Understanding Mass Resolution of Foil-Based Time-of-Flight Mass Spectrometry

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Abstract The fractional mass uncertainty of linear, foil-based time-of-flight space instruments is affected by the energy, path length, and timing uncertainties. Carbon foils are typically used in time-of-flight instruments to generate secondary electrons, but carbon foils also add unwanted effects to the instrument response. We present a complete characterization that studies the extent to which carbon foils degrade the mass resolution by parameterizing each component of the fractional mass uncertainty. Using the parameterization, the limiting factors of the fractional mass resolution are determined for a range of incident ion energies. The parameterization can be used as a tool for instrument developers to quickly assess the mass resolution and possibly mitigate the limiting factors of the mass resolution.

1. Introduction

Direct measurement of plasma composition is critical for understanding Earth's magnetosphere and ionosphere along with dynamics of solar wind particles. Plasma compositional variation over time and phase space provides insight into the structure, dynamics, and coupling for application to space weather and solar physics. A proven technique for distinguishing common ions in space plasmas is time-of-flight (TOF) mass spectrometry (Allegretti et al., 2016; McComas et al., 2004; Wüst, 1998). Examples of successful implementation of this technique include: NASA Van Allen Probes/Helium-Oxygen-Proton-Electron (HOPE) (Funsten et al., 2013), Advanced Composition Explorer (ACE)/Solar Wind Ion Composition Spectrometer (SWICS) (Gloeckler et al., 1998), Cluster/ion Composition and Distribution Function analyser (CODIF) (Möbius et al., 1998; Rème et al., 1997), and Juno/Jovian Auroral Distributions Experiment (JADE) (McComas et al., 2017). Measurement of ion composition has contributed significantly to our current understanding of magnetospheric structure, energization and loss mechanisms, and associated hazards in space.

However, many questions remain unanswered regarding the source and evolution of heavy ion species in space (Denton et al., 2016; Gallagher & Comfort, 2016; Ilie & Liemohn, 2016; Kronberg et al., 2014; Welling & Liemohn, 2016). For example, there is continued debate over the formation mechanism for the oxygen torus (Nosé et al., 2015), a region of enhanced O⁺ density over a limited range of L-shell (Chappell, 1982). Recent modeling results combined with a revival of the older literature provide strong evidence that the lack of N⁺ measurements limits our understanding of major structures and dynamic processes in space (Ilie & Liemohn, 2016). Ionospheric outflow, a primary source of heavy ions in magnetosphere, has been a topic of significant interest for decades. However, the community lacks a detailed, self-consistent ionospheric outflow model (Welling & Liemohn, 2016)—we do not fully understand ion outflow for primary ions such as O⁺, much less for minor ions such as N⁺. Once N⁺ reaches the magnetosphere, we do not understand its influence on geomagnetic storms nor the processes by which it is lost (Ilie & Liemohn, 2016; Liu et al., 2005). In addition to the science questions, it is also important to quantify the presence of oxygen in the near-Earth space environment due to its potential for causing significant damage to spacecraft (Banks et al., 2004; Fernandes et al., 2015; Paillas, 1993; Tahara et al., 1995; Tennyson, 1993), which is of sufficient interest to satellite operators (e.g., Brinza, 1993; Roussel & Bourdon, 2000).

There are also many unanswered questions about the origins of solar wind, energetic particles, and the nature of the interstellar medium, which can be addressed by resolving the mass and charge states of heavy ions. Study of the high-charge state ions is of great importance as they allow us to link the observed solar wind to source regions on the Sun (e.g., Feldman et al., 2005; Zhao et al., 2009). Their relative abundances, established in the chromosphere, inform us about the acceleration mechanisms of the solar wind, and their charge state ratios provide information on the temperature profile of the corona (e.g., Feldman...
et al., 2005; Laming, 2015; Von Steiger et al., 2000). Pickup ions originate from interstellar neutrals and from an as-yet to be identified “inner source”, most likely dust grains near the Sun (Gloeckler & Geiss, 1998). These pickup ions inform us about the nature of the interstellar medium (e.g., Sokół et al., 2019; Zank et al., 2018), and they are also postulated to be a seed population for interplanetary suprathermal ions and energetic particles (e.g., Kollman et al., 2019; Mason, 2013). In order to make the measurements necessary to address outstanding science questions in space physics, it is important to continue developing and refining mass spectrometry techniques.

A basic example of a linear, foil-based TOF mass spectrometer is shown in Figure 1a. The energy-per-charge of the incident ions is typically selected using an electrostatic analyzer (ESA). The selected ions are then post-accelerated to foil $F$ and, subsequently, enter the drift box. In (a), the secondary electron generated at foil $F$ is detected on $D_1$, which starts the timer for the TOF measurement. The timer stops when the ion reaches the stop detector. In (b), the selected ion from the top-hat ESA generates a secondary electron at foil $F$, which is detected on CEM $D_1$. Once the ion reaches the stop surface, it generates another secondary electron, which is detected on CEM $D_2$ and stops the timer. In (c), the secondary electron generated at the foil $F$ is detected on the MCP, which starts the timer. The ion is then detected on the SSD and generates another secondary electron that is detected on the MCP and stops the timer.

Two implementations of this technique are shown in Figures 1b and 1c. Figure 1b schematically shows the HOPE mass spectrometers (Funsten et al., 2013) aboard the Van Allen Probes (Mauk et al., 2013). In this implementation, the ESA is a top-hat analyzer (Carlson et al., 1982), start detector $D_1$ is a channel electron multiplier (CEM), and the stop detector is replaced with a stop surface that generates a secondary electron measured by stop CEM $D_2$. One variation of this technique replaces the stop surface with a solid-state detector (SSD), which yields a total energy measurement and thus enables determination of the ion’s charge state; a variant of this design was implemented on the SWICS aboard the ACE using a small-angle deflection ESA (Gloeckler et al., 1998).

Figure 1c shows another example of a TOF mass spectrometer. This design was implemented on the implanted ion spectrometer on the GIOTTO payload (Wilken et al., 1987) and more recently on the Medium-Energy Particle experiments-ion mass analyzer aboard the exploration of Energization and Radiation in Geospace mission (renamed Arase postlaunch) (Yokota et al., 2017). Here the ion exiting the top-hat ESA is accelerated to the carbon foil $F$ where it generates a secondary electron that is measured
by the microchannel plate (MCP), which starts the timer. The incident ion on the foil carries much more energy than the secondary electron it generates and, thus, travels in a straight-line trajectory to the SSD where it generates another secondary electron, which is detected on the MCP and stops the timer. After accounting for the signal loss due to the nuclear stopping power, the SSD provides an additional measurement of the ion energy in the drift box, which is not necessary for the ion mass-per-charge measurement.

For linear TOF instruments, such as those shown in Figure 1, the ion mass \( m \) is determined from the velocity and energy measurements:

\[
m = 2E_f \left( \frac{t}{d} \right)^2 \tag{1}
\]

where \( E_f \) is the final kinetic energy of the particle at the exit surface of the foil (this includes any energization from the acceleration voltage and energy losses from traversing the foil), \( t \) is the TOF measurement, and \( d \) is the path length over which the TOF is measured. The mass resolution is defined as \( m/\delta m \) where, for this study, \( \delta m \) is the full-width at half maximum (FWHM) of the mass peak. The spread in the mass peak \( \delta m \) is traditionally taken at the 50% level; however, we note that for species with different abundances, for example, hydrogen and helium ions, separation at the 50% level might not be sufficient to distinguish these ion species.

