The Influence of Spacecraft Charging on Low-Energy Ion Measurements Made by RPC-ICA on Rosetta

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Abstract Spacecraft charging is problematic for low-energy plasma measurements. The charged particles are attracted to or repelled from the charged spacecraft, affecting both the energy and direction of travel of the particles. The Ion Composition Analyzer (RPC-ICA) on board the Rosetta spacecraft is suffering from this effect. RPC-ICA was measuring positive ions in the vicinity of comet 67P/Churyumov-Gerasimenko, covering an energy range of a few eV/q to 40 keV/q. The low-energy part of the data is, however, heavily distorted by the negatively charged spacecraft. In this study we use the Spacecraft Plasma Interaction Software to model the influence of the spacecraft potential on the ion trajectories and the corresponding distortion of the field of view (FOV) of the instrument. The results show that the measurements are not significantly distorted when the ion energy corresponds to at least twice the spacecraft potential. Below this energy the FOV is often heavily distorted, but the distortion differs between different viewing directions. Generally, ions entering the instrument close to the aperture plane are less affected than those entering with extreme elevation angles.

Plain Language Summary The Rosetta spacecraft followed comet 67P/Churyumov-Gerasimenko for 2 years, providing data giving new insights into the nature of comets. The Ion Composition Analyzer (RPC-ICA) on board the spacecraft measures positive ions in the vicinity of the comet. The instrument can measure low-energy ions, which play an important part in the processes taking place in this environment. To fully understand the environment around the comet, we have to understand these low-energy ions. Unfortunately, this part of the RPC-ICA data is distorted by the spacecraft potential. A spacecraft in space interacts with the surrounding environment, which charges the spacecraft surface to a positive or negative potential. Rosetta was commonly charged to a negative potential throughout the mission, which means that the positive ions measured by RPC-ICA were attracted to the spacecraft. Consequently, both the energy and the travel direction of the ions changed before detection. We investigate how the low-energy ions measured by RPC-ICA have been affected by the spacecraft potential. We use the Spacecraft Plasma Interaction Software to model these effects. The results give us a lower energy limit above which we can trust the measurements and show that some parts of the instrument are more heavily affected than others.

1. Introduction

Spacecraft charging and its interference with scientific measurements cause inevitable issues for space missions. Differential charging can lead to discharges that can cause serious damage to a spacecraft, and efforts are made to minimize these effects. Another issue, which has received less attention, is the interference with scientific measurements. Especially in situ low-energy plasma measurements are affected, since the measured charged particles are attracted to or repelled from the charged spacecraft. This causes a shift in particle energy and affects the particle trajectories, distorting the field of view (FOV) of an instrument measuring them.

The processes causing spacecraft charging have been discussed ever since the early work by Langmuir in the beginning of the twentieth century (Langmuir & Blodgett, 1924; Mott-Smith & Langmuir, 1926), but it was the birth of the spaceflight era in the 1950s that evoked the idea that these processes might also apply for spacecraft. The spacecraft surface interacts with the surrounding environment, charging it to a positive or negative potential. Various processes contribute to the charging, where the resulting potential is ultimately decided by a current balance (e.g., Garrett, 1981; Whipple, 1981). The dominating currents are often the electron current, caused by electrons from the plasma colliding with the spacecraft, and the photoelectron...
current. During certain circumstances other processes, like ion currents, secondary electron emission, wake effects, and induced differential potentials due to ambient magnetic fields, can also become important.

One instrument suffering from the effects of spacecraft charging is the Ion Composition Analyzer (RPC-ICA, Nilsson et al., 2007) on board the Rosetta spacecraft (Glassmeier et al., 2007). Rosetta was launched in 2004 to study comet 67P/Churyumov-Gerasimenko. It arrived at the target in August 2014, when the comet was at a heliocentric distance of more than 3.6 AU. Rosetta followed the comet for 2 years, providing measurements from a weakly active comet further away from the Sun to a more active comet at perihelion at 1.24 AU. RPC-ICA is part of a suite of plasma instruments on board Rosetta, the Rosetta Plasma Consortium (RPC, Carr et al., 2007). The purpose of RPC is to make in situ measurements of the cometary plasma environment.

RPC-ICA is designed to study the interaction between the cometary particles and the solar wind, which is done by sampling the distribution function of positive ions.

When a comet approaches the Sun, a coma of sublimated ice and dust particles is created. This neutral atmosphere gets ionized by photoionization and electron impact ionization, and the newly born ions get picked up and accelerated by the convective electric field of the solar wind (e.g., Cravens & Gombosi, 2004; Galand et al., 2016; Szegö et al., 2000). The ions are, however, born cold. Both the accelerated population and a relatively cold population with low bulk velocity are observed with RPC-ICA (Nilsson, Stenberg Wieser, Behar, Simon Wedlund, et al., 2015; Nilsson, Stenberg Wieser, Behar, Wedlund, et al., 2015; Nilsson et al., 2017). From April 2015 to February 2016 Rosetta intermittently encountered a magnetic field free region, known as the diamagnetic cavity (Goetz, Koenders, Hansen, et al., 2016; Goetz, Koenders, Richter, et al., 2016). Inside this cavity, the majority of the ions are cold (e.g., Masunaga et al., 2019). RPC-ICA can measure energies down to a few electron volt and can therefore study the processes related to these cold ions.

Unfortunately, the low-energy part of the RPC-ICA data is heavily affected by the spacecraft potential, which limits the full exploitation of the data.

