The Influence of Varying Spacecraft Potentials and Debye Lengths on In Situ Low-Energy Ion Measurements

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Abstract  Low-energy ions are difficult to measure, mainly due to spacecraft charging. The ions are attracted to or repelled from the charged surface prior to detection, which changes both the energy and travel direction of the ions. This results in distortions of the data, and the changed travel directions distort the effective field of view (FOV) of the instrument performing the measurements. The ion composition analyzer (RPC-ICA) was measuring positive ions down to an energy of a few eV around comet 67P/Churyumov-Gerasimenko. Low-energy ions play important parts in processes in the cometary environment, but the FOV of RPC-ICA has been shown to get severely distorted at low ion energies. Several factors are believed to affect the distortion level. In this study we use the Spacecraft Plasma Interaction Software (SPIS) to investigate the influence of varying spacecraft potentials and Debye lengths on the FOV distortion of RPC-ICA. We show that the distortion level is dependent on the Debye length of the surrounding plasma, but the sensitivity varies substantially between different viewing directions of the instrument. We also show that a small nonlinearity exists in the relation between FOV distortion, ion energy, and spacecraft potential, mainly caused by the photoemission and bulk flow of the cometary plasma.

1. Introduction

Low-energy ions play important parts in many processes in planetary environments. Parts of the terrestrial magnetosphere are dominated by low-energy (tens of eV) ions, which also tend to dominate ion outflow and escape (André & Cully, 2012). Low-energy ions have also been shown to influence the dynamics of magnetic reconnection (André et al., 2010). Also at Mars low-energy ions have been shown to contribute significantly to the outflow (Dong et al., 2017; Fränz et al., 2015), and the situation is probably similar at Venus (Brace et al., 1987). For Mars it has furthermore been shown that the dependence of ion escape on solar wind and solar upstream parameters is energy dependent. Low-energy ion fluxes (<30 eV) are, for example, more sensitive to EUV variations than higher energies, making low-energy ions important for the understanding of atmospheric evolution (e.g., Dubinin, Fraenz, Pätzold, McFadden, Halekas, et al., 2017; Dubinin, Fraenz, Pätzold, McFadden, Mahaffy, et al., 2017).

Also at comets low-energy ions are important for the physical processes. Plasma is created by local ionization of the neutral coma, with a newborn ion being initially cold since it retains the speed of the original molecule. It is then subject to the interplay of electrodynamic and collisional interactions. If the collisions dominate, the ions will flow with the neutral gas; if not, their motion will trace the electric field. The inner coma was previously thought to be collisionally dominated (e.g., Cravens, 1989; Gombosi, 2015), and the ion-neutral momentum transfer efficient enough to resist the pressure of the outside magnetic field, creating a magnetic field free region known as the diamagnetic cavity. No solar wind ions can enter this region. However, the detailed measurements made by Rosetta (Glassmeier et al., 2007) at comet 67P/Churyumov-Gerasimenko during different levels of cometary activity complicated the picture. The solar wind was found to disappear well outside the diamagnetic cavity (Behar et al., 2017; Nilsson et al., 2017), and for the outgassing rates encountered by Rosetta, ion collisional coupling was typically found to be marginal (Vigren & Eriksson, 2017). Hence, ion motion may or may not be coupled to the neutral gas (Odelstad et al., 2018), and the formation of the diamagnetic cavity is not as easily explained (Goetz, Koenders, Hansen, et al., 2016; Goetz, Koenders, Richter, et al., 2016). Low-energy ion measurements are therefore of highest interest to establish the physical processes.
Unfortunately, low-energy ions are difficult to measure. One major difficulty arises due to spacecraft charging. The surface of the spacecraft interacts with the surrounding environment, resulting in a charge transfer and a charge up of the spacecraft surface to a positive or negative potential (see, e.g., Garrett (1981) and Whipple (1981) for a discussion about the charging processes). This is problematic for in situ measurements of low-energy ions that are either attracted to or repelled from the charged spacecraft surface before detection. This affects both the energy and travel direction of the ions. If the spacecraft potential is positive, parts of the ion distribution will not be able to reach the instrument, provided positive ions. If the spacecraft potential is negative, the spacecraft will instead accelerate the positive ions and make particles with energies below the energy range of the instrument detectable.

If the spacecraft potential is known, the energy shift can be corrected for. The influence on the travel direction of the ions is more complex and will result in a distortion of the effective field of view (FOV) of the instrument due to focusing or defocusing effects. Bergman et al. (2020) used the Spacecraft Plasma Interaction Software (SPIS, Thiébault et al., 2013) to study the FOV distortion of the ion composition analyzer (RPC-ICA, Nilsson et al., 2007) on board Rosetta. Rosetta was commonly charged to a negative potential of around −10 to −20 V throughout the mission, where strong negative potentials were typically observed close to perihelion (Odelstad et al., 2015, 2017). RPC-ICA was measuring positive ions, and the ions were attracted to the negatively charged spacecraft before detection, resulting in distortions of the low-energy data.