To obtain an expression for the mass resolution from Equation 1, we must quantify \( \delta m \). The quadrature sum is typically used to calculate the uncertainty in a particular variable; for example, for a function \( f(x,y) \), the uncertainty \( \delta f \) is (e.g., Taylor, 1982)

\[
\delta f = \sqrt{\left( \frac{\partial f}{\partial x} \right)^2 \delta x^2 + \left( \frac{\partial f}{\partial y} \right)^2 \delta y^2 + 2 \frac{\partial f}{\partial x} \frac{\partial f}{\partial y} \delta(x,y)} \tag{2}
\]

where \( \delta x \) and \( \delta y \) are the uncertainties in \( x \) and \( y \), respectively, and \( \delta(x,y) \) is the covariance. The covariance is a measure of the correlation between two variables; for example, if two variables are independent, the covariance term approaches zero. The upper bound on Equation 2 is derived using the Schwarz inequality, which allows \( \delta(x,y) \) to be rewritten as the product of \( \delta x \) and \( \delta y \). This upper limit describes the maximum uncertainty in a simplistic equation that is always valid regardless of whether the variables are correlated. For a function \( f(x,y) \), the upper bound is (e.g., Taylor, 1982)

\[
\delta f \leq \left| \frac{\partial f}{\partial x} \right| \delta x + \left| \frac{\partial f}{\partial y} \right| \delta y. \tag{3}
\]

Equation 3 is applied to the mass equation for a TOF mass spectrometer (Equation 1) to calculate the maximum fractional mass uncertainty:

\[
\frac{\delta m}{m} \leq \frac{1}{m} \left( \left| \frac{\partial m}{\partial E_f} \right| \delta E_f + \left| \frac{\partial m}{\partial d} \right| \delta d + \left| \frac{\partial m}{\partial t} \right| \delta t \right) = \left( \frac{\delta E_f}{E_f} \right) + 2 \left( \frac{\delta d}{d} + \frac{\delta t}{t} \right). \tag{4}
\]

The three components of the fractional mass uncertainty \( (\delta m/m) \) are defined as follows: fractional energy uncertainty \( (\delta E_f/E_f) \), fractional path length uncertainty \( (\delta d/d) \), and fractional timing uncertainty \( (\delta t/t) \).

Below, for simplicity, we drop the word “fractional” when referring to each uncertainty (i.e., fractional mass uncertainty is referred to as mass uncertainty).

Although carbon foils have proven to be essential for TOF mass spectrometry (Allegrini et al., 2016; McComas et al., 2004; Wüest, 1998), the foils add additional uncertainty to the mass measurement (McComas et al., 1990). Energy loss and straggling as well as the angular scattering of ions that traverse a carbon foil degrade the mass resolution (Allegrini et al., 2006, 2014; Ebert et al., 2014; Funsten et al., 1993; McComas et al., 2004). In Equation 4, the energy loss and straggling out of the carbon foil contributes to \( \delta E_f/E_f \) whereas the angular scattering of ions affects \( \delta d/d \). Employing thinner foils minimizes these foil effects and enhances the measurement precision of the incident particle energy or speed (Allegrini et al., 2006, 2014; Ebert et al., 2014; Funsten et al., 1993; McComas et al., 1990; Vira et al., 2020). However, limited effort has
gone into quantifying the extent to which carbon foils degrade the mass resolution of space-based instruments that employ this TOF technique.

In this study, we characterize the contributions of the energy, timing, and path length uncertainties to the overall mass uncertainty (Equation 4) for a linear, foil-based TOF mass spectrometer in order to quantify the interplay between the factors driving the mass uncertainty. We simulate distributions for energy loss and straggling as well as the angular scattering through a carbon foil using the Monte-Carlo particle-interaction code SRIM (Stopping Range of Ions in Matter) (Ziegler et al., 1985). Using the simulated distributions, each component of the mass uncertainty is parametrized. The result of this study is a tool available to instrument developers that calculates the factors driving the mass uncertainty of a TOF instrument. By quantifying the contributions to the overall mass uncertainty, the tool enables TOF instrument design choices that minimize the mass uncertainty and thus optimize the mass measurement.

Although the tool provided in this study is specifically focused on foil-based TOF instruments, with minor modifications, a similar technique can be applied to determine the driving mass uncertainty factors of other types of TOF instruments. For example, in gated TOF instruments (Radionova et al., 2016; Wüest, 1998; Yokota, 2018), the mass uncertainty is still described by Equation 4, but the energy and angular degradation is driven by the gating technique rather than the carbon foil. Similarly, for instruments that use start surfaces instead of carbon foils to create secondary electrons (e.g., Barabash et al., 2009; Collier et al., 2001), Equation 4 is again applicable but the energy and angular losses would instead be characterized for the start surface (Stude et al., 2016).

We also note that to achieve a mass resolution \( m/\delta m \) of >8 in a TOF-based mass spectrometer, researchers have employed a linear electric field (LEF) or other type of reflectron geometry in which the exit ions from the start foil enter a tuned electric field that causes them to undergo “time focusing,” which can greatly increases the mass resolution (McComas et al., 1990). For example, the ion mass spectrometer on the Cassini mission was a foil-based TOF mass spectrometer that employed an LEF scheme and achieved a mass resolution of ~60 (Nordholt et al., 1998; Young et al., 2004). However, such instruments are complex and resource intensive while also having a low sensitivity because these instruments rely on the incident ions exiting the start foil as a positive ion, which occurs <50% of the time depending on the incident energy and species (Allegrini et al., 2014; Bürgi et al., 1990; Bürgi et al., 1993; Funsten, Barracough, & McComas, 1993). Thus, there is still a need for linear, foil-based TOF instruments, and it is important to understand the factors that limit their mass resolution. In this study, we restrict our analysis to linear TOF instruments, although the parameters that drive the mass uncertainty in reflectron systems are the same as described here, albeit in a more intricate manner.

2. Fractional Mass Uncertainty Components

For foil-based TOF mass spectrometers, there are three components to the mass uncertainty: energy \( \delta E/E_f \), path length \( \delta d/d \), and timing \( \delta t/t \) uncertainties (defined in Equation 4), which we characterize in this section. First, we discuss the two parameters that comprise the energy uncertainty: the ESA energy passband and energy loss and straggling through the foil. We then examine the path length uncertainty which is determined from the angular scattering distribution through the carbon foil. Lastly, we discuss the energy-independent estimate for the timing uncertainty.

2.1 Fractional Energy Uncertainty

As shown in Figure 1, ions incident on a TOF instrument first pass through the ESA, which filters the ions by the energy-per-charge. The selected ions are then accelerated toward an ultrathin carbon foil, traverse the foil, and subsequently enter the drift box (Figure 1). We define \( E_i \) as the ion energy incident on the carbon foil:

\[
E_i = E_0 - qV_{\text{post}}
\]  

where \( E_0 \) is the average ion energy exiting the ESA prior to post-acceleration, \( q \) is the charge of the incident ion, and \( V_{\text{post}} \) is the post-acceleration voltage used to accelerate the ions toward the foil. The final average energy \( E_f \) of the ions entering the TOF drift box is as follows:
\[ E_f = (E_0 - qV_{post}) - E_{loss} \]  

where \( E_{loss} \) is the average energy lost by an ensemble of ions traversing a carbon foil.