Throughout the mission, Rosetta was commonly charged to a negative potential (Odelstad et al., 2017). This contradicts the preparatory studies made for Rosetta, where the potential was predicted to be a few volts positive (Berthelier & Roussel, 2004; Roussel & Berthelier, 2004). Instead, the potential was usually below −10 V and occasionally below −20 V. The positive ions measured by RPC-ICA were therefore accelerated toward the spacecraft, which caused an energy shift. For low-energy ions the particle trajectories were also heavily affected, distorting the FOV of the instrument. A wide angular spread of low-energy ions is frequently observed in the data, which has been attributed to the attracting spacecraft potential (Nilsson et al., 2017). If the spacecraft potential is known, the shift in energy can be corrected for. The FOV distortion of the instrument is, however, complex and not straight forward to correct for. Modelling of the spacecraft plasma interactions is therefore necessary.

In this study, we use the Spacecraft Plasma Interaction Software (SPIS, Thiébault et al., 2013) to model the influence of the spacecraft potential on the low-energy ion measurements made by RPC-ICA. We investigate the distortion of the FOV for different ion energies, with the aim of finding an energy level above which the measurements are not distorted. Below this level, we compare the severity of the distortion for different viewing directions of the instrument. All simulation results are available at https://data.irf.se/bergman2019jgr.

2. Instrument Description

RPC-ICA is a mass resolving ion spectrometer, covering an energy range of a few eV/q to 40 keV/q (Nilsson et al., 2007). The basic design of the instrument comprises four main parts: an electrostatic acceptance angle filter, a spherical electrostatic analyzer (ESA), a magnetic momentum filter, and a microchannel plate. The electrostatic acceptance angle filter is determining the elevation angle of the accepted incoming particles with respect to the radial axis. The elevation angle is controlled by two electrostatic plates put to different potentials. By changing the potential difference between the plates, ions with different incoming elevation angles are deflected to enter the instrument. The instrument can accept particles arriving from ±45° with respect to the aperture plane, as illustrated in Figure 1a. This range is scanned in 16 steps with a resolution of 5.625°. Particles passing through the acceptance angle filter enter the ESA, analyzing the energy of the particles. Only particles within the energy passband pass through the ESA. The total energy range is covered by sweeping the energy passband over 96 energy steps. In the magnetic momentum filter a cylindrical
magnetic field is used to determine the particles' mass per charge. Finally, the ions are detected by the microchannel plate.

Important for this study is the arrival angle of the ions. The acceptance angle filter controls the incoming angle in elevation, but the instrument also determines the azimuthal arrival direction of the ions. The instrument is cylindrically symmetric, and the total FOV in the azimuthal direction (360° in total) is divided into 16 sectors, as illustrated in Figure 1b. Each sector is covering a FOV of 22.5°, which is also the angular resolution of the instrument. The azimuthal angle is defined to be 0° between sectors 8 and 9 and the angle is then measured in the clockwise direction, as described by Nilsson et al. (2007) and shown in Figure 1b.

3. Method
3.1. SPIS

SPIS is a simulation tool developed to study the interactions between a spacecraft and the surrounding plasma (Thiébault et al., 2013). It determines the spacecraft potential and the resulting potential field around the spacecraft, given a certain plasma environment and spacecraft characteristics. The software furthermore provides particle tracing tools to study how particles move around the spacecraft.

SPIS is an open source software, primarily using a particle-in-cell (PIC) approach for the matter modelling. In this study we model the ions as full PIC, while the electrons are assumed to be in Maxwell-Boltzmann equilibrium with the potential. SPIS calculates the electric fields by solving the Poisson equation. Since the Debye length is small compared to the spacecraft length scales, we choose a 1/r^2 (presheath) boundary condition for the potential instead of a vacuum (1/r) approximation.

In the following sections, the different parts of the modelling chain are described. This includes the modelling of spacecraft structures and surface properties (section 3.2), modelling of the plasma environment (section 3.3) and instrument modelling and particle tracing (section 3.4). For all the work we use SPIS version 5.2.4.

3.2. Spacecraft Model

The spacecraft model is shown in Figure 2. To the left, the whole simulation volume (size of 70 × 60 × 60 m) is shown, where the outermost ellipse corresponds to the external boundary (the edge of the simulation volume). The innermost ellipse is a helper surface used to control the meshing of the computational volume (i.e., the volume between the spacecraft surface and the external boundary). To the right, the spacecraft and instrument models are shown in more detail. The spacecraft is simply a box with two solar panels with the correct dimensions, while RPC-ICA is modelled as a cylinder with each azimuthal sector separately defined.
During the analysis each sector is simulated and studied individually. The Langmuir probe instrument (RPC-LAP, Eriksson et al., 2007) is also included in the model. SPIS allows for an increased mesh resolution in regions where a more detailed modelling is necessary. Generally, the mesh resolution at the external boundary can be reduced considerably compared to the required resolution close to the spacecraft. The spacecraft is meshed with a grid size small enough to resolve the Debye length and small details in the spacecraft model. For the spacecraft body this is varying between 5 and 25 cm and for RPC-ICA the grid size is set to 2 cm. At the external boundary a grid size of 3 m is enough to resolve the potential field and keep a reasonable simulation time. In the computational volume the grid size is gradually increased with distance from the spacecraft.

Large spacecraft surfaces exposed to the Sun dominate the contribution to the photoemission, and these surfaces on Rosetta are covered with indium tin oxide. The whole spacecraft is therefore modelled with indium tin oxide as surface material, which previously has been shown to yield reasonable spacecraft potential results for Rosetta simulations (Johansson et al., 2016). Furthermore, all spacecraft surfaces are connected and conducting and the whole spacecraft hence floats at the same potential with respect to the plasma.

