequencies) derived from RPC-LAP probe1 ion current measurements. Middle panel. Blue and orange points represent the cross-calibrated outputs computed from ion current measured by RPC-LAP probe1 and probe2, respectively. Bottom panel. The plot shows quality values (y-axis) for the cross-calibrated density w.r.t. time (x-axis), in blue for densities obtained from probe1 and in orange for densities obtained from probe2.

Figure 4 does not represent an isolated case, but is a typical illustration of the behavior of cross-calibrated densities derived with ion currents measurements from RPC-LAP probe1 and probe2. For this reason, ion current obtained with RPC-LAP probe2 are excluded from the cross-calibration procedure.

In the same way, cross-calibrated densities obtained from floating potential measured by the two RPC-LAP probes are compared in Figure 5. Contrarily from the previous comparison, probe2 electric potential measurements do not seem to suffer contamination effects or, at least, the RPC-LAP probe contamination does not seem to influence the RPCMIP/RPCLAP cross-calibrated densities. Figure 5 is a 5-minute plot showing the comparison between cross-calibrated outputs obtained from electric potential measurements from the two RPC-LAP probes as input. As for Figure 4, the top panel represents the comparison between the RPC-MIP plasma density and the RPCMIP/RPCLAP cross-calibrated density (derived from RPC-LAP probe1 measurements), both converted in plasma frequency. White points represent the cross-calibrated RPCMIP/RPCLAP plasma frequency obtained from RPC-LAP probe1 electric potential measurement. The middle panel represent the comparison between simultaneous cross-calibrated densities, derived from simultaneous electric potential measurements on RPC-LAP probes. Blue and orange points represent the cross-calibrated densities derived from RPC-LAP probe1 and probe2, respectively. In the bottom panel the quality values are represented in the same color as middle panel: blue points refer to cross-calibrated outputs from probe1, while orange dotted line refers to cross-calibration outputs from probe2. The discontinuity in quality values shown in the bottom panel of Figure 5 is associated to the different cases (section 4.4) used to compute cross-calibrated densities, uncertainties and qualities. In particular, the represented time interval is located in between two cross-calibration half-windows. Such sharp variation in quality values is always present when one cross-calibration half window is discarded. Figure 5 is representative of the comparison between cross-calibrated densities obtained from electric potential measurements: a clear agreement is observed between the two cross-calibrated outputs, and also with the RPC-MIP plasma density detections. The two RPC-LAP inputs are thus considered as equivalent. For RPC-LAP macros considered in the cross-calibration procedure, floating potential measurements from probe2 are always simultaneous with floating potential measurements from probe1. For the sake of consistency with the previous choice, cross-calibration from RPC-LAP probe1 is then always prioritized.

Moreover, RPC-LAP probe2 is believed to suffer from a contamination issue (details in *RD2*) affecting measurements especially after May 2016. For this reason, measurements from probe1 are in general preferred over probe2.

These comparison studies made between cross-calibrated outputs obtained from different RPC-LAP inputs are only possible after the cross-calibrated density derivation. A large number of a posteriori comparisons have been performed and led to the conclusions discussed above. As a consequence, RPCMIP/RPCLAP cross-calibrated densities available on the PSA are always obtained with RPC-LAP probe1 measurements as input.