The energy uncertainty \( \delta E_f / E_f \) is derived by propagating the error through Equation 5 using the upper bound uncertainty (Equation 3), which results in:

\[
\frac{\delta E_f}{E_f} \leq \frac{1}{E_f} \left( \frac{\partial E_f}{\partial E_0} \delta E_0 + \frac{\partial E_f}{\partial E_{loss}} \delta E_{loss} \right) = \frac{\delta E_0}{E_f} + \frac{\delta E_{loss}}{E_f}
\]

where \( \delta E_0 \) is the FWHM of the ESA energy bandpass and the energy straggling (\( \delta E_{loss} \)) is defined as the FWHM of the energy loss distribution through the foil. Note that the post-acceleration voltage is assumed to be accurately known and thus its uncertainty is zero, a reasonable assumption for modern instrumentation. We refer to \( \delta E_f / E_f \) as the energy uncertainty, \( \delta E_0 / E_0 \) as the ESA energy uncertainty, and \( \delta E_{loss} / E_f \) as the energy loss and straggling uncertainty.

The ESA typically has a narrow passband characterized by \( \delta E_0 / E_0 \), which affects the ESA energy uncertainty \( \delta E_0 / E_f \). We note that the ESA passband \( \delta E_0 / E_0 \) has historically been referred to as the energy resolution, but in this manuscript, we call this quantity the ESA passband. For this analysis, we assume that ESA passband \( \delta E_0 / E_0 \) is constant with ion energy. One could account for an energy-dependent ESA by parameterizing the \( \delta E_0 \) term in Equation 7.

Ions traversing the foil lose some energy through Coulombic collisions with the carbon atoms and electronic interactions with the electrons within the foil. This energy loss is energy dependent: the fractional energy loss is greater at lower energies than at higher energies. We simulate the particle interaction using SRIM, which implements a binary collision approximation to track the trajectories of atomic projectiles as they penetrate materials (Ziegler et al., 1985). Within SRIM, a comprehensive program called TRIM (Tracking Range of Ions in Matter) is included. This program calculates the energy of the ions exiting the foil along with the kinetic phenomena associated with ion energy loss. The energy loss and straggling were modeled using TRIM through carbon foils with a thickness of 80 Å, a typical carbon foil thickness assuming a density of 2.253 g cm\(^{-3}\) (Bhattara et al., 2017). Figure 2 shows histograms of ion energies exiting the foil for 30 keV hydrogen (green), helium (purple), and oxygen (black) incident ions. The vertical dashed lines represent \( E_f \), while \( \delta E_{loss} \) is shown by the horizontal arrow for each ion species. The average energy loss and width of the distribution is determined by empirically fitting the distributions to a skewed Gaussian to account for the asymmetric tail for low energy ions.

**Figure 2.** Histograms of the transmitted energy \( E_{f,j} \) for 30 keV hydrogen (green), helium (purple), and oxygen (black) ions through a carbon foil (thickness of 80 Å). These histograms are generated from TRIM and simulated using 40,000 incident particles. The average final energy \( E_f \) and FWHM \( \delta E_{loss} \) are shown by the vertical dotted lines and arrows (color coded by particle species), respectively. For 30 keV protons, the average energy loss \( E_{loss} \) is 1.14 keV and the energy loss width \( \delta E_{loss} \) is 0.83 keV; for helium ions, \( E_{loss} \) is 1.39 keV and \( \delta E_{loss} \) is 1.38 keV; for oxygen ions, \( E_{loss} \) is 3.08 keV and \( \delta E_{loss} \) is 2.43 keV.
Angular scattering distributions are conventionally parameterized in terms of the scattering half-angle $\psi_{1/2}$. TRIM is used to reproduce the laboratory characterization of carbon foils and empirical determination of the scattering half-angle. The angular scattering distribution and the associated scattering half-angle are useful metrics for characterizing the thickness of a foil (Fernandes et al., 2019; Funsten et al., 1992, 1993, 1994; Funsten & Shappirio, 1997; Högberg & Norden, 1970). In laboratory experiments, the scatter distribution through a carbon foil is typically measured on an MCP (Ebert et al., 2014; Funsten et al., 1993; Vira et al., 2020). The measured distribution is then fitted to a cylindrically symmetric Gaussian, which is the expected shape of the distribution (Hanle & Kleinpoppen, 1979), to determine the scattering half-angle.

We use the simulation software TRIM to reproduce the laboratory characterization of carbon foils and empirical determination of the scattering half-angle. TRIM is used to track the lateral positions, depth, and velocities of each ion as it exits a material. We model various ion species through an 80 Å carbon foil with incident energies between 7 and 60 keV to acquire the angular scattering distributions. Mirroring the technique used in laboratory measurements, we fit the distributions to a cylindrically symmetric Gaussian to determine the scattering half-angle. We use the scattering half-angle to determine the path length uncertainty—a novel application of this quantity.

Figure 3a shows a 2D plot of the TRIM-determined scatter distribution for 10 keV oxygen ions passing through an 80 Å carbon foil. The ion trajectories are propagated out to a distance of 40 mm from the exit surface of the foil, analogous to the foil-MCP distance used in laboratory experiments. Figure 3b shows a vertical collapse of the scatter distribution from Figure 3a where the red line is a Gaussian fit to the collapsed distribution. The HWHM from the Gaussian fit is proportional to the scattering half-angle; for this simulation, the scattering half-angle is 13.1°. We note that the distribution shown in Figure 3a is cylindrically symmetric so the resulting calculations of the scattering half-angle from vertical or horizontal collapses are the same.

The angular scattering distribution and the associated scattering half-angle are useful metrics for characterizing the thickness of a foil (Fernandes et al., 2019; Funsten et al., 1992; Vira et al., 2020) but are not adequate for quantifying how angular scattering degrades the TOF measurement. To quantify the impact of the path length uncertainty on the instrument response, the probability distribution of ions exiting the foil must be calculated. The probability distribution describes the most probable scattering angle for an ensemble of
particles, and it is calculated by multiplying the scatter distribution with the solid angle. The path length resolution can then be calculated directly from the probability distribution for an ensemble of ions.

In Figure 4a, the probability density of the scattering angles simulated in TRIM is shown for 10 keV oxygen ions passing through an 80 Å carbon foil. The most probable path length \( d \) is calculated from \( \theta_0 \), the angle associated with the peak of the probability distribution, using \( d = L / \cos(\theta_0) \) where \( L \) is the length of the TOF system. The quantity \( \delta d \) is the estimated FWHM of the probability distribution, defined in terms of the lower bound \( \theta_- \) and upper bound \( \theta_+ \) (shown in Figure 4a). The path length uncertainty is therefore:

\[
\frac{\delta d}{d} = \cos(\theta_0) \left[ \frac{L}{\cos(\theta_-)} - \frac{L}{\cos(\theta_+)} \right] = \cos(\theta_0) \left[ \frac{1}{\cos(\theta_-)} - \frac{1}{\cos(\theta_+)} \right].
\]  

(9)

Note, this expression is independent of the length of the drift box \( L \) so it is universally applicable to any linear, foil-based TOF instrument. The comparison of the probability densities for hydrogen (green), helium (purple), and oxygen (black) ions are shown in Figure 4b. At the same incident energy, the probability density of the angular scatter distribution for increasingly heavy ions is characterized by a significantly higher angle of the distribution maximum as well as a wider angular width, both of which are expected based on scattering theory and experiment at keV energies (Funsten et al., 1993; Meyer 1971).