The coordinate system used is centered at the spacecraft and defined as in Figure 2, that is, with the $z$ axis pointing towards the side of the spacecraft where RPC-ICA is mounted, the $y$ axis pointing in the same direction as the symmetry axis of RPC-ICA, and the $x$ axis completing the right-handed system. This is the prevalent coordinate system used for Rosetta. The typical position of the spacecraft with respect to the comet and the Sun in this frame is with the comet in the positive $z$ direction and the Sun in the positive $x$ direction. This is the defined position of the comet and the Sun in the simulations.

### 3.3. Plasma Model and Simulation Environment

The spacecraft potential is controlled by the plasma environment and the ultraviolet radiation from the Sun. Consequently, the potential of the spacecraft varied throughout the mission. For this study, we choose a plasma model yielding a spacecraft potential typically observed close to perihelion. A summary of the chosen plasma parameters is shown in Table 1. A few potential surfaces from the resulting potential field around the spacecraft are shown in Figure 3.

When the comet approaches the Sun a cavity in the solar wind is formed (Behar et al., 2017). From April 2015 (corresponding to a heliocentric distance of 1.76 AU) to December 2015 (1.64 AU, after perihelion) the spacecraft was inside of this cavity. The simulations are carried out for such a case with the solar wind excluded from the plasma model. Only the cometary ions are included, together with a test population necessary for the

| Parameter       | Electron population | Cometary ion population ($\text{H}_2\text{O}^+$) |
|-----------------|---------------------|-----------------------------------------------|
| Density (cm$^{-3}$) | 1,000               | 1,000                                         |
| Temperature (eV)   | 8                   | 0.5                                           |
| Velocity (km/s)    | 0                   | 4                                             |
particle tracing, described in more detail in section 3.4. The distance to the Sun, mainly determining the photoemission from the spacecraft surface, is set to 1.7 AU, that is, approximately the heliocentric distance where the solar wind disappears from the RPC-ICA data.

The majority of the cometary ions in the vicinity of 67P are water group ions (Fuselier et al., 2015, 2016; Nilsson, Stenberg Wieser, Behar, Simon Wedlund, et al., 2015), and we assume all ions to be water ions (H\textsubscript{2}O\textsuperscript{+}) with a mass of 18 amu/e.

We use a bulk velocity of 4 km/s for the cometary ions. This is in agreement with the results by Odelstad et al. (2018), reporting stable velocities around 3.5–4 km/s inside the diamagnetic cavity. Vigren et al. (2017) found ion speeds in the range 2–8 km/s near perihelion, and modelling results also agree with these values (Vigren \\& Eriksson, 2017). The ions are assumed to flow radially outward from the comet nucleus, corresponding to a flow in the negative z direction in the coordinate system used.

An ion density of 1,000 cm\textsuperscript{-3} is justified from the study by Henri et al. (2017), where the plasma density inside the diamagnetic cavity is determined from the Mutual Impedance Probe (RPC-MIP, Trotignon et al., 2007) data. They find a plasma density varying from ~100 to ~1,500 cm\textsuperscript{-3} between different diamagnetic regions, where the higher densities are observed close to perihelion.

The cometary ions are born cold (Galand et al., 2016), and for this study an ion temperature of 0.5 eV is considered representative of the environment.

To ensure a quasi-neutral plasma, the electron density is set equal to the total ion density. The electron temperature has to be chosen carefully, since the spacecraft potential is highly dependent on this value. We use an electron temperature of 8 eV, resulting in a potential of −21 V. This is a potential typical for the mission, and it is also low enough to give clear particle tracing results. The electron temperature of 8 eV is in good agreement with results from RPC-LAP, where a dominating population with a temperature of 5–10 eV is found (Eriksson et al., 2017). RPC-LAP data also indicate the presence of a colder electron population with a temperature below 0.1 eV, which is not considered in this study, since the warm population is dominating the electron flux to the spacecraft (Odelstad et al., 2015, 2017, 2018).

**Figure 3.** SPIS result showing the potential field around the spacecraft when the plasma model described in section 3.3 is used. A few selected potential surfaces are plotted, specified by the figure in the upper left corner. The spacecraft potential is −21 V.
No magnetic fields are included in the simulations. 67P does not have an intrinsic magnetic field (Auster et al., 2015), and when the spacecraft is close enough to the comet to be inside of the diamagnetic cavity, the interplanetary magnetic field (IMF) is also absent (Goetz, Koenders, Hansen, et al., 2016; Goetz, Koenders, Richter, et al., 2016). The effect of the IMF on the RPC-ICA data for periods when the spacecraft is located outside of the diamagnetic region could be investigated further but is outside the scope of this study.

To reduce the complexity and the simulation time, secondary electron emissions from impacting electrons and ions are not considered. This is a valid simplification since the emission will be insignificant at these particle energies.

### 3.4. Particle Tracing in SPIS

To study the distortion of the FOV, we use the particle tracing tool provided by SPIS. Each sector in the model of RPC-ICA, described in section 3.2, is defined as a particle detector. SPIS uses backtracking from detector to external boundary to relate the distribution at detector and external boundary (Matéo-Vélez et al., 2013). Acceptance angles for each detector in both azimuth and elevation are defined, which for a complete sector (integrated over all elevation angles) becomes $22.5^\circ \times 90^\circ$ and for one individual elevation bin $22.5^\circ \times 5.625^\circ$. The particle tracing principle is illustrated in Figure 4. This illustrative sketch shows two different scenarios, one for high (Figure 4a) and one for low (Figure 4b) energy ions, traced from the same part of the instrument. These are extreme cases, shown to illustrate the possible difference between high and low energies. The color scale has no physical meaning.