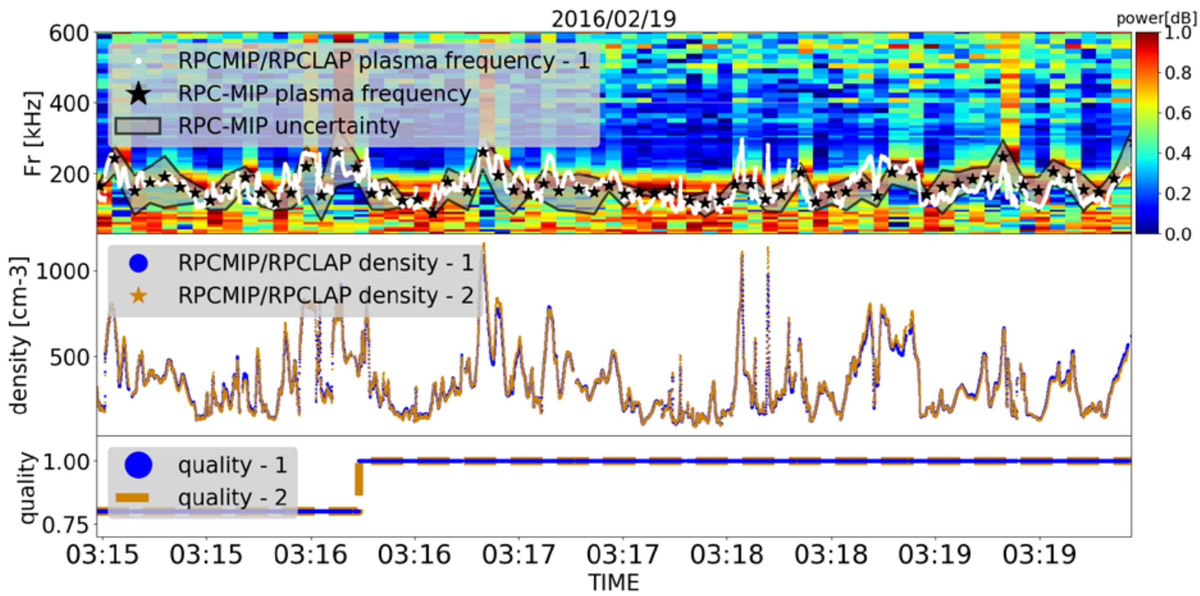

Figure 5: **Comparison between cross-calibrated outputs from identical input measurements (electric potential) on probe1 and probe2.** Top panel. The background shows the color-coded normalized spectra from RPC-MIP measurements, w.r.t. time (x-axis) and frequency (y-axis). Black stars represent the RPC-MIP plasma frequency detections, together with the associated uncertainty (the light-grey shaded area). White points represent the cross-calibrated outputs (converted to plasma frequencies) derived from RPC-LAP probe1 floating potential measurements. Middle panel. Blue and orange points represent the cross-calibrated outputs computed from floating potential measured by RPC-LAP probe1 and probe2, respectively. Bottom panel. The plot shows quality values (y-axis) for the cross-calibrated density w.r.t. time (x-axis), in blue for densities obtained from probe1 and in orange for densities obtained from probe2.

6. Validation

The validation of the RPCMIP/RPCLAP density dataset is conducted through an automatic validation/filtering step and a visual validation step. The former is performed by imposing thresholds on final cross-calibrated densities and uncertainties. The latter is performed on small time-scale (5-minutes) comparison plots between RPCMIP/RPCLAP cross-calibrated densities and RPC-MIP plasma densities (as shown in Figure 4 and 5). The two steps are described in the following subsections.

6.1 Automatic filtering and validation

Before visual validation, the output densities are filtered out by imposing a maximum value of 0.90 on the uncertainty-to-density ratio. This filtering is needed only on particular events, when densities are extremely low or when the assumptions adopted in the cross-calibration procedure are not valid.

A second automatic validation is directly performed by comparing estimates obtained from two consecutive half-windows (see section 4.4). In particular, two estimates of cross-calibrated density for the same RPC-LAP measurement generally enable a reduction of the uncertainties and lead to better quality values.

6.2 Visual validation

A visual validation of the RPCMIP/RPCLAP densities is performed comparing, on small time scales, cross-calibrated densities with the RPC-MIP measurements, as illustrated in Figure 4 and Figure 5. The visual validation allows to check the consistency of RPCMIP/RPCLAP densities with respect to RPC-MIP (absolute) plasma density detections and also with RPC-MIP power spectra. Visual validation is performed for some test cases throughout the mission. This step allowed to fix the empirical parameters (namely the 10% relative error for cross-calibrated densities and the correction factor k discussed in section 4.4.2 and section 4.4.3, respectively) related to the 5 possible cases for derivation of cross-calibrated densities, uncertainties and qualities, described in section 4.4.

The observed agreement with RPC-MIP plasma densities confirms the robustness of the procedure and validates a posteriori the choice of the models. Nonetheless, the user should be aware that some disagreements might arise when the plasma is highly dynamic within a cross-calibration window (not only in terms of density values, but also in terms of electron temperatures, plasma composition and/or increase of secondary effects, neglected in the analysis) or when the best fitting procedure fails in retrieving reliable correspondence between RPC-MIP and RPC-LAP inputs and the RPCMIP/RPCLAP densities are associated with low quality values.