The path length uncertainty is calculated from the TRIM scatter distributions using Equation 9. Figure 5 shows (a) the scattering half-angle (left vertical axis) and path length uncertainty (right vertical axis) as a function of the scattering half-angle for 40,000 oxygen ions at 10 keV.

Figure 4. (a) Probability density of the scattering angle for 40,000 10 keV oxygen ions passing through an 80 Å carbon foil, determined from TRIM. The maximum probability occurs at \( \theta_0 \); the lower bound and upper bounds of the estimated FWHM are \( \theta_- \) and \( \theta_+ \), respectively. (b) Probability density for 40,000 10 keV hydrogen (green), helium (purple), and oxygen (black) ions as a function of the scattering angle. At a given energy, oxygen ions have a significantly wider angular scatter distribution than hydrogen or helium ions.
function of the incident energy on the foil $E_i$ and (b) path length uncertainty as a function of the scattering half-angle for hydrogen (green), helium (purple), and oxygen (black) ions. A single relationship between the path length uncertainty and scattering half-angle is observed for all ion species (Figure 5b, gray line):

$$\frac{\delta d}{d} \approx 3.46 \cdot 10^{-4} \psi_{1/2}^{2.11}. \quad (10)$$

This empirical power law relationship can be used to approximate the contribution of the scattering half-angle to the path length uncertainty independent of ion species. The simulation results shown in Figure 5a provide the path length uncertainty values that are propagated through the mass uncertainty (Equation 4).

### 2.3 Fractional Timing Uncertainty

The timing uncertainty $\delta t/t$ includes the precision of the timing circuit, size of the TOF bins, and the time difference between the start and stop signals from the TOF measurement. The electronic precision and TOF bins contribute to $\delta t$ while $t$ is the time difference in the TOF measurement. We estimate the TOF measurement $t$ from the shortest TOF measurement, which occurs at the highest energy for a particular instrument. We use the shortest TOF measurement because that results in the largest timing uncertainty. For example, for the HOPE mass spectrometers, the TOF bin size is 2.5 ns and the electronic precision is $\leq 1$ ns in each channel (Funsten et al., 2013), leading to a $\delta t$ of $\sim 3$ ns. The shortest TOF measurement is $\sim 20$, $\sim 30$, and $\sim 50$ ns for hydrogen, helium, and oxygen ions, respectively (Funsten et al., 2013); note that these timing values are taken at the largest ESA acceptance energy, which is 50 keV. The largest values of the timing uncertainty for HOPE are summarized in Table 1.

HOPE did not require a low $\delta t$ so, for other instruments, $\delta t$ is considerably less than $\sim 3$ ns. For example, for ACE/SWICS, the electronic precision and TOF bin size results in a $\delta t$ of $\sim 0.5$ ns (Gloeckler et al., 1998). The shortest TOF measurement is $\sim 30$, $\sim 50$, and $\sim 100$ ns for hydrogen, helium, and oxygen ions, respectively (Gilbert et al., 2014; Gloeckler et al., 1998). Note that the shortest TOF measurements correspond to an energy of $\sim 60$ keV. Table 1 summarizes the largest values of the timing uncertainty based on SWICS. We use the timing uncertainty values from SWICS for the remaining calculations presented in this manuscript.

| Species | Shortest TOF $t$ | $\delta t/t$ (for $\delta t = 3$ ns) | Shortest TOF $t$ | $\delta t/t$ (for $\delta t = 0.5$ ns) |
|---------|-----------------|---------------------------------|-----------------|---------------------------------|
| $H^+$   | $\sim 20$ ns    | 0.15                            | $\sim 30$ ns    | 0.017                           |
| $He^+$  | $\sim 30$ ns    | 0.10                            | $\sim 50$ ns    | 0.010                           |
| $O^+$ (or $N^+$) | $\sim 50$ ns | 0.06                            | $\sim 100$ ns   | 0.005                           |

Table 1: Fractional Timing Uncertainty $\delta t/t$ for Hydrogen, Helium, and Oxygen Ions for HOPE and SWICS
Figure 6. (a) Path length uncertainty $\delta d/d$, (b) energy straggling $\delta E_{\text{loss}}$ and (c) average energy loss $E_{\text{loss}}$ as a function of energy incident on a foil for hydrogen (green), helium (purple), nitrogen (brown), and oxygen (black) ions. The data shown in all subplots result from TRIM simulations. The dashed lines show power law fits for each ion species, with fit parameters provided in Table 2.

Table 2

|       | H    | He   | N    | O    |
|-------|------|------|------|------|
| $\delta d/d$ | $0.20 E_i^{-2.04}$ | $0.74 E_i^{-2.05}$ | $8.27 E_i^{-2.03}$ | $8.96 E_i^{-2.00}$ |
| $\delta E_{\text{loss}}$ | $0.54 E_i^{-0.12}$ | $0.71 E_i^{-0.20}$ | $0.59 E_i^{-0.43}$ | $0.75 E_i^{-0.35}$ |
| $E_{\text{loss}}$ | $0.33 E_i^{-0.36}$ | $0.28 E_i^{-0.47}$ | $1.19 E_i^{-0.29}$ | $1.43 E_i^{-0.23}$ |

Because these values are more representative of the timing precision required for a modern, high-resolution mass spectrometer. This allows us to ignore any energy variation of the TOF measurements to reduce the complexity of the analysis shown in Section 3.

### 3. Parameterization of Fractional Mass Uncertainty

We have used TRIM simulations to estimate the energy and path length uncertainties and previous flight instruments to estimate the timing uncertainty. We can substitute the energy uncertainty (Equation 7) into the expression for mass uncertainty (Equation 4) and rewrite the mass uncertainty as:

$$\frac{\delta m}{m} \leq \frac{\delta E_0}{E_f} + \frac{\delta E_{\text{loss}}}{E_f} + 2 \left( \frac{\delta d}{d} + \frac{\delta t}{t} \right)$$  \hspace{1cm} (11)

where again, $\delta E_0$ is the FWHM of the ESA energy bandpass, $E_f$ is the average ion energy exiting the foil, $\delta E_{\text{loss}}$ is the energy straggling defined as the FWHM of the energy loss distribution through the foil, $\delta d/d$ is the path length uncertainty, and $\delta t/t$ is the timing uncertainty. The estimates of fractional energy, path length, and timing uncertainties described in Section 2 are used to calculate the mass uncertainty for four ion species: hydrogen, helium, nitrogen, and oxygen. We introduce nitrogen as a relevant species for assessing the ability to separate species in the C+/N+ /O+ group, which is important for addressing pressing questions in the space physics community (Ilie & Liemohn, 2016).

We parametrize each component that is affected by carbon foils as a function of the incident energy $E_i$ to quantify the driving factors of the mass uncertainty. Figure 6 shows the (a) path length uncertainty $\delta d/d$, (b) energy straggling $\delta E_{\text{loss}}$ and (c) average energy loss $E_{\text{loss}}$ as a function of incident energy on the foil $E_i$ for hydrogen (green), helium (purple), nitrogen (brown), and oxygen (black) ions. Power law fits to the data (shown in the dashed lines) are provided in Table 2 where energy is in units of keV. The fit results are used to calculate the components of the mass uncertainty for a particular energy incident on the foil.