The FOV ranges from $-45^\circ$ to $+45^\circ$ in the elevation direction and is divided into 16 steps. At low energies the actual bore sight direction for each elevation step is energy dependent. To simplify the simulations, we define 17 equally spaced elevation angle intervals that are independent of the energy and interpolate the results afterward to the actual elevation angle present in the instrument.

For our application the particle tracing tool has limitations. First, it is not possible to define and track individual particles. Only distribution functions can be defined, and an isotropic Maxwellian distribution function is used for the traced particles. To study specific particle energies, the interesting energies are selected afterward from the distribution function. Second, the population used for the particle tracing has to be one of the already existing particle populations in the simulation. We therefore add a test population with zero bulk velocity (for an isotropic flow of particles, ensuring that all directions are studied equally). To cover the whole energy range of interest, the temperature has to be high enough for a broad distribution ($T \approx 50$ eV to cover an energy range of 0–100 eV without ending up too far out in the tail of the distribution function). The density of this population is set 6 orders of magnitude lower than the cometary ion density, and does not affect the plasma potential.
We convert the resulting velocity distribution functions, both at the external boundary and at detection, to travel direction and flux, where the travel direction is calculated from simple algebra and the flux for each direction is given by the second moment of the velocity distribution function.

4. Results and Discussion

In this section the results from two different simulation cases are presented. The first case looks at the whole sectors without dividing them into the separate elevation bins. This corresponds to a nominal FOV of 22.5° × 90° for each sector. The second case divides each sector into the 17 elevation bins described in section 3.4. This corresponds to a nominal FOV of 22.5° × 5.625° for each bin. From now on, each separate elevation bin will be referred to as one pixel of the instrument.

Results from a selection of sectors and pixels, showing the general features and characteristics of the distortion of the FOV, are presented here. Results for all sectors and all pixels are, however, available as supporting information. The interested reader is referred to this source.

4.1. Whole Sector Simulations

In Figure 5 particle tracing results for sectors 3, 5, and 7 are shown for four different energy intervals. Each individual plot shows the whole sky, with azimuthal angle on the x axis and elevation angle on the y axis. The dashed square represents the nominal FOV of the studied sector. The distortion of the FOV is shown by the color scale, corresponding to the flux of particles at the external boundary reaching the sector from different directions. Nominally, the colored area of the plot would coincide perfectly with the dashed square. The deviation from this shows the distortion of the FOV for this particular energy range and viewing direction.

The calculated flux is in units of m⁻²s⁻¹sr⁻¹. However, the absolute value of the flux is not relevant since it is highly dependent on the input to the simulation. The color scale is therefore normalized with respect to the maximum flux for each individual sector and energy interval. Important to note is that in terms of flux, the results for the different sectors and energy intervals are not comparable because of this individual normalization (max in one plot is not necessarily the same as max in another plot). Also important to note is that the unit of m⁻²s⁻¹sr⁻¹ and the equirectangular projection cause the plots to suffer from the same distortion that will make landmasses close to the poles on a world map appear larger than they actually are. Consequently, bright areas close to the poles contribute less to the total flux than apparent.

Four energy intervals are presented in Figure 5: 40–80 (a–c), 20–40 (d–f), 10–20 (g–i), and 5–10 eV (j–l). These are the energies of the ions at the external boundary, that is, their energies before being accelerated by the spacecraft. The enhanced distortion of the FOV when lowering the energy of the ions is apparent. For the lowest energies the distortion is severe. However, in section 4.2 we will see that different individual pixels contribute differently to the distortion.

The highest energy interval, 40–80 eV, corresponds to approximately twice the spacecraft potential. For these energies the actual FOV coincides reasonably well with the nominal FOV of the sector. Consequently, if the energy of the ions is more than twice the spacecraft potential, the direction can be trusted.

Already for high energies we can see a slight shift in the FOV. The FOV for sector 3 is displaced to the right (toward higher azimuthal angles), while the FOV of sector 7 is displaced to the left (toward lower azimuthal angles), while sector 5 is more or less centered. This seems to be an effect of where the sectors are located with respect to the spacecraft body. Sector 5 is located on top of RPC-ICA, while sectors 3 and 7 are positioned toward the right and left, respectively, when looking at the instrument from the front (see Figure 1b). The FOV is displaced toward the attracting spacecraft body. This becomes more pronounced at lower energies. Even though sectors 3, 5, and 7 are located close to each other on the instrument, the distortion of the FOV for low energies differs substantially between the sectors. The same effect is observed for sectors located on the other side of the instrument (not shown). Sector 13 is located on the opposite side from sector 5, and the FOV of this sector is also centered in azimuth. Sectors located on each side of this sector exhibit displacements of the FOV, with sector 11 displaced towards lower azimuthal angles and sector 15 toward higher.

For all sectors in Figure 5, the distortion gets more severe for extreme elevation angles (elevations close to −45° and + 45°). This is discussed in more detail in section 4.2 where we evaluate the distortion for
individual pixels, but some features in Figure 5 are worth mentioning. Ions coming from extreme elevations have trajectories with a longer path close to the spacecraft, and hence, a heavier distortion is observed for these elevations. When comparing these extreme elevations, that is, high (>+30°) and low (<−30°) elevations, it is clear that the distortion is heavier for low elevations. For sectors 3 and 7 a “tail” forms for low elevations, which is not as pronounced for high elevations. One possible explanation is that the major part of the spacecraft body is located in this direction (see Figure 1a), and consequently, these elevations are more heavily affected.