The global agreement with RPC-MIP power spectra confirms the overall quality of the final RPCMIP/RPCLAP density dataset. In particular, it allows comparison even when RPC-MIP detections are not possible due to low signal-to-noise ratios.

The visual validation is the final step of the cross-calibration procedure. Its output corresponds to the final, delivered RPCMIP/RPCLAP cross-calibrated density dataset.

7. Cross-calibrated RPC-MIP/LAP electron density dataset

7.1 Dataset description

The RPCMIP/RPCLAP cross-calibrated plasma density, as a derived product, is provided in L5 datasets. Since the cross-calibration process is driven by RPC-LAP measurements, the data files enclosed in this dataset are compliant in time-size with the RPC-LAP files and the time-stamps of the RPCMIP/RPCLAP density estimates correspond to the time-stamps of the input RPC-LAP measurements from which they are obtained.

Uncertainties and quality values are provided alongside the RPCMIP/RPCLAP density estimates. The user is encouraged to take them into account when performing his analysis.

A sample of this dataset, compared to the RPC-MIP density measurements, is shown in Figure 5. In the top panel the red stars and the violet shade represent RPC-MIP measurements and their uncertainties respectively; the yellow points represent the RPCMIP/RPCLAP densities and the black shadow represents the uncertainty surrounding the cross-calibrated measurements. In the bottom panel are represented the qualities associated to the cross-calibrated densities from top panel.

Figure 6 illustrates the reasons that lead to the production of a cross-calibrated density dataset. First, this new dataset is characterized by a higher sampling frequency, passing from 0.4 Hz (at best) to 57.8 Hz. Second, the cross-calibrated density dataset is able to go beyond the instrumental capacities of RPC-MIP by obtaining low density estimates when the instrument is in SDL mode (operational mode more suited for high density measurements, as described in *RD1*).

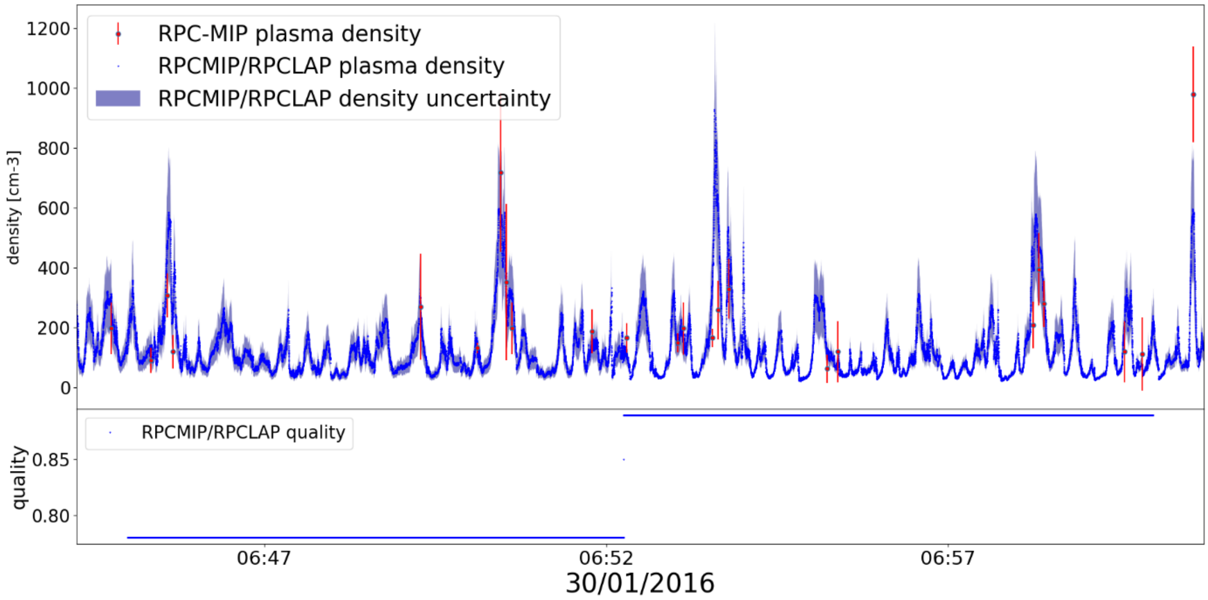

Figure 6: **RPC-MIP/LAP cross-calibration is able to produce low density measurements, not accessible with RPC-MIP only.** Top panel: Red bounded points represent the RPC-MIP densities with the associated density uncertainty. Blue points represent the cross-calibrated densities. Light blue shadow represents the uncertainty of the RPCMIP/RPCLAP density estimates. Bottom panel: blue points represent the quality of the RPCMIP/RPCLAP density estimates.