As shown in Figure 6a, the path length uncertainty decreases as the ion energy incident on the foil increases. This is as expected, since ions scatter less as the energy increases (Figure 5a). In Figures 6b and 6c, the FWHM of the energy loss distribution $\delta E_{\text{loss}}$ and average energy loss $E_{\text{loss}}$ through the foil both increase as the incident energy increases. For example, for 7 keV protons passing through a foil, $E_{\text{loss}}$ is 0.62 keV and $\delta E_{\text{loss}}$ is 0.65 keV, whereas for 60 keV protons, $E_{\text{loss}}$ is 1.34 keV and $\delta E_{\text{loss}}$ is 0.85 keV. Although the average energy loss $E_{\text{loss}}$ is larger for 60 keV protons than for 7 keV protons, the fractional energy loss (i.e., $E_{\text{loss}}/E_i$) is larger at 7 keV than at 60 keV, which agrees with our expectation (Bohr, 1948). The same argument explains the $\delta E_{\text{loss}}$ dependence on energy (Figure 6b).

The mass uncertainty can be written in terms of the ESA width $\delta E_0$ and ion energy incident on the foil (Equation 5: $E_i = E_0 + qV_{\text{post}}$) by combining the parametrizations from Table 2 with Equations 5 and 11:

$$\frac{\delta m}{m} |E_i, \delta E_0| \approx \frac{\delta E_0}{E_i - E_{\text{loss}}[E_i]} + \frac{\delta E_{\text{loss}}[E_i]}{E_i - E_{\text{loss}}[E_i]} + 2 \frac{\delta d}{d} \frac{|E_i|}{E_i} + 2 \frac{\delta t}{t}.$$  \hspace{1cm} (12)

Figure 7 shows the mass resolution $m/\delta m$, defined as the inverse of the mass uncertainty, as a function of the ESA passband $\delta E_0/E_0$ and incident energy on the foil $E_i$ for hydrogen (green), helium (purple),
and oxygen (black) ions. Note, for clarity in Figure 7, we did not include nitrogen because it is similar to oxygen. We plot the mass resolution as opposed to the mass uncertainty to keep with convention, such that a larger value of $m/\delta m$ corresponds to a more capable instrument. The energy out of the ESA $E_0$ is varied from 10 eV to 60 keV, a typical detection range of space plasma instruments, and a post-acceleration voltage of $-10$ kV is used to calculate the incident energy on the foil. The ESA passband $\delta E_0/E_0$ is varied from 0.01 to 0.20, a typical range for space plasma ESAs. For example, for the ACE/SWICS instrument, the ESA passband is 5% (Gloeckler et al., 1998), whereas, for Van Allen Probes/HOPE, the ESA passband is 15% (Funsten et al., 2013).

In Figure 7, the proton mass resolution $m/\delta m$ consistently lies above that of helium, which consistently lies above that of the heavier species like oxygen. This is intuitive as the energy loss and straggling as well as the angular scattering is larger for heavier ions, resulting in a lower $m/\delta m$. We also note that the mass resolution improves as the ESA passband $\delta E_0/E_0$ decreases, particularly at higher energies. To better understand the
variation of the mass resolution as a function of the ESA passband \( \delta E_0/E_0 \) and incident ion energy \( E_i \), cross sections of Figure 7 are shown in Figure 8. Figure 8 shows the mass resolution \( m/\delta m \) at (a) \( \delta E_0/E_0 = 0.05 \) as a function of \( E_i \) and at (b) \( E_i = 30 \) keV as a function of the ESA passband for hydrogen (green), helium (purple), nitrogen (brown), and oxygen (black) ions using a post-acceleration voltage of \(-10\) kV. In Figure 8a, the mass resolution improves by a factor of \( \sim 3.2 \) – \( 3.8 \) as the incident energy increases from 10 to 70 keV for nitrogen and oxygen ions, whereas, for hydrogen and helium ions, the mass resolution is less variable over the same range and only increases by a factor of \( \sim 1.2 \) – \( 1.8 \). The mass resolution improves with increasing energy due to the reduced fractional energy loss and straggling as well as angular scattering at higher energies. In Figure 8b, the mass resolution decreases by a factor of \( \sim 2.1 \) – \( 3.1 \) for all ion species as the ESA passband increases. To further investigate these relationships, we plot mass spectra at two different energies and ESA energy uncertainties in Figure 9.

In Figure 9a, sample mass spectra are plotted for two different energies incident on the foil, \( E_i \) of 10 keV (solid line) and 49 keV (dashed line) with \( \delta E_0/E_0 = 0.05 \). The energies incident on the foil are a combination of \(-10\) kV post-acceleration voltage and out of the ESA energies of \( E_0 = 10 \) eV for the solid line and \( E_0 = 39 \) keV for the dashed line. The widths of the nitrogen (brown) and oxygen (black) peaks decrease as the ion energy incident on the foil increases because the fractional energy loss and straggling and angular scattering uncertainties of the mass uncertainty decrease; this decrease in the mass peak width corresponds to an increase in the mass resolution since the peaks more easily resolved. However, for the hydrogen (green) and helium (purple) ions, the mass peak widths are not as dependent on the incident energy since the energy loss and straggling and angular scattering contribute less to the overall distribution width in comparison to the heavier ions. This feature is consistent with Figure 8a: as the incident energy increases, the mass resolution improves.

In Figure 9b, sample mass spectra are plotted for two different ESA passbands, one at \( \delta E_0/E_0 = 0.05 \) (solid line) and another at \( \delta E_0/E_0 = 0.20 \) (dotted line), at \( E_i = 30 \) keV (corresponding to a post-acceleration of \(-10\) kV and \( E_0 \) of \( 20 \) keV). As the ESA passband increases from 0.03 to 0.20, the nitrogen (brown) and oxygen (black) peaks broaden and start to merge, which makes it difficult to resolve the peaks. This result is also seen in Figure 8b: as the ESA passband increases (worse performance), the mass resolution decreases, reducing the separation between the mass peaks.

4. Driving Factors of Fractional Mass Uncertainty

The capability of a foil-based TOF mass spectrometer is affected by ESA passband, energy loss and straggling, angular scattering, and timing uncertainty. To quantify the contribution of each factor, we use the parameterization from Equation 12 and fits from Table 2 to determine the percent contribution of each mass uncertainty term. Note that the driving factors of the mass uncertainty limit the mass resolution in return. Therefore, understanding these driving factors will aid with space instrument design as this will help instrument developers mitigate effects that degrade the mass resolution.
In Figure 10, the top panels show the mass resolution \( (m/\delta m) \) (left vertical axis, increasing scale) and the mass uncertainty \( (\delta m/m) \) (right vertical axis, decreasing scale) while the bottom panels show the percent contribution of each component of mass uncertainty \( \delta m/m \). The ESA energy uncertainty \( \delta E_0/E_f \) is shown with dotted lines, the energy loss and straggling uncertainty \( \delta E_{\text{loss}}/E_f \) with dashed lines, the path length uncertainty \( \delta d/d \) with dashed-dotted lines, and the timing uncertainty \( \delta t/t \) with solid lines. The four columns, from left to right, are for hydrogen (green), helium (purple), nitrogen (brown), and oxygen (black) ions. For this figure, \( V_{\text{post}} = -10 \text{ kV} \) and \( \delta E_0/E_0 = 0.05 \).