4.1.1. Finer Energy Intervals
The energy intervals presented in Figure 5 are rather broad. The width is set taking into account the limited amount of particles traced in the simulation, and finer energy intervals result in poorer statistics. No

Figure 5. Particle tracing results for sector 3 (a, d, g, and j), sector 5 (b, e, h, and k), and sector 7 (c, f, i, and l), for four different energy intervals: 40–80 (a–c), 20–40 (d–f), 10–20 (g–i), and 5–10 eV (j–l). Azimuthal angle is on the x axis, and elevation angle is on the y axis. The dashed square represents the nominal FOV of the sector, while the color scale corresponds to the flux of particles at the external boundary reaching the sector from different directions. The geometrical locations of the comet and the Sun are in directions (90°, 0°) and (0°, 0°), respectively.
important information is, however, lost, since the FOV broadens and spreads out in a uniform way without discontinuities. In Figure 6 four narrower intervals for sector 3 are shown: 10–12, 12–14, 14–16, and 16–18 eV (cf. the 10–20 eV interval in Figure 5). The statistics are poor, but it is possible to see the general shape of the FOV. The FOV smoothly spreads out from higher to lower energy intervals, and there are no distinct areas corresponding to certain ion energies. We assume that this is true for the rest of the studied sectors and energy intervals as well.

4.1.2. Numerical Artefacts
SPIS is a numerical solver giving unavoidable numerical artefacts in the results. These are caused by, for example, limited grid resolution, a limited amount of test particles and memory limitations. One effect can be observed in, for example, the low-energy (5–10 eV) plots in Figure 5: uniform areas with an even shape, often circular or quadrangular. These areas are due to coarse angular binning of the velocity distribution close to the origin (an effect of even binning in velocity). “Noise” in the potential field (see, e.g., the potential surfaces in Figure 3, they are not entirely smooth) may cause additional numerical effects. The smallest potential variation is limited by the accuracy of the SPIS potential solver, and particles with energies close to or below this accuracy limit get “trapped” in the field. To reduce this effect, we avoid the lowest part of the energy spectrum. The lowest energy interval presented hence starts at 5 eV.

4.1.3. Shadowing
The spacecraft body shadows parts of the nominal FOV of RPC-ICA. The lowest elevation angles for sectors 10–15 and 0 get shadowed for all ion energies since they are looking into the spacecraft body (Nilsson et al., 2007). Additional shadow effects appear because of the FOV distortion at low energies. In Figure 7 three examples of shadowing effects are shown. These plots are similar to the ones shown in Figure 5, but instead of showing the flux of particles at the external boundary, they show the flux of particles at detection. They hence show the travel direction of the particles when entering the sector. The dashed square is still the nominal FOV. In Figure 7 the results for sectors 11, 13, and 5 are presented. Only three energy intervals are shown. The two highest energy intervals (20–40 and 40–80 eV) are very similar, and therefore, 40–80 eV is excluded from the figure.

Sector 11 gets geometrically shadowed by the spacecraft body for low elevations. The shadowed area grows slightly when the energy of the ions is decreased, but the shadowing is more or less constant over different energies. Sector 13 shows an additional shadowing, appearing at high elevations. This is caused by the solar

Figure 6. Particle tracing results for sector 3 for four narrow energy intervals: 16–18 eV (a), 14–16 (b), 12–14 (c), and 10–12 eV (d). The dashed square represents the nominal FOV of the sector, while the color scale corresponds to the flux of particles at the external boundary reaching the sector from different directions.
panel, located in the FOV of this sector. Also this shadowing is more or less constant over different energies. The shadowing of sector 5, on the other hand, is a result of the distortion of the FOV at low energies. This sector is located on top of the instrument, with the spacecraft body far away from the nominal FOV. However, for low ion energies, we can see that some shadowing appears for the lowest elevation angles. This illustrates the severity of the FOV distortion for some instrument pixels. All shadowed pixels have been removed from the results. Some partially shadowed pixels have, however, been kept since they still give important information about the FOV distortion. All partially shadowed pixels have been flagged in the supporting information.

4.2. Individual Pixel Simulations

The FOV of the lowest energy interval presented in Figure 5 is severely distorted for all presented sectors. To see the contribution from each elevation bin within each sector, we divide all sectors into the 17 elevation bins, as described in section 3.4. Elevation 0 corresponds to a bin centered at an elevation angle of $-45^\circ$ (see Figure 1a), while elevation 16 has an elevation angle of $+45^\circ$.

The result for the lowest energy interval (5–10 eV) of sector 3 is shown in Figure 8. The lowest elevation angle is presented in panel (a), and then the angle is gradually increased to the right and downwards. The severe FOV distortion appearing at low energies is mainly caused by extreme (i.e., high and low) elevation angles. Elevation bins in the middle of the interval, that is, elevation angles close to the aperture plane, get considerably less distorted by the spacecraft potential.