Bergman et al. (2020) showed that the low-energy part of the data obtained by RPC-ICA indeed is severely distorted, but the severity of the distortion is varying between different viewing directions of the instrument. The distortion is hence strongly geometry dependent. Generally, extreme elevation angles are more heavily distorted than elevations in the aperture plane (see Figure 1). Even though the distortion level varies between the pixels, the distortion can generally be considered insignificant when the ion energy at infinity is above twice the spacecraft potential.

Bergman et al. (2020) studied the distortion for one specific plasma model and a corresponding spacecraft potential of −21 V. We expect several factors to affect the distortion level. One of those is the spacecraft potential. Different spacecraft potentials will yield different distortion levels, but if the relation between distortion and spacecraft potential is linear, that is, if the same ratio between ion energy and spacecraft potential yields similar distortion features independent of the value of the spacecraft potential, the simulation results for one single spacecraft potential is enough to estimate the distortion at other potentials and ion energies. The first aim of this study is to investigate this linearity. Another factor expected to affect the distortion level is the Debye length of the surrounding plasma. The Debye length is the most important parameter determining the shielding properties of the spacecraft, and we can therefore expect the ion trajectories to be differently affected by different Debye lengths. The second aim of this study is to investigate this effect. Finally, we also analyze the accuracy of the simplified spacecraft model used by Bergman et al. (2020). Additional structures not included in the model may result in additional focusing effects. We investigate if these effects significantly affect the simulation results.

2. Instrument Description

RPC-ICA (Nilsson et al., 2007) measured positive ions in the vicinity of comet 67P, with the purpose of investigating the cometary particles’ interaction with the solar wind. The energy of the ions is analyzed with a spherical electrostatic analyzer (ESA), covering energies from a few eV/q to 40 keV/q. This energy range is divided into 96 energy steps. The particle’s mass per charge is determined in a magnetic momentum filter.

The nominal total FOV of the instrument is 360° × 90°. In azimuth the total FOV of 360° is divided into 16 sectors of 22.5° each. An electrostatic acceptance angle filter controls the elevation angle of the incoming ions. The total FOV of 90° in this direction is divided into 16 elevation steps, where each step has a resolution of 5.625°. One individual instrument pixel hence has a FOV of 22.5° × 5.625°. This is illustrated in Figure 1.

3. Method

In this study we use the SPIS software to simulate the spacecraft plasma interactions and the ion trajectories. We use the method developed by Bergman et al. (2020). For details regarding this underlying method the
The reader is referred to that source. Only a summary will be given here. The simulations done by Bergman et al. (2020) will for the rest of this paper be referred to as the reference simulations.

### 3.1. Basic Simulation Setup

For this study we use a particle-in-cell (PIC) solver for the ions, while the electrons are approximated by an equilibrium Maxwell-Boltzmann distribution. For the fields we use a 1/r^2 decay at the boundary (pre-sheath conditions).

We use the same simplified spacecraft model as Bergman et al. (2020), where the only included instruments are RPC-ICA and RPC-LAP. The sensitivity of the results to a more detailed spacecraft model is however investigated (section 4.4). The simulation volume is an ellipsoid with a size of 70 × 60 × 60 m. We use an adaptive mesh size, varying from 3 m at the external boundary to 5–25 cm at the spacecraft body, ensuring a resolved Debye length close to the spacecraft. Close to RPC-ICA the resolution is increased to 2 cm.

In our model indium tin oxide (ITO) is exclusively used as surface material. On the actual spacecraft ITO is used to cover large surface areas exposed to the Sun, which contribute the most to the photoemission. In the model the Sun is located in the positive x-direction (see, e.g., Figures 1 and 2) at a distance of 1.7 AU. The comet is located in the positive z-direction.

As a starting point we use the same plasma model as Bergman et al. (2020). This model consists of one cometary H_2O^+ population with a density of 1,000 cm⁻³ (Henri et al., 2017), a temperature of 0.5 eV (Galand et al., 2016) and a bulk velocity of 4 km/s (Odelstad et al., 2018; Vigren et al., 2017; Vigren & Eriksson, 2017). The electron population has a density of 1,000 cm⁻³ (to ensure quasi-neutrality) and a temperature of 8 eV (Eriksson et al., 2017; Odelstad et al., 2015, 2017, 2018). This model corresponds to a Debye length of ~0.66 m and yields a spacecraft potential of −21 V.