In Figure 10, the top panels show the mass resolution \( (m/\delta m) \) (left vertical axis, increasing scale) and the mass uncertainty \( (\delta m/m) \) (right vertical axis, decreasing scale) while the bottom panels show the percent contribution to mass uncertainty for each contributing factor (ESA energy uncertainty \( \delta E_0/E_f \) — dotted line, energy loss and straggling uncertainty \( \delta E_{\text{loss}}/E_f \) — dashed line, path length uncertainty \( \delta d/d \) — dashed-dotted line, and timing uncertainty \( \delta t/t \) — solid line). From left to right, columns show results for hydrogen (green), helium (purple), nitrogen (brown), and oxygen (black) ions. The ion energies exiting the ESA range from 10 eV to 60 keV and are then post-accelerated by 10 keV. For this plot, the ESA has a passband \( \delta E_0/E_0 \) of 0.05.

The top panels in Figure 10 show that the mass resolution has a stronger energy dependence for heavier ions, which is consistent with Figure 8a. The bottom panels are used to quantify the dominant factors of the mass uncertainty at different incident energies. For hydrogen and helium ions, the ESA uncertainty increases as the incident energy increases and dominates the mass uncertainty at energies above 30–40 keV; however, for nitrogen and oxygen ions, the contribution from \( \delta E_0/E_f \) increases with increasing ion energy but is never the dominant factor of the mass uncertainty. In contrast, the energy loss and straggling uncertainty \( \delta E_{\text{loss}}/E_f \) decreases with increasing energy and dominates the mass uncertainty at energies <30–40 keV for hydrogen and helium ions. However, for nitrogen and oxygen ions, the energy loss and straggling uncertainty dominates the mass uncertainty at all ion energies. The length uncertainty \( \delta d/d \) is not a significant contributor at any energy for hydrogen and helium ions. However, for nitrogen and oxygen ions, \( \delta d/d \) contributes up to 35% of \( \delta m/m \) at energies below ~20 keV and then decreases at higher energies. The timing uncertainty \( \delta t/t \) is assigned an energy-independent value specific to each ion species, but its relative contribution increases at higher energies for all ion species. For protons, \( \delta t/t \) contributes up to ~30% of \( \delta m/m \); however, for other ion species, \( \delta t/t \) only contributes up to ~10% of \( \delta m/m \).

Next, we examine the percent contribution of each term in the mass uncertainty \( \delta m/m \) (Equation 12) as a function of \( E_0 \) and \( qV_{\text{post}} \) in Figure 11. In this plot, the absolute value of the post-acceleration voltage ranges from 4 to 30 kV and the energy out of the ESA ranges from 10 eV to 60 keV. Thus, the energy incident on the foil ranges from 4.01 to 90 keV (note: 4 keV oxygen ions have sufficient energy to pass through an 80 Å carbon foil). Each row, from top to bottom, gives the percent contribution due to the ESA energy \( \delta E_0/E_f \), energy loss and straggling \( \delta E_{\text{loss}}/E_f \), path length \( \delta d/d \), and timing \( \delta t/t \) uncertainties to the overall mass uncertainty. The first column shows the results for helium ions, the second for oxygen ions. The helium results shown in Figure 11 are similar to those for protons; however, we show the helium results as they are more relevant than protons for distinguishing heavier ions species. In each subplot, the percent contribution is plotted.
using a diverging color bar where blue indicates that the factor contributes <50%, white that the factor contributes 50%, and red that the factor contributes >50% of the mass uncertainty. For this plot, $\delta E_0/E_0 = 0.05$. The gray borders on the plot indicate regions of no data due to being outside the range of the simulated energies and post-acceleration voltages.

In the first row, the ESA energy uncertainty dominates the mass uncertainty for helium ions at energies $E_0 \approx 50$ keV for all post-acceleration voltages. However, for oxygen ions, the ESA energy uncertainty is never a dominant contributor of the mass uncertainty. For both ion species, the ESA uncertainty contributes up to ~40% at energies out of the ESA above 15 keV and for all post-acceleration voltages.

In the second row of Figure 11, the percent contribution of $\delta E_{\text{loss}}/E_f$ is characterized for helium and oxygen ions. For helium ions, the energy loss and straggling dominate the mass uncertainty at $E_0 < 12$ keV for all post-acceleration voltages. At an energy out of the ESA of ~40 keV, the energy loss and straggling uncertainty is no longer a dominant source of the mass uncertainty. For oxygen ions, energy loss and straggling contribute up to ~60% of the mass uncertainty for $V_{\text{post}} > 8$ kV and all values of $E_0$. However, for oxygen ions at $E_0 > 10$ keV, the energy loss and straggling dominate the mass uncertainty for all post-acceleration voltages.

The third row of Figure 11 addresses $\delta d/d$. For helium ions, at all energies out of the ESA and post-acceleration voltages, the path length uncertainty is never a dominant source of the mass uncertainty.
By expressing the mass uncertainty as a function of the energy incident on the foil as opposed to the energy loss and straggling uncertainty, which is a dominant contributor for species with lower acceleration voltages as shown in Figure 11. However, for an instrument that has an ESA passband of larger than 5%, the relative contribution of the ESA energy uncertainty would increase and could dominate the mass uncertainty at high (>10 keV) energies out of the ESA. Therefore, it would be important for instrument developers to minimize the ESA passband if they are interested in measuring high energy (>10 keV) particles.

In Figure 11, the path length uncertainty only affects the mass uncertainty for a narrow range of energies incident on the foil as opposed to the energy loss and straggling uncertainty, which is a dominant contributor to the mass uncertainty for a wider range of energies. In order to maximize the mass resolution of this example instrument, it is more important to focus on minimizing the energy loss and straggling rather than the angular scattering of ions through ultrathin foils, which would help in developing methods to reduce these contributors for specific TOF instruments. We note that for thicker foils the relative contributions of energy loss and straggling uncertainty as well as path length uncertainty would increase.

Since the path length uncertainty is not a dominant source of error, lengthening the drift box would not significantly decrease the contribution of the path length uncertainty. However, lengthening the TOF region would increase the TOF measurements \( t \), decreasing the \( \delta t / t \) contribution to the mass uncertainty. For an instrument that has a large timing uncertainty, for example, Van Allen Probes/HOPE, the mass resolution could be improved by lengthening the drift box, improving the electronic jitter, or reducing the bin size. But, for an instrument like ACE/SWICS, where the timing uncertainty is never a dominant source of error (Figure 11), lengthening the drift box or improving the electronics is not a useful way to improve the mass resolution.