Figure 7. Particle tracing results showing the travel direction of the particles at detection. The dashed square represents the nominal FOV of the sector, while the greyscale corresponds to the flux of particles at detection. Results for sector 11 (a, d, and g), sector 13 (b, e, and h), and sector 5 (c, f, and i) are shown for three different energy intervals: 20–40 (a–c), 10–20 (d–f), and 5–10 eV (g–i).
Figure 8. Particle tracing results for each pixel of sector 3. Only the lowest energy interval (5–10 eV) is presented. The dashed square represents the nominal FOV of the pixel, while the color scale corresponds to the flux of particles at the external boundary reaching the pixel from different directions. (a) The result for elevation 0 and (g) for elevation 16. (b)-(p) The results for elevations 1–15.
The same general features are observed for sectors 2–8 (not shown), that is, sectors located on the upper half of the instrument. The distortion for different elevation bins varies a bit between the sectors, but generally, the five to six lowest elevation bins and the two to three highest are the ones most severely distorted. Generally, the distortion is worse for low elevation angles. The reader is referred to the supporting information for results for all sectors.

Sectors 0–1 and 9–15 behave differently from sectors 2–8. Most of them are partly shadowed by the spacecraft. They can be classified into three main groups showing similar behavior: sectors 9–12, sectors 13–14, and sectors 15–1. In Figure 9 the low-energy results for sector 11 are shown as an example of the first group. The main general characteristic of this group is that higher elevation angles are less distorted. The lower elevation bins are completely or partly shadowed by the spacecraft (thereof the missing lower elevations in Figure 9), which explains the behavior of these sectors. Ions entering the instrument with a lower elevation angle have to pass closer to the charged spacecraft body.

The next group of sectors, sectors 13–14, are to a large extent shadowed by both the spacecraft body and the solar panels (see Figure 7). Consequently, we only have a few pixels capable of detecting particles.

Sectors 15 and 0–1 are located on the right hand side of the instrument, when looking at the instrument from the front. The lowest elevation angles are shadowed by the spacecraft, but otherwise, these sectors behave similarly as sectors 2–8, with high elevation angles severely distorted. Generally, the spread of the FOV is more severe for these sectors, even for less distorted pixels.

One trend visible for all sectors (here only shown for sectors 3 and 11 in Figures 8 and 9, respectively) is how the actual FOV wanders from low to high elevations. For low elevation bins, the actual FOV is located below the nominal FOV. When the elevation angle is increased, the FOV wanders toward higher elevations, until the actual FOV is located above the nominal FOV. Again, this is a result of where the pixel is looking with respect to the spacecraft body. For each sector we can find one pixel that is more or less centered in elevation (i.e., the FOV coincides with the nominal FOV in the elevation direction). For sectors located on top of the instrument this pixel typically appears around elevation bin 10–11, while for sectors located on the other side elevation bins 15–16 are the centered ones. As previously shown, sector 5 is also centered in the azimuthal direction, which means that we for this sector can find a pixel that is centered in

Figure 9. Particle tracing results for the unshadowed pixels of sector 11. Only the lowest energy interval (5–10 eV) is presented. The dashed square represents the nominal FOV of the pixel while the color scale corresponds to the flux of particles at the external boundary reaching the pixel from different directions. (a) The result for elevation 11 and (f) for elevation 16.
both azimuth and elevation. This pixel (elevation 10) is shown in Figure 10 for four different energy intervals. The FOV only spreads out without wandering away while lowering the ion energy. Of all instrument pixels, this pixel gets least distorted by the spacecraft potential. Sector 13 is located on the opposite side of the instrument compared to sector 5 and is also centered in the azimuthal direction. This sector, however, suffers from some heavy shadowing effects and, therefore, has other limitations.

Even for “good” pixels, that are less distorted by the spacecraft, the FOV grows in size when the ion energy is lower. For elevation 10 of sector 5, shown in Figure 10, the FOV of the pixel grows to a size of approximately $50^\circ \times 25^\circ$ (compared to the nominal FOV of $22.5^\circ \times 5.625^\circ$), which is a considerable increase. All pixels grow to at least this angular size for low energies. This implies an overlap in FOV between the pixels. Note though, that the particle trajectories are deterministic, and this overlap is possible since only travel direction and not physical location at the external boundary is considered. The increased FOV has implications for the geometric factor of the instrument (Lavraud & Larson, 2016), which should be investigated further.

5. Conclusions and Final Remarks

In this study we used SPIS to model the influence of the spacecraft potential on the low-energy ion measurements made by RPC-ICA. We studied the distortion of the FOV for different ion energies and showed the following:

1. The travel direction of the ions can be trusted when their energy at infinity corresponds to at least twice the spacecraft potential.
2. The FOV of one instrument pixel grows to, at least, $50^\circ \times 25^\circ$ for low energies (5–10 eV).
3. Extreme elevation angles should be avoided for sectors 0–8 and 15 since these are heavily distorted by the spacecraft potential.
4. A large part of sectors 13–14 are shadowed by the spacecraft, with only a couple of nonshadowed pixels.
5. Higher elevation angles are less distorted for sectors 9–12.

Figure 10. Particle tracing results for elevation 10 of sector 5 for four different energy intervals: 40–80 (a), 20–40 (b), 10–20 (c), and 5–10 eV (d). The dashed square represents the nominal FOV of the pixel, while the color scale corresponds to the flux of particles at the external boundary reaching the pixel from different directions.
In this study we did not consider the influence of a magnetic field. When the spacecraft is located outside of the diamagnetic cavity and is exposed to the IMF the electrons will be forced to move along the magnetic field lines to a larger extent than the ions, due to their different gyroradii, which may affect the charging of the spacecraft (Tribble, 2003). A magnetic field may furthermore indirectly affect the ion trajectories. The effect on the results is assumed to be negligible, but could be investigated for different magnetic field orientations. We also considered only one plasma model. A different model would change the spacecraft potential, which would affect the simulation results. However, we assume that this would mainly shift the distortion in energy, so that the undistorted case still appears at an energy of twice the spacecraft potential.