The particle tracing tool provided by SPIS (Matéo-Vélez et al., 2013) uses a test particle approach to study the distribution of particles detected by a surface. We define each sector of RPC-ICA as one individual particle detector and trace the particles backwards to the external boundary to relate these distributions. For symmetry purposes, we define 17 elevation steps instead of 16, where elevation bin 8 is centered at 0° and bins 0 and 16 at −45° and +45°, respectively. For the real instrument, the bore sight direction of each elevation bin is energy dependent at low energies, and the simulation results have to be subsequently interpolated.
3.2. Spacecraft Potential

In the simulations done by Bergman et al. (2020) the spacecraft potential floats with respect to the plasma. SPIS then determines the value of the potential from the current balance. In this study we want to separate effects caused by different spacecraft potentials from those caused by different Debye lengths of the surrounding plasma. To study the influence of different spacecraft potentials on the FOV distortion we therefore fix the potential at certain values while keeping the same plasma model. By doing this we separate effects caused by the spacecraft potential from effects caused by different Debye lengths. We fix the potential at $-40$ and $-10$ V, while keeping the Debye length at 0.66 m. We then compare these results to the results yielded by the reference simulation (corresponding to a potential of $-21$ V).

3.3. Debye Length

To investigate the influence of varying Debye lengths on the instrument FOV, we vary the electron temperature and density in our model so that the spacecraft potential remains at $-21$ V, while the Debye length changes. We limit the analysis to Debye lengths typical for the Rosetta mission. Apart from the Debye length of 0.66 m yielded by the reference plasma model, we choose parameters yielding Debye lengths of 0.34 and 3.40 m. This range is expected to cover the main part of the interesting plasma environments encountered by Rosetta. The corresponding values of the electron density and temperature are listed in Table 1. Note that these parameters are not necessarily representative of the actual environment around the spacecraft. They are chosen to yield the same spacecraft potential, which is necessary to separate effects caused by the spacecraft potential from those caused by the Debye length. The ion density is set equal to the electron density in all cases to ensure quasi-neutrality, and the ion temperature is 0.5 eV. In Figure 2 the resulting potential field around the spacecraft is shown for all studied Debye lengths. It is clear

![Figure 2](image)

**Figure 2.** Simulation results from SPIS showing a few potential surfaces of the potential field around the spacecraft when the Debye length of the surrounding plasma is 0.34, 0.66, and 3.4 m. The color scale is identical for all three cases, and the spacecraft potential is $-21$ V.

| Debye length [m] | Electron density [cm$^{-3}$] | Electron temperature [eV] | Spacecraft potential [V] |
|------------------|------------------------------|---------------------------|--------------------------|
| 0.34             | 3,000                        | 6.2                       | $-21$                    |
| 0.66             | 1,000                        | 8                         | $-21$                    |
| 3.4              | 100                          | 21.5                      | $-21$                    |

*Note. The resulting spacecraft potential is $-21$ V for all three cases.*
that the noise level increases for shorter Debye lengths (the potential surfaces are less smooth). For the shortest Debye length we therefore enhance the resolution of the mesh, and to avoid effects caused by the remaining noise level we exclude ion energies below 5 eV from the analysis.

3.4. Detailed Spacecraft Model

Other instruments and different spacecraft structures are blocking the nominal FOV of RPC-ICA. The resulting geometrical shadowing can be predicted, but the resulting effect on the potential field might cause additional focusing effects on the particle trajectories. To investigate these effects, we add structures representing the Ion and Electron Sensor (RPC-IES, Burch et al., 2007) and the Microwave Instrument for the Rosetta Orbiter (MIRO, Gulkis et al., 2007) to the model. These are two instruments known to shadow the nominal FOV of RPC-ICA. The new spacecraft model is shown in Figure 3. The instruments are modeled without details, but the simplified models are enough to estimate the instruments’ influence.

3.5. Simulation Comparison

We compare our simulation results to the results obtained by Bergman et al. (2020). We do the comparison for a few selected instrument pixels, marked in Figure 4. In each panel of Figure 4 the whole FOV of RPC-ICA is shown, where each cell of the grid represents the nominal FOV of one instrument pixel. The gray area corresponds to the approximate position of the spacecraft in the FOV (Nilsson, 2019). Note that this is a simplified shadow map, only serving as an indicator of where different spacecraft structures are located in the FOV. The instrument pixels outlined in white in Figure 4 are the ones used for the comparison. In Figure 4a the pixels used for the simulations investigating effects caused by the spacecraft potential and the Debye length are shown. We study one pixel for each sector, except for sector 13 and 14 that are heavily shadowed by the spacecraft. For sector 5 we also study the influence on different elevation angles. To study the more detailed spacecraft model we simulate a few pixels that most likely are affected by the new model, that is, those with a FOV in the vicinity of the added instruments. Those are shown in Figure 4b.

SPIS randomly samples initial values of ion positions and velocities from user-defined distributions, resulting in statistical variations in the simulation outputs. To estimate the resulting uncertainty in the results from the reference simulation, we run 18 simulations for a few selected instrument pixels, with the same geometry and plasma conditions, but different randomly selected particles. The simulation setup is identical to the setup used by Bergman et al. (2020). From these simulations we estimate the uncertainty in FOV size and position. Uncertainty estimates are available for the pixels filled with red in Figure 4. We base the main analysis on these pixels and verify the results for the other pixels by estimating the uncertainty from the closest pixels where uncertainty estimates are available.