### 5. A Tool for Instrument Developers

We leverage the results presented in the previous section to create a tool for instrument developers which estimates the mass uncertainty. This tool also allows instrument developers to identify the factors driving the mass uncertainty, which can be used to modify the instrument design to mitigate these driving effects.

| Fractional mass uncertainty (\( \delta m/m \)) |
|----------------------------------------------|
| \( H^+ \) | \( \delta E_\theta \) + 0.54 \( E_i^{0.12} \) + 0.40 \( E_i^{-2.04} \) + \( \frac{\delta t}{t} \) |
| \( He^+ \) | \( \frac{E_i - 0.33 E_i^{0.38}}{E_\theta} \) + 0.71 \( E_i^{0.20} \) + 1.48 \( E_i^{-2.05} \) + \( \frac{\delta t}{t} \) |
| \( N^+ \) | \( \frac{E_i - 0.28 E_i^{0.27}}{E_\theta} \) + 0.59 \( E_i^{0.43} \) + 16.54 \( E_i^{-2.03} \) + \( \frac{\delta t}{t} \) |
| \( O^+ \) | \( \frac{E_i - 1.19 E_i^{0.22}}{E_\theta} \) + 0.75 \( E_i^{0.33} \) + 17.92 \( E_i^{-2.00} \) + \( \frac{\delta t}{t} \) |

The last component of the mass uncertainty is \( \delta t/t \), which is characterized in the last row of Figure 11. A species-dependent, energy-independent value based on SWICS is used to approximate the timing uncertainty (summarized in Table 1). In Figure 11, for helium ions, the timing uncertainty contributes up to ~30% of the mass uncertainty at \( V_{post} \geq 8 \) kV. In comparing the second and third rows, the energy loss and straggling matters more than the angular scattering for \( V_{post} > 8 \) kV.

The energy uncertainty \( \delta E_\alpha/E_f \) contributes up to 50% of the mass uncertainty for energies above ~50 keV at all post-acceleration voltages as shown in Figure 11. However, for an instrument that has an ESA passband of larger than 5%, the relative contribution of the ESA energy uncertainty would increase and could dominate the mass uncertainty at high (>10 keV) energies out of the ESA. Therefore, it would be important for instrument developers to minimize the ESA passband if they are interested in measuring high energy (>10 keV) particles.

Table 3

| Fractional Mass Uncertainty \( \delta m/m \) Parameterized in Terms of the Energy Incident on the Foil \( E_i \) and the ESA Energy FWHM Width \( \delta E_\theta \) for Hydrogen, Helium, Nitrogen, and Oxygen Ions |
|-----------------------------------------------|
| \( H^+ \) | \( \delta E_\theta \) + 0.54 \( E_i^{0.12} \) + 0.40 \( E_i^{-2.04} \) + \( \frac{\delta t}{t} \) |
| \( He^+ \) | \( \frac{E_i - 0.33 E_i^{0.38}}{E_\theta} \) + 0.71 \( E_i^{0.20} \) + 1.48 \( E_i^{-2.05} \) + \( \frac{\delta t}{t} \) |
| \( N^+ \) | \( \frac{E_i - 0.28 E_i^{0.27}}{E_\theta} \) + 0.59 \( E_i^{0.43} \) + 16.54 \( E_i^{-2.03} \) + \( \frac{\delta t}{t} \) |
| \( O^+ \) | \( \frac{E_i - 1.19 E_i^{0.22}}{E_\theta} \) + 0.75 \( E_i^{0.33} \) + 17.92 \( E_i^{-2.00} \) + \( \frac{\delta t}{t} \) |
of energies and ESA widths. Table 3 shows the parameterized mass uncertainties for hydrogen, helium, nitrogen, and oxygen ions for 80 Å carbon foils where \( E_0 \) is in units of keV; these parameterizations are calculated from Equation 12 and fits shown in Table 2. We provide two example applications of this tool.

We first apply the tool to the HOPE mass spectrometers, which measure 1 eV to 50 keV ions and electrons using a post-acceleration voltage of ~11 kV in ion mode. The instrument has an ESA passband of 15% in FWHM and timing uncertainty values shown in Table 1 (Funsten et al., 2013). Using Table 3, the mass resolution and driving factors of the mass uncertainty can be assessed for various ion species. For example, at \( E_0 = 10 \) keV, the mass resolution \( m/\delta m \) is ~2.4, ~2.9, and ~2.8 for \( H^+, He^+, \) and \( C^+/N^+/O^+ \), respectively. These predicted mass resolutions \( m/\delta m \) are all >2, which agrees with the reported instrument performance (Funsten et al., 2013). By taking ratios of the terms in the mass uncertainty equations from Table 3, we find that the ESA uncertainty contributes ~18%–22%, energy loss and straggling uncertainty contributes ~9%–20%, path length uncertainty contributes ~0.20%–1%, and timing uncertainty contributes ~58%–72% to the mass uncertainty for \( H^+ \) and \( He^+ \). For the \( C^+/N^+/O^+ \) group, the ESA uncertainty contributes ~27%, energy loss and straggling contribute ~40%, path length uncertainty contributes ~11%–13%, and timing uncertainty contributes ~20% to the mass uncertainty. Note that the proton mass resolution \( m/\delta m \) is smaller than that of the other ion species because the relative contribution of the timing uncertainty is largest for protons, which has the shortest TOF measurement. Therefore, the mass resolution of 10 keV particles with mass below ~4 amu could be enhanced by improving the timing electronics. For the \( C^+/N^+/O^+ \) group, the energy loss and straggling as well as path length uncertainty contribute to ~51%–53% of the mass uncertainty; thus, mass resolution could be enhanced for \( C^+/N^+/O^+ \) ions at \( E_0 = 10 \) keV by reducing the foil thickness. This tool can also be easily applied to other TOF instrumentation, such as Cluster/CODIF (Rème et al., 1997) in the outer magnetosphere or the recently launched Solar Orbiter/Solar Wind Analyser (SWA) (Muller et al., 2013).

Improved mass spectrometry capability is required to address some of the most pressing questions regarding the composition, structure, and dynamics of the terrestrial magnetosphere. For example, an area of renewed interest is the role of nitrogen in magnetospheric dynamics (see Ille & Liemohn, 2016, and references therein). For an instrument to distinguish \( O^+ \) from \( N^+ \), at similar abundances, a mass resolution \( m/\delta m \) >8 is required. From the parameterization provided in Table 3, an ESA passband of 5%, post-acceleration of ~35 kV, and timing uncertainty \( \delta t/t \) of 0.01 could be used to achieve a mass resolution of >8 for \( E_0 \) between 10 eV and 60 keV. With a large post-acceleration voltage of ~35 kV, the angular scattering is not a significant contributor to the mass uncertainty, even in the \( C^+/N^+/O^+ \) mass range. Alternatively, one could employ a thinner foil to reduce the contributions of the energy loss and straggling to the mass resolution.

A mass resolution \( m/\delta m \) of ~8 can also be achieved using a LEF or other types of reflectron schemes (McComas et al., 1990). But these instruments are often complex and resource intensive, and they typically have a low sensitivity due to the requirement that the incident ion exits the foil as a positive ion. Therefore, there is a need for linear, foil-based TOF instruments. With the information provided in this study, instrument developers can now quickly assess the mass resolution and determine the limiting factors of the mass resolution to potentially optimize the performance based on the target plasma properties and measurement requirements.