Other instruments, located close to RPC-ICA on the spacecraft, may have an additional impact on the RPC-ICA measurements. Furthermore, exposed areas on the solar panels put to high voltages may also affect particle trajectories and alter the spacecraft potential. A more detailed spacecraft model can be used to investigate these effects.

The results from this study show that the change in particle trajectories should be considered when working with low-energy plasma measurements. Generally, the travel direction of the particles cannot be trusted. We believe that these simulations can be used to correct the least distorted low-energy data obtained by RPC-ICA, which will enable us to further study the low-energy ions around 67P/Churyumov-Gerasimenko.

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References
Auster, H.-U., Apathy, I., Berghofer, G., Fornacon, K.-H., Remizov, A., Carr, C., et al. (2015). The nonmagnetic nucleus of comet 67P/Churyumov-Gerasimenko. Science, 349(6247), aaa5102. https://doi.org/10.1126/science.aaa5102
Behar, E., Nilsson, H., Alho, M., Goetz, C., & Tsurutani, B. (2017). The birth and growth of a solar wind cavity around a comet—Rosetta observations. Monthly Notices of the Royal Astronomical Society, 469(Suppl. 2), S396-S403. https://doi.org/10.1093/mnras/stx1871
Berthelier, J.-J., & Roussel, J.-F. (2004). A study of the electrical charging of the Rosetta orbiter: 2. Experimental tests in a laboratory plasma. Journal of Geophysical Research, 109, A01105. https://doi.org/10.1029/2003JA009834
Carr, C., Cupido, E., Lee, C., Balogh, A., Beek, T., Burch, J., et al. (2007). RPC: The Rosetta Plasma Consortium. Space Science Reviews, 128(1-4), 629-647. https://doi.org/10.1007/s11214-006-9136-4
Cravens, T., & Gombosi, T. (2004). Cometary magnetospheres: A tutorial. Advances in Space Research, 33(11), 1968-1976. https://doi.org/10.1016/j.asr.2003.07.053
Eriksson, A., Boström, R., Gill, R., Åhlén, L., Jansson, S.-E., Wahlund, J.-E., et al., & The LAP Team (2007). RPC-LAP: The Rosetta Langmuir Probe instrument. Space Science Reviews, 128(1-4), 729-744. https://doi.org/10.1007/s11214-006-9003-3
Eriksson, A. I., Engelhardt, I. A., André, M., Boström, R., Edberg, N. I., Johansson, F. L., et al. (2017). Cold and warm electrons at comet 67P/Churyumov-Gerasimenko. Astronomy & Astrophysics, 605. https://doi.org/10.1051/0004-6361/201630159
Fuselier, S. A., Altwege, K., Balsiger, H., Berthelier, J. J., Beth, A., Bieler, A., et al. (2016). Ion chemistry in the coma of comet 67P near perihelion. Monthly Notices of the Royal Astronomical Society, 462(Suppl 1), S677-S777. https://doi.org/10.1093/mnras/stw2149
Fuselier, S. A., Altwege, K., Balsiger, H., Berthelier, J. J., Bieler, A., Brions, C., et al. (2015). ROSINA/DFMS and IES observations of 67P: Ion-neutral chemistry in the coma of a weakly outgassing comet. Astronomy & Astrophysics, 583, A2. https://doi.org/10.1051/0004-6361/201526210
Galand, M., Héritier, K. L., Odelstad, E., Henri, P., Broiles, T. W., Allen, J. E., et al. (2016). Ionospheric plasma of comet 67P probed by Rosetta at 3 AU from the Sun. Monthly Notices of the Royal Astronomical Society, 462(Suppl 1), S331-S351. https://doi.org/10.1093/mnras/stw2891
Garrett, H. B. (1981). The charging of spacecraft surfaces. Reviews of Geophysics and Space Physics, 19(4), 577-616.
Glassmeier, K.-H., Boehnhardt, H., Koschny, D., Kühl, E., & Richter, I. (2007). The Rosetta mission: Flying towards the origin of the Solar System. Space Science Reviews, 128, 1–21. https://doi.org/10.1007/s11214-006-9140-8
Goetz, C., Koenders, C., Hansen, K. C., Burch, J., Carr, C., Eriksson, A., et al. (2016). Structure and evolution of the diamagnetic cavity at comet 67P/Churyumov-Gerasimenko. Monthly Notices of the Royal Astronomical Society, 462(Suppl 1), S459-S467. https://doi.org/10.1093/mnras/stw3148
Goetz, C., Koenders, C., Richter, I., Altwege, K., Burch, J., Carr, C., et al. (2016). First detection of a diamagnetic cavity at comet 67P/Churyumov-Gerasimenko. Astronomy & Astrophysics, 588, A24. https://doi.org/10.1051/0004-6361/201527728
Henri, P., Vallières, X., Hajra, R., Goetz, C., Richter, I., Glassmeier, K. H., et al. (2017). Diamagnetic region(s): Structure of the unmagnetized plasma around Comet 67P/CG. Monthly Notices of the Royal Astronomical Society, 469(Suppl. 2), S372-S379. https://doi.org/10.1093/mnras/stx1540
Johansson, F., Henri, P., Eriksson, A., Vallières, X., Lebreton, J.-P., Béghin, C., Odelstad, E. (2016). Simulations of the Rosetta spacecraft interaction with comet plasma. Proceedings of the 14th International Spacecraft Charging Technology Conference. ESA, Noordwijk. Langmuir, I., & Blodgett, K. B. (1924). Currents limited by space charge between concentric spheres. Physical Review, 24(1), 49–59. https://doi.org/10.1103/PhysRev.24.49
Lavraud, B., & Larson, D. (2016). Correcting moments of in situ particle distribution functions for spacecraft electrostatic charging. Journal of Geophysical Research: Space Physics, 121, 8462-8474. https://doi.org/10.1002/2016JA022591
Masunaga, K., Nilsson, H., Behar, E., Stenberg Wieser, G., Wieser, M., & Goetz, C. (2019). A flow pattern of accelerated cometary ions inside and outside the diamagnetic cavity of comet 67P/Churyumov-Gerasimenko. Astronomy & Astrophysics, 630, A43. https://doi.org/10.1051/0004-6361/201935122
Matéo-Vélez, J.-C., Sarrailh, P., & Forest, J. (2013). User manual—Annex 2—Advanced use for scientific applications.
Mott-Smith, H., & Langmuir, I. (1926). The theory of collectors in gaseous discharges. Physical Review, 28(4), 727–763. https://doi.org/10.1103/PhysRev.28.727
Nilsson, H., Lundin, R., Lundin, K., Barabash, S., Borg, H., Norberg, O., et al. (2007). RPC-ICA: The ion composition analyzer of the Rosetta Plasma Consortium. *Space Science Reviews*, 128(1-4), 671–695. https://doi.org/10.1007/s11214-006-9031-z