For the comparison we focus on the size and position of the FOV. Differences related to detected flux are outside the scope of this study.

4. Results and Discussion

4.1. Description of Simulation Results and Uncertainty Analysis

We illustrate the particle tracing results as flux maps. One example is shown in Figure 5. This is the result for sector 3, elevation 8, when the setup for the reference simulation is used, that is, the spacecraft potential is $-21$ V and the Debye length $0.66$ m. Each row represents one energy interval.

The first column (panel a-d) shows the result from one single simulation. In each panel the whole sky is shown, as seen from the instrument, with azimuthal angle on the x-axis and elevation angle on the y-axis. Each cell of the grid corresponds to the nominal FOV of one instrument pixel. The dashed cell represents the studied instrument pixel, and the color scale shows the flux of particles at the external boundary that are reaching the pixel from different directions. The size of the colored area can therefore be taken to correspond to the effective FOV of this pixel for the studied energy interval. It is clear that the FOV grows in size and changes position when the ion energy is decreased.

In the second column (panel e-h) the statistics have been improved by combining 18 simulations. For each direction the mean flux is plotted. By improving the statistics small artifacts are removed, and the result is evened out, but the result yielded by one single simulation agrees reasonably well with the mean.
The third column (panel i–l) shows the standard deviation of the flux for each direction from the same 18 simulations. As expected the standard deviation is low at the center of the FOV, where the flux is high, but the uncertainty increases towards the edges. These types of standard deviation plots are in the following sections used to estimate differences in FOV position.

4.2. Spacecraft Potential

The purpose of this analysis is to investigate whether the particle tracing results scale linearly with the spacecraft potential (i.e., if the FOV distortion is equal when the ratio between the spacecraft potential and the ion energy is the same). Initially, we study the size of the FOV. In Figure 6 the results describing the size of the FOV for different spacecraft potentials and ion energies are shown. The FOV size has been calculated from the flux maps by setting the outer edge to 10% of the maximum flux for that pixel and energy interval. Panels a–g show the results for a potential of $-10$ V and panels h–n the results for $-40$ V. Each row shows the results for one instrument pixel. Only the pixels where uncertainty estimates are available are shown (the ones marked with red in Figure 4). In each panel the vertical lines represent the new simulation results.

Figure 3. The spacecraft model used to estimate the influence of other instruments and detailed spacecraft structures on the particle tracing results. The instruments colored in red, RPC-IES and MIRO, have been added to the simple spacecraft model.

Figure 4. The nominal FOV of RPC-ICA, where each cell of the grid corresponds to the FOV of one instrument pixel and the gray area shows approximately where the spacecraft is blocking the FOV. Pixels marked with white are the ones simulated, and for pixels filled with red uncertainty estimates are available for the reference simulation. In (a) the simulated pixels for the spacecraft potential and Debye length simulations are shown. The pixels marked in (b) are the ones used for the detailed spacecraft model.
for four different energy intervals, where red corresponds to an energy interval starting at 2 times the spacecraft potential (20–40 eV for the potential of −10 V and 80–160 eV for the potential of −40 V), green corresponds to an energy interval starting at the value of the spacecraft potential (10–20 eV for −10 V and 40–80 eV for −40 V), yellow corresponds to an energy interval starting at 0.5 times the spacecraft potential (5–10 eV for −10 V and 20–40 eV for −40 V), and blue corresponds to an energy interval starting at 0.25 times the spacecraft potential (2.5–5 eV for −10 V and 10–20 eV for −40 V). The horizontal double-headed arrows represent the uncertainty estimates made for the reference simulation, corresponding to a potential of −21 V (and energy intervals scaled accordingly). The tips of the arrows represent the obtained minimum and maximum value, and the thicker part of the arrow represents the region located within the standard deviation. If