7.2 Caveats

The granularity of the RPCMIP/RPCLAP dataset files is based on the RPC-LAP files granularity: basically, one file per RPC-LAP macro. This does not necessarily imply that the data within a single file is equally spaced in time, especially because of the RPC-LAP down-sampling step (Section 3) and/or small idle periods in the RPC-LAP 32-s on-board acquisition sequence (RD2). Furthermore, time intervals may be missing due to events affecting input measurements.

Given the adopted definition of preliminary quality for measurements from the same cross-calibration window, the quality of RPC-MIP in burst mode is globally larger than when RPC-MIP is in normal mode. Such quality may be overestimated.

The cross-calibration procedure is able to overcome the presence of small gaps in the RPC-MIP input measurements, up to gaps of the size of a sliding window. For larger gaps in the input, there will also be a gap in the cross-calibrated dataset. In Figure 7, top panel, the cross-calibrated densities (converted to plasma frequency) well agree with the background RPC-MIP normalized power spectra, even when it is not possible to automatically derive RPC-MIP densities. This a posteriori validation emphasizes that even in such cases the cross-calibration procedure performs well.

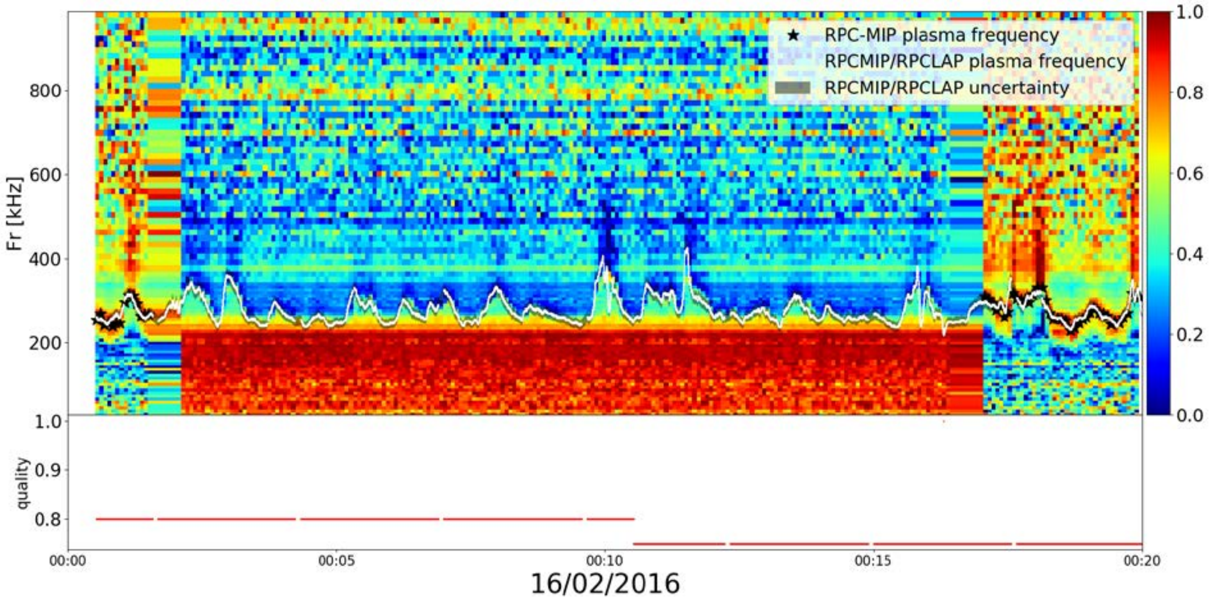

Figure 7: **RPCMIP/RPCLAP densities and small RPC-MIP data gaps.** Top panel: the background represents the color-coded normalized RPC-MIP calibrated power spectra; black stars represent RPC-MIP densities converted to plasma frequencies; white points and the black shaded area represent the RPCMIP/RPCLAP densities and their uncertainties respectively converted to plasma frequency. Bottom panel: red points represent the quality indexes of the cross-calibrated estimates from top panel.