Nilsson, H., Stenberg Wieser, G., Behar, E., Simon Wedlund, C., Kallio, E., Gunell, H., et al. (2015). Evolution of the ion environment of comet 67P/Churyumov-Gerasimenko. *Astronomy & Astrophysics*, 583, A20. https://doi.org/10.1051/0004-6361/201526142

Nilsson, H., Stenberg Wieser, G., Behar, E., Wedlund, C. S., Gunell, H., Yamauchi, M., et al. (2015). Birth of a comet magnetosphere: A spring of water ions. *Science*, 347(6220), aaa0571. https://doi.org/10.1126/science.aaa0571

Nilsson, H., Wieser, G. S., Behar, E., Gunell, H., Wieser, M., Galand, M., et al. (2017). Evolution of the ion environment of comet 67P during the Rosetta mission as seen by RPC-ICA. *Monthly Notices of the Royal Astronomical Society*, 469(Suppl_2), S252–S261. https://doi.org/10.1093/mnras/stx1491

Odelstad, E., Eriksson, A. I., Edberg, N. J. T., Johansson, F., Vigren, E., André, M., et al. (2015). Evolution of the plasma environment of comet 67P from spacecraft potential measurements by the Rosetta Langmuir probe instrument. *Geophysical Research Letters*, 42, 10,128–10,134. https://doi.org/10.1002/2015GL066599

Odelstad, E., Eriksson, A. I., Johansson, F. L., Vigren, E., Henri, P., Gilet, N., et al. (2018). Ion velocity and electron temperature inside and around the diamagnetic cavity of comet 67P. *Journal of Geophysical Research: Space Physics*, 123, 5870–5893. https://doi.org/10.1029/2018JA025542

Odelstad, E., Stenberg Wieser, G., Wieser, M., Eriksson, A., Nilsson, H., & Johansson, F. (2017). Measurements of the electrostatic potential of Rosetta at comet 67P. *Monthly Notices of the Royal Astronomical Society*, 469, S568–S581. https://doi.org/10.1093/mnras/stx2232

Roussel, J.-F., & Berthelier, J.-J. (2004). A study of the electrical charging of the Rosetta orbiter: I. Numerical model. *Journal of Geophysical Research*, 109, A01104. https://doi.org/10.1029/2003JA009836

Szegö, K., Glassmeier, K. H., Bingham, R., Bogdanov, A., Fischer, C., Haerendel, G., et al. (2000). Physics of mass loaded plasmas. *Space Science Reviews*, 94(3-4), 429–671. https://doi.org/10.1023/A:1026568530975

Thiébault, B., Mateo-Velez, J.-C., Forest, J., & Sarrailh, P. (2013). *SPIS 5.1 User Manual*. Princeton, New Jersey: Princeton University Press.

Trotignon, J. G., Michau, J. L., Lagoutte, D., Chabassière, M., Chalumeau, G., Colin, F., et al. (2007). RPC-MIP: The mutual impedance probe of the Rosetta Plasma Consortium. *Space Science Reviews*, 128(1-4), 713–728. https://doi.org/10.1007/s11214-006-9005-1

Vigren, E., André, M., Edberg, N. J. T., Engelhardt, I. A. D., Eriksson, A. I., Galand, M., et al. (2017). Effective ion speeds at ~200–250 km from comet 67P/Churyumov-Gerasimenko near perihelion. *Monthly Notices of the Royal Astronomical Society*, 469(Suppl_2), S142–S148. https://doi.org/10.1093/mnras/stx1472

Vigren, E., & Eriksson, A. (2017). A 1D model of radial ion motion interrupted by ion-neutral interactions in a cometary coma. *The Astronomical Journal*, 153(4), 150. https://doi.org/10.3847/1538-3881/aa6006

Whipple, E. C. (1981). Potentials of surfaces in space. *Reports on Progress in Physics*, 44(11), 1197–1250.