**Figure 5.** Simulation results for one instrument pixel (sector 3, elevation 8) from the reference simulation. In (a–d) the result from one single simulation is shown for four different energy intervals. The dashed square is the nominal FOV of the pixel, while the colorscale represents flux of particles at the external boundary that are reaching the pixel from different directions. In (e–h) the mean of 18 simulations is shown and in (i–l) the standard deviation of the same 18 simulations (calculated for each azimuth and elevation in the plot).
Figure 6. Simulation results showing the size of the FOV for 7 different pixels for two spacecraft potentials: $-10$ V (a–g) and $-40$ V (h–n). The horizontal arrows represent the results yielded by the reference simulation (spacecraft potential of $-21$ V), where the thicker part of the arrow represents the region located within the standard deviation and the arrow ends represent the obtained minimum and maximum value. The uncertainty has been calculated from 18 simulations. The vertical lines represent the new simulation result. The colors represent different ion energy intervals, where blue corresponds to an interval starting at 1/4 times the spacecraft potential (2.5–5 eV for $-10$ V and 10–20 eV for $-40$ V). Similarly, yellow, green, and red correspond to an interval starting at 1/2, 1, and 2 times the spacecraft potential, respectively.
the new simulation result, that is, the vertical line, is located within the region covered by the standard deviation, possible differences between this result and the reference simulation result are below the uncertainty level of SPIS, and we consider the results equal. Note that the y-axes in Figure 6 have no physical meaning. The horizontal arrows are put on different levels to enhance visibility. Also note that the x-axis is scaled differently for different panels due to the pixels’ different distortion levels at low energies. Sector 5, elevation 2, is, for example, severely distorted at low energies with a FOV covering more than half the sphere.

In Figure 6 we can see a small trend towards a nonlinear relationship between FOV size and spacecraft potential, especially for the two lowest ion energies. When the potential is $−10$ V the FOV has a tendency to grow in size for the same spacecraft potential-ion energy ratio, compared to the $−21$ V results. The results end up at the higher end of the uncertainty range or above. This trend is visible for most of the pixels. Sector 5, elevation 2, shows a clear trend in the other direction, but this is a severely distorted pixel, and an unpredicted behavior can therefore be expected. Note that the lowest energy interval for a potential of $−10$ V is very low, from 2.5 to 5 eV. For the rest of the analysis we exclude energies below 5 eV to avoid issues with the numerical accuracy SPIS solves for the potential distribution around the spacecraft, which can cause artificial scattering of particles with very low energies due to purely numerical effects. There is therefore a possibility that the results from the lowest energy interval of the $−10$ V case have been affected by such numerical effects, which indeed would enhance the size of the FOV. However, since we see the same trend for the 5–10 eV energy interval, artificial effects are not the sole explanation for this discrepancy. When the spacecraft potential is $−40$ V we instead see a trend towards smaller FOVs for the same spacecraft potential-ion energy ratio, which strengthens the hypothesis of a slightly nonlinear relationship. However, no difference between the simulations is visible for the highest energy interval. We can hence conclude that the conclusion by Bergman et al. (2020) still holds: Above an ion energy corresponding to twice the spacecraft potential the size of the FOV is not significantly affected.

In Table 2 the estimated change in FOV size compared to the reference simulation is listed for the different pixels. Only the results corresponding to the lowest energy interval (1/4 times the spacecraft potential) are shown, since those are most heavily affected. The uncertainty has been calculated assuming the same standard deviation as for the reference simulation. This is not entirely correct since the uncertainty increases when the distortion level increases, and the uncertainty is hence slightly underestimated for the $−10$ V case and slightly overestimated for the $−40$ V case. However, the values listed in Table 2 still gives an indication of the FOV change for different pixels. Apart from the extreme elevation angles of sector 5 (elevation 2 and 14), all pixels behave similarly. The FOV growth compared to the reference simulation is usually around 30–60% for the $−10$ V case, and for the $−40$ V case the FOV is shrinking with about the same amount.

We also study discrepancies related to the position of the FOV. This is done manually through inspection. In Figure 7 an example of how this is done for four different pixels, for the lowest energy interval, is shown. The gray scale corresponds to the standard deviation of each plot pixel calculated from the 18 “uncertainty simulations.” The red line corresponds to the outer edge of the FOV (calculated as 10% of max) obtained by the new simulation. We can discern a small difference in the positioning of the FOV for a couple of the pixels, but no general trend is visible.

Results for the pixels where uncertainty estimates are not available are not shown here, but to verify that these pixels behave in a similar way we estimate the uncertainty level from the closest pixel where such is available. From these estimates we find nothing deviating from the conclusions already drawn. A few pixels show no difference from the reference simulation, while a few exhibit a greater discrepancy than the 30–60% already concluded, but no clear trend within the variations is apparent.

We hypothesize that the observed nonlinearity mainly arises due to the photoemission and bulk flow of the cometary ions. The plasma sheath around an absorbing body like a spacecraft is very complicated and can generally not be described by simple Debye shielding expressions like the well-known potential field around a small isolated charge. In this simple expression the potential at any point would scale linearly with the potential of the isolated charge, and particles traveling through the field with identical initial positions and travel directions would have identical trajectories, provided the initial energy is scaled according to the potential of the isolated charge. Our particle tracing results would then scale linearly with the spacecraft potential. However, for an absorbing spacecraft with complex geometry the situation is not nearly as simple,
Table 2