RPC-MIP LDL instrumental resolution limits the plasma density detection to the [5 cm^{-3} -, 350 cm^{-3}] range, as illustrated in Figure 8, where RPC-MIP is able to retrieve only part of the plasma electron density (white stars in top panel, red points in middle panel). However, providing that a sufficient portion of the plasma density falls into the RPC-MIP detection range, the RPCMIP/RPCLAP cross-calibrated density can be derived outside of the RPC-MIP detection range.
The low RPC-MIP detection rate, due to the plasma density being partially out of RPC-MIP accessible range, artificially decreases the quality indexes associated to the RPCMIP/RPCLAP estimated plasma densities, as shown in the Figure 8 bottom panel. In these particular cases, we recommend to carefully check the consistency between RPCMIP/RPCLAP cross-calibrated densities, RPC-MIP L5 plasma densities and RPC-MIP L3 power spectra signatures (as done in top panel of Figure 8) in order to assess the quality of RPCMIP/RPCLAP cross-calibrated estimates. Applying filters based on quality indexes can be misleading in these situations.

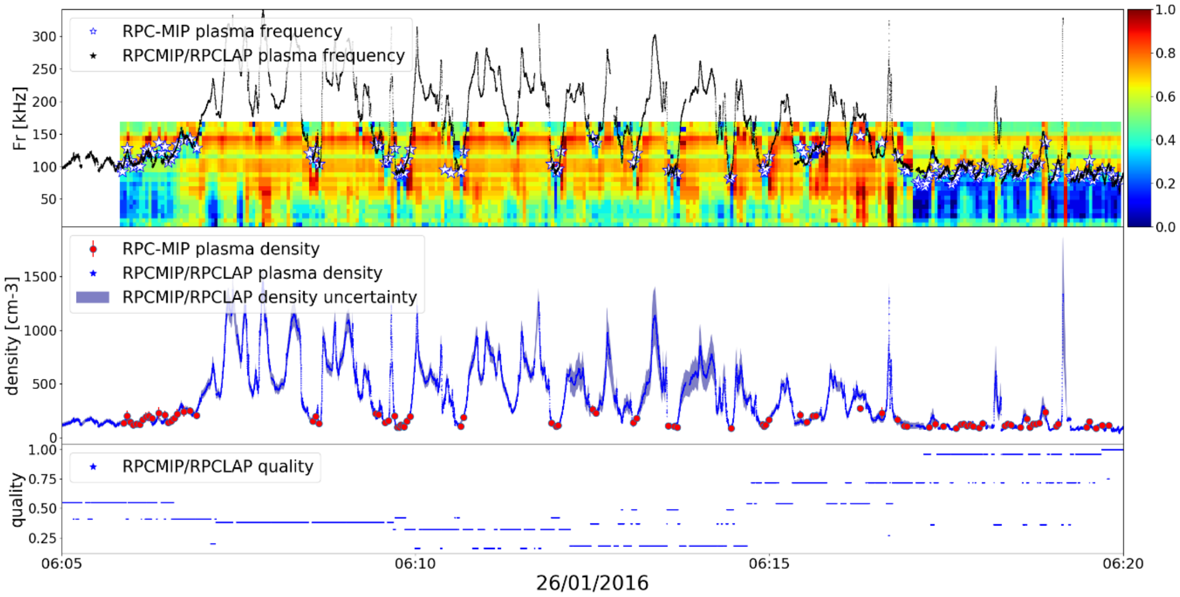

Figure 8: RPCMIP/RPCLAP densities derived from RPC-MIP LDL mode densities. Top panel: the background represents the color-coded normalized RPC-MIP calibrated power spectra; white stars with blue edges represent RPC-MIP densities converted to plasma frequencies; black points represent the RPCMIP/RPCLAP cross-calibrated densities converted to plasma frequency. Middle panel: red points and red bars represent respectively RPC-MIP plasma densities and their uncertainties, blue points and the blue shaded area represent the RPCMIP/RPCLAP cross-calibrated densities and their uncertainties. Bottom panel: blue points represent the quality indexes of the cross-calibrated estimates.

7.3 Overview plots

Overview plots, provided with the RPC-MIP density dataset, are daily plots that enable to locate the presence of time intervals with cross-calibrated densities and to check the consistency between the L5 RPC-MIP density estimates and the L3 RPC-MIP power spectra signatures.

The overview plots are described in *RD1*.