### References

Allegrini, F., Ebert, R. W., & Funsten, H. O. (2016). Carbon foils for space plasma instrumentation. Journal of Geophysical Research: Space Physics, 121, 3931–3950. https://doi.org/10.1002/2016JA022570

Allegrini, F., Ebert, R. W., Fuselier, S. A., Nicolaou, G., Bedworth, P. V., Sinton, S. W., & Trattner, K. J. (2014). Charge state of ~1 to 50 keV ions after passing through graphene and ultrathin carbon foils. Optical Engineering, 53(2), 024101. https://doi.org/10.1117/1.OE.53.2.024101

Allegrini, F., McComas, D. J., & Young, D. T. (2006). Energy loss of 1 eV to 50 keV H, He, C, O, Ne, and Ar transmitted through thin carbon foils. Review of Scientific Instruments, 77(4), 044501. https://doi.org/10.1063/1.2185490

Banks, B. A., de Groh, K. K., & Miller, S. K. (2004). Low earth orbital atomic oxygen interactions with spacecraft materials. MRS Proceedings, 851, NN8.1. https://doi.org/10.1557/PROC-851-NN8.1

Barabash, S., Bhardwaj, A., Wieser, M., Sritharan, R., Kurian, T., Varier, S., et al. (2009). Investigation of the solar wind–moon interaction onboard Chandrayaan-1 mission with the SARA experiment. Current Science, 96(4), 526–532.

Bhattara, B., Pandey, A., & Drabold, D. A. (2017). Evolution of amorphous carbon across densities: An inferential study. Carbon, 131, 168–174. https://doi.org/10.1016/j.carbon.2018.01.103

Bohr, N. (1948). The penetration of atomic particles through matter. In Niels Bohr Collected Works (Chap. 22, Vol. 8, pp. 423–568). Amsterdam: Elsevier. https://doi.org/10.1016/S1876-6503(08)70172-5

### Acknowledgments

The authors acknowledge Michelle Thomsen for her numerous thoughtful discussions. This work was performed under the auspices of the U.S. Department of Energy, and it was authorized for public release and assigned document number LA-UR-20-20898. This research was supported by the Los Alamos National Laboratory Center for Space and Earth Sciences. Data from authors are available at this link (https://doi.org/10.5281/zenodo.3603322).
McComas, D. J., Allegreni, F., Pollock, C. J., Funsten, H. O., Rizea, S., & Gloeckler, G. (2004). Ultra-thin (~10 nm) carbon foils in space instrumentation. Review of Scientific Instruments, 75(11), 4863–4870. https://doi.org/10.1063/1.1809265

McComas, D. J., Nordholt, J. E., Bame, S. J., Barraclough, B. L., & Gosling, J. T. (1990). Linear electric field mass analysis: A technique for three-dimensional high mass resolution space plasma composition measurements. Proceedings of the National Academy of Sciences, 87(15), 5925–5929. https://doi.org/10.1073/pnas.87.15.5925

Meyer, L. (1971). Plural and multiple scattering of low-energy heavy particles in solids. Physica Status Solidi (b), 44(1), 253–268. http://doi.org/10.1002/pssb.220440127

Möbius, E., Kistler, L. M., Popecki, M. A., Crocker, K. N., Granoff, M., Jiang, Y., et al. (1998). The 3-D plasma distribution function analyzers with time-of-flight mass discrimination for cluster, FAST, and Equator-S in Measurement Techniques in Space Plasmas: Particles. https://doi.org/10.1029/GM102p0243

Mulder, D., Marsden, R. G., St. Cyr, O. C., & Gilbert, H. R. (2013). Solar orbiter: Exploring the Sun-heliosphere connection. Solar Physics, 285(1–2), 25–70. https://doi.org/10.1007/s11207-012-0085-7

Nordholt, J. E., Berthelier, J.-J., Burr, D. M., Funsten, H. O., Goldstein, R., Illiano, J.-M., et al. (1998). The Cassini ion mass spectrometer: Performance metric and techniques. In Geophysical Monograph Series, 102, 209–214. https://doi.org/10.1029/98GM102p0209

Paillous, A. (1993). Radiation damage to surface and structure materials. In R. N. DeWitt, D. Duston, & A. K. Hyder (Eds.), The Behavior of Systems in the Space Environment (pp. 383–405). Dordrecht, Netherlands: Springer. https://doi.org/10.1007/978-94-011-2048-7_17

Radionova, A., Filipović, I., & Derrick, P. J. (2016). In pursuit of resolution in time-of-flight mass spectrometry: A historical perspective. Mass Spectrometry Reviews, 35(6), 738–757. https://doi.org/10.1002/mas.21470

Rème, H., Bosquèd, J. M., Sauvaud, J. A., Cros, A., Dandouras, J., Aoustin, C., et al. (1997). The cluster ion spectrometry (CIS) experiment. Space Science Reviews, 79(1–2), 303–350. https://doi.org/10.1023/A:1004929816409

Rousset, J.-F., & Bourdon, A. (2000). Oxygen interaction with materials III: Data interpretation via computer simulation. Journal of Spacecraft and Rockets, 37(3), 324–330. https://doi.org/10.2514/2.3582

Sokól, J. M., Kubiak, M. A., & Bazyewski, M. (2019). Interstellar neutral gas species and their pickup ions inside the heliospheric termination shock: The large-scale structures. Astrophysical Journal, 879(1), 24. https://doi.org/10.3847/1538-4357/ab21c4

Stude, J., Wieser, M., & Barabash, S. (2016). Scattering of hydrogen, nitrogen and water ions from micro pore optic plates for application in spaceborne plasma instrumentation. Nuclear Instruments and Methods in Physics Research B, 385, 9–14. https://doi.org/10.1016/j.nimb.2016.08.014

Tahara, H., Zhang, L., Hiramatsu, M., Yasui, T., Yoshikawa, T., Setsuhara, Y., & Miyake, S. (1995). Exposure of space material insulators to energetic ions. Journal of Applied Physics, 78(6), 3719–3723. https://doi.org/10.1063/1.359951

Taylor, J. R. (1982). Chapter 3 in an introduction to error analysis: The study of uncertainties in physical measurements (pp. 75). Mill Valley, Calif.: Univ. Science Books.

Tennyson, R. C. (1993). Atomic oxygen and its effect on materials. In R. N. DeWitt, D. Duston, & A. K. Hyder (Eds.), The Behavior of Systems in the Space Environment (pp. 233–257). Dordrecht, Netherlands: Springer. https://doi.org/10.1007/978-94-011-2048-7_10

Vida, A. D., Fernandes, P. A., Funsten, H. O., Morley, S. K., Yamaguchi, H., Liu, F., & Moody, N. A. (2020). Angular scattering of protons through ultrathin graphene foils: Application for time-of-flight instrumentation. Review of Scientific Instruments, 91(3), 033302. https://doi.org/10.1063/1.5134766

Von Steiger, R., Schwadron, N. A., Fisk, L. A., et al. (2000). Composition of quasi-stationary solar wind flows from Ulysses/solar wind ion composition spectrometer. Journal of Geophysical Research: Space Physics, 105(A12), 27217–27238. https://doi.org/10.1029/1999JA000358

Welling, D. T., & Liemohn, M. W. (2016). The ionospheric source of magnetospheric plasma is not a black box input for global models. Journal of Geophysical Research: Space Physics, 121, 5559–5565. https://doi.org/10.1002/2016JA022646

Wilken, B., Weiss, W., Stüedemann, W., & Hasebe, N. (1987). Giotto implanted ion spectrometer (IIS): Physics and technique of detection. Journal of Physics E: Scientific Instruments, 20(6), 778–785. https://doi.org/10.1088/0022-3758/20/6/036

Wüst, J. F., Biersack, J. P., & Littmark, U. (1985). Stopping and range of ions in solids. Boston, MA: Springer.