| Sector | Elevation | Spacecraft potential | Debye length |
|--------|-----------|----------------------|--------------|
|        |           | −10 V                | −40 V        | 0.34 m | 3.4 m |
|        |           | $n_e = 1,000 \text{ cm}^{-3}$ | $n_e = 1,000 \text{ cm}^{-3}$ | $n_e = 3,000 \text{ cm}^{-3}$ | $n_e = 100 \text{ cm}^{-3}$ |
|        |           | $T_e = 8 \text{ eV}$ | $T_e = 8 \text{ eV}$ | $T_e = 6.2 \text{ eV}$ | $T_e = 21.5 \text{ eV}$ |
| 3      | 8         | + (34 ± 18) %        | − (25 ± 18) % | + (113 ± 18) % | − (42 ± 18) % |
| 5      | 2         | − (38 ± 14) %        | − (27 ± 14) % | + (29 ± 19) %  | 0 % |
| 5      | 8         | + (37 ± 20) %        | − (24 ± 20) % | + (129 ± 32) % | 0 % |
| 7      | 8         | + (37 ± 26) %        | − (33 ± 26) % | + (128 ± 26) % | − (52 ± 26) % |
| 0      | 13        | 0 %                  | − (52 ± 28) % | + (178 ± 37) % | − (75 ± 37) % |
| 11     | 14        | + (64 ± 17)%         | − (52 ± 17) % | + (966 ± 17) % | − (70 ± 17) % |

Note: The uncertainty has been calculated assuming the same standard deviation as for the reference simulation. A plus sign means an increase in FOV size and a minus sign a decrease. Only the results corresponding to the lowest energy interval (1/4 times the spacecraft potential) are shown. Also listed are the density ($n_e$) and temperature ($T_e$) of the corresponding electron population.

Our results suggest that there is a small nonlinearity in the relationship between spacecraft potential and FOV distortion at low energies. The discrepancy is, however, small for the studied range of spacecraft potentials and mainly affects the size of the FOV. The main directional information is unchanged. For applications where precise information about the FOV is necessary, for example, for g-factor calculations, the nonlinearity may have to be taken into consideration. For such precise calculations several simulations should also be run and an average of the results calculated to decrease the uncertainty.

4.3. Debye Length

In Figure 8 and Table 2 the results describing the FOV size for different Debye lengths are shown and listed. Panels a–g in Figure 8 show the results for a Debye length of 0.34 m and panels h–n the results for a Debye length of 3.4 m. The uncertainty arrows represent the reference simulation with a Debye length of 0.66 m. It is clear that the Debye length has an influence on the FOV, with an enhanced distortion with a shorter Debye length, and vice versa. An interesting result is, however, that the sensitivity varies substantially between different pixels. Bergman et al. (2020) identified four groups of sectors exhibiting similar behavior in terms of FOV distortion: sectors 2–8, sectors 9–12, sectors 13 and 14, and sectors 15–1. These groups also seem to exhibit similar behavior in terms of sensitivity to variations in the Debye length, and we will discuss them group by group. As already mentioned, sectors 13 and 14 are excluded from the analysis due to the shadowing by the spacecraft.

Sectors 2–8 are sectors located on the upper half of the instrument (i.e., are pointing towards positive z-axis, see Figure 1). For these sectors the sensitivity increases towards the “side” of the instrument, when looking at the instrument from the front (along the y-axis towards negative y). Sector 5 is located on “top”
Figure 7. FOV position for 4 different pixels for two spacecraft potentials: −10 V (a–d) and −40 V (e–h). The red line represents the outer edge of the FOV (calculated as 10% of max), and the grayscale represents the standard deviation of the reference simulation (spacecraft potential of −21 V). See section 4.1 and Figure 5 for details about the standard deviation calculations. The dashed square represents the nominal FOV of the pixel. Only results for the lowest energy interval (1/4 times the spacecraft potential) are shown.
Figure 8. Simulation results showing the size of the FOV for 7 different pixels for two Debye lengths: 0.34 m (a–g) and 3.4 m (h–n). The horizontal arrows represent the results yielded by the reference simulation (Debye length of 0.66 m), where the thicker part of the arrow represents the region located within the standard deviation and the arrow ends represent the obtained minimum and maximum value. The uncertainty has been calculated from 18 simulations. The vertical lines represent the new simulation result. The colors represent different ion energy intervals, where blue, yellow, green, and red represent 5–10, 10–20, 20–40, and 40–80 eV, respectively. The spacecraft potential is $-21$ V.
of the instrument (i.e., close to the positive \( z \)-axis) and was shown by Bergman et al. (2020) to get symmetrically distorted around azimuth. This sector is the least sensitive to changes in the Debye length. For the pixel located in the aperture plane the difference in FOV size is below the uncertainty level of SPIS for a long Debye length and only around 30% for a short Debye length. If we go towards sectors with higher or lower azimuth, the sensitivity gradually increases. The results for sectors 2, 4, 6, and 8 are not shown, but for a short Debye length we estimate a FOV enhancement of 60% for sector 4, 40% for sector 6, and around 600–700% for sectors 2 and 8. Sector 3 and 7 show a FOV enhancement of a bit more than 100%, as listed in Table 2, which makes the relationship clear: sectors located on the side of the instrument are more sensitive to changes in the Debye length than those located on top of it. For a long Debye length the trend is not as clear. Sector 5 still shows no difference from the reference simulation, but the other sectors have a consistent FOV decrease around 40–60% (also pixels not shown).

Sectors 9–12 are generally sensitive to changes in the Debye length. Sector 11 shows an extreme increase in FOV of almost 1,000% when the Debye length is decreased to 0.34 m (observe that the uncertainty range for this FOV increase is highly underestimated in Table 2, since it is based on the uncertainty for the less distorted reference simulation, as described in the previous section). We estimate the increase to be around 800% for sector 12 and 300% for sector 10 (not shown). The FOV of sector 9 shows no change when the Debye length is decreased. This indicates that the sensitivity for the sectors in this group increases towards the "bottom" of the instrument (i.e., towards spacecraft). When the Debye length is increased to 3.4 m we also observe a significant effect on the FOV. For sectors 9 and 10 we estimate a decrease of 20–40%, and for sector 11 and 12 the decrease is around 70%.

For sectors 15–1 we also observe a significant effect on the FOV when decreasing the Debye length. For sector 0 we observe a FOV growth of about 180%, as listed in Table 2. We estimate the increase to be similar (around 200%) for sector 1. The FOV increase for sector 15, however, are estimated to be as much as 700%. This indicates a similar behavior as for the previously mentioned group: The sensitivity increases towards the bottom of the instrument. This group of sectors is characterized by a high sensitivity also at longer Debye lengths. The FOV of sector 0 shrinks with 75% at a Debye length of 3.4 m, and we estimate sectors 1 and 15 to be similar. This group is generally more sensitive to changes towards a longer Debye length than sectors 2–8 and 9–12.

For sector 5 we study the effect on different elevation angles. Extreme elevation angles are often heavily distorted, which makes the analysis difficult. For the rest of the elevation angles we can see a trend towards a lower sensitivity for less distorted pixels. Bergman et al. (2020) identify elevation 10 of sector 5 as the least distorted pixel of the whole instrument. This pixel also seems to be insensitive to changes in the Debye length, with no observable FOV change for neither short nor long Debye lengths. The same is true for elevation 12. For elevation 14 we start to see an influence for short Debye lengths. In the other direction elevation 8, 6, and 4 show an estimated FOV increase at short Debye lengths of 30%, 130%, and 90%, respectively. For a long Debye length the difference is below the uncertainty level for elevation 8 and 6, and for elevation 4 the decrease is around 80%.

In Figure 9 we analyze the FOV position for a few pixels at the lowest energy interval. For a short Debye length the enhanced distortion makes this type of analysis difficult for some of the pixels, but we can clearly see for a long Debye length that the position of the FOV is affected. The FOV both shrinks in size and gets displaced. The amount of degrees the position changes differs between the pixels. Generally, we observe a larger displacement for pixels that also is heavily affected in terms of FOV size. For sector 11 we estimate the FOV to be displaced by as much as 20 degrees in elevation, compared to the reference simulation. We also observe a shift in different directions for the short and long Debye length, where the FOV for a Debye length of 0.34 m shifts towards lower elevations, while at a Debye length of 3.4 m it shifts towards higher elevations.

Differences in FOV size and position due to different Debye lengths mainly appear at low energies. However, for some pixels we observe a small effect also at higher energies, which means that the distortion level at an energy of twice the spacecraft potential may be slightly lower or higher, depending on the Debye length. However, we estimate the difference from the results by Bergman et al. (2020) to be small, and the limit for a distortion that is not significant can for most applications still be set to an ion energy of twice the spacecraft potential.
**Figure 9.** FOV position for 4 different pixels for two Debye lengths: 0.34 m (a–d) and 3.4 m (e–h). The red line represents the outer edge of the FOV (calculated as 10% of max), and the grayscale represents the standard deviation of the reference simulation (Debye length of 0.66 m). See section 4.1 and Figure 5 for details about the standard deviation calculations. The dashed square represents the nominal FOV of the pixel. Only results for the lowest energy interval (5–10 eV) are shown.
A varying sensitivity between different pixels to a changing Debye length is not surprising. The Debye length not only determines the distance of the potential surfaces to the spacecraft. It also, to some extent, determines the shape of the surfaces. For a short Debye length the potential surfaces are shaped after the spacecraft structures, while for a long Debye length the surfaces have a smoother shape. Depending on a particle’s trajectory through this field, it will be more or less affected by the differently shaped surfaces. A particle passing through more or less parallel to the direction of the electric field will be less affected by the shapes of the surfaces compared to a particle passing through close and parallel to, for example, a spacecraft surface.

4.4. Detailed Spacecraft Model

To investigate the possible influence of a more detailed spacecraft model on the particle tracing results, we add MIRO and RPC-IES to our model and do the comparison for the pixels shown in Figure 4b. Uncertainty estimates are available for three pixels. The result for these pixels is shown in Figure 10.

Panels a and b correspond to the pixels with a FOV in the vicinity of MIRO. Sector 1, elevation 4, is looking directly at MIRO, while sector 2, elevation 7, has a FOV very close to MIRO without looking directly at the instrument. We observe a small effect on the pixel looking directly at MIRO at the three highest energy intervals. For the lowest energies, this pixel is heavily shadowed by other parts of the spacecraft body, which probably limits the influence of additional structures on these energies. On sector 2, elevation 7, we see no influence, indicating that only pixels directly shadowed by an additional structure will be affected by it. For the rest of the pixels (not shown) we see an effect on elevation 8 of sector 1 and elevation 5 of sector 2. These are pixels that partly are directly shadowed by MIRO. We also see a small effect at low energies for elevation 8 of sector 1. This pixel is not directly shadowed by the instrument, indicating a small focusing effect. For this pixel the FOV grows slightly towards lower elevations, indeed indicating that ions passing above MIRO are guided into RPC-ICA. For the rest of the pixels no such effects are, however, visible.

Panel c corresponds to a pixel looking directly at RPC-IES. No influence on the FOV is observable for this pixel. However, for sector 8, elevation 6, we observe an effect on the FOV for low energies (not shown). The FOV grows towards lower elevations and azimuth when RPC-IES is added to the model. This pixel is not looking directly at RPC-IES, indicating that a focusing effect is responsible for the observed discrepancy. No effects are observed for the other studied pixels.

It is possible that the sensitivity to details in the spacecraft model is dependent on the Debye length. A shorter Debye length may increase the sensitivity since the potential surfaces are to a greater extent shaped after the spacecraft structures, but this effect has not been investigated.

4.5. Photoemission

A factor not treated so far is the distance of the spacecraft to the Sun. For all simulations presented in this paper the distance to the Sun is set to 1.7 AU. A different distance will affect the photoemission from the spacecraft, in turn altering the spacecraft potential and the amount of photoelectrons in the surrounding environment. In section 4.2 we showed that the photoemission has an influence on the potential field around the spacecraft, at least when comparing different spacecraft potentials. There is therefore a possibility that different heliocentric distances would affect the particle tracing results. To investigate if the effect is significant, we run two additional simulations where the distance to the Sun is set to the maximum and minimum value encountered by Rosetta (3.6 and 1.24 AU, respectively). We keep the spacecraft potential at $-21$ V for both simulations. We observe no differences between the simulation results and conclude that this effect can be neglected. It is, however, possible that a less negative spacecraft potential is more sensitive to changes in the photoemission, as concluded in section 4.2. For further details about the photoemission of Rosetta throughout the mission, see Johansson et al. (2017).

5. Conclusions

In this study we used the SPIS software to investigate the influence of different spacecraft potentials and Debye lengths on the low-energy FOV distortion of RPC-ICA on Rosetta. We also investigated the sensitivity of the simulation results to a more detailed spacecraft model. The results show the following:

1. A small nonlinearity exists in the relation between FOV distortion and spacecraft potential, that is, the same ratio between the ion energy and the spacecraft potential does not necessarily yield identical
distortions for different spacecraft potentials. This nonlinearity is mainly caused by the photoemission and the bulk flow of the cometary ions. The nonlinear factor is however small and mainly affects the size of the FOV, and for most applications a linear approximation is adequate. The nonlinearity is only observed at the lowest energies, and the distortion is still insignificant at an ion energy above twice the spacecraft potential, as concluded by Bergman et al. (2020).

2. The FOV distortion at low energies is dependent on the Debye length. A short Debye length generally results in a more severe distortion than a long Debye length. The sensitivity to different Debye lengths, however, varies substantially between different instrument pixels. For some pixels we observe an effect also at energies around twice the spacecraft potential, but the effect is small and for most applications the distortion can be considered insignificant at these energies.

3. The simplified spacecraft model is adequate for most instrument pixels. Pixels directly shadowed by an additional structure can suffer from additional distortions, and we observe focusing effects for a couple of pixels located in the vicinity of an added structure. The majority of the pixels not directly shadowed are, however, not affected.

The results show that the FOV distortion due to spacecraft charging of an in situ instrument measuring low-energy charged particles is complex and often strongly geometry dependent. Some of the results can, however, be generalized and applied to other spacecraft. We assume that the energy limit of twice the value of the spacecraft potential holds for other spacecraft as well, provided the geometry of the new system does not cause a more complex distortion than for RPC-ICA. Furthermore, a linear relationship between FOV distortion, spacecraft potential, and ion energy can generally not be assumed, and a short Debye length of the surrounding plasma generally results in more severe distortions.

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