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First Flight and Redesign of the Thermal Ion Gated Time of Flight (TIGTOF)

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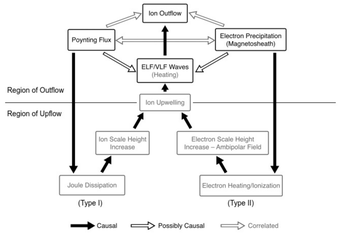
Abstract

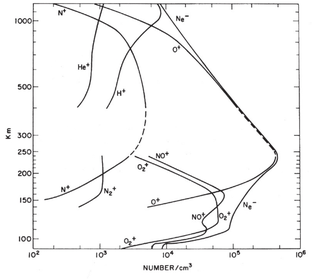
The escape of atmospheric particles at high latitudes is a well documented process called ion outflow. On Earth, outflowing O+ is most commonly observed, followed by significant populations of heavier molecular ions (e.g. N2+). Although we can measure upflow on Earth, we lack the basic data necessary to fully understand the role that differing ion masses play in the upflow process. The Thermal Gated Ion Time of Flight (TIGTOF) is being developed to measure in-situ particle fluxes in the cusp-region ionosphere, and will allow us to:

1.) examine the role of molecular ions in ion upflow processes.
2.) provide a proper characterization of the energy budget as input to ionosphere-thermosphere coupling models.

Science Background



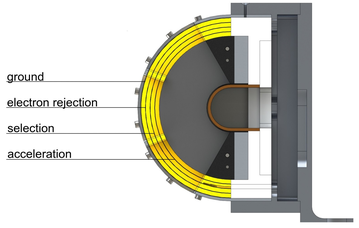
Ion outflow is a two-stage process through which atmospheric particles gain energies sufficient to escape Earth's gravitational field. The first stage of ion outflow is called upflow, in which ions are lifted from 100 - 300 km up to 500 - 600 km. There are two types of iupflow: Type I is ionospheric convection (Joule heating), and Type II is driven by soft electron (~ 100s of eV) precipitation. The second stage is called outflow, during which particles are lifted from 500 - 600 km and higher. Upflowing particles must receive additional energization in order to achieve escaping velocity, or else they may return to lower altitudes (downflow). Figure adapted from Strangeway et al. 2004.



Precipitating electrons associated with Type II ion upflow couple energy most efficiently between ~ 230 - 250 km, where the primary constituents of Earth's atmosphere are O, O2, and N2. Low collision rates at these altitudes gravitationally stratify the atmosphere, resulting in O+ being the dominant ion species with a significant N2+ population also present. Ground and in-situ observations have predominately shown O+ to be the dominant upflowing particle species at sounding rocket (~ hundreds of km) and satellite (~ thousands of km) altitudes (Shelley et al. 1972, Waite et al. 1985, and Yau et al. 1985). Strangely enough, significant populations of N2+ have been observed as outflowing at satellite altitudes despite the lack of upflowing N2+ observations at lower altitudes. The processes which produce the observed preferential upflow of O+ over N2+ are not well understood and require further investigation. Figure adapted from Johnson et al. 1969.

TIGTOF v.1

TIGTOF is a Retarding Potential Analyzer (RPA) that utilizes a gated Time of Flight (TOF) method to measure ion mass and relative number densities of particle species within a population. TIGTOF's ability to distinguish between three distinct mass regimes, i.e. protons, heavy ions (e.g. O+, 16 amu), and heavier molecular ions (e.g. N2+, 28 amu), will be crucial for understanding the impact of increased mass throughout the magnetosphere.



Design Principle

TIGTOF's gated TOF is controlled by the four screens across its aperture :

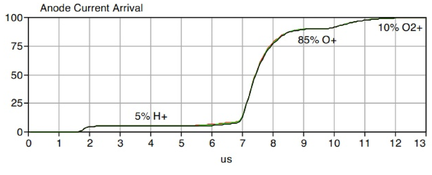
1.) ground: provides uniform entrance field to incident ions.
2.) electron rejection: repels electrons; accelerates ions.
3.) selection: determines admitted energy of particle; controls TOF gate.
4.) acceleration: accelerates ions toward the anode.

The delay between the opening of the TOF gate and the arrival of particles at the central anode provides the TOF. Combining the measured TOF with the TOF path length gives the velocity of the measured ion, while comparison with the admitted energy yields ion mass.

Flight Results

A prototype of TIGTOF (v.1) was flown on the Cusp Region EXperiment (CREX-2) sounding rocket in December 2021. Analysis of CREX-2's flight data has shown that :

1.) Modeled fits to the flight data are inconsistent during the initial and final stages of the flight (possibly due to higher ram velocities on the upleg and downleg) but are somewhat consistent during the majority of the flight.
2.) Our numerical model does not account for the physical "wrinkles" in the screen material, which could introduce additional errors into the TOF calculations.
3.) The observed time of flight delay for O+ is much higher than can be accounted for by timing errors and/or mechanical tolerances alone.

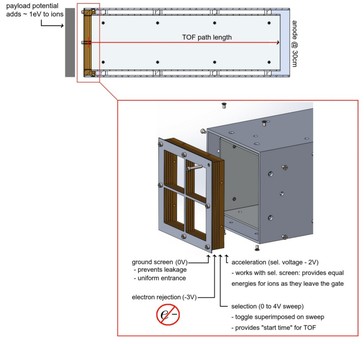


At the anode, the collected charge produces a waveform derived from the combination of arrival times for each mass group, with smaller ions arriving at the anode first.

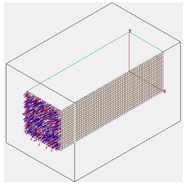
NET : implementing an overall larger TIGTOF with a larger entrance area, reduced FOV, and longer TOF path would improve signal strength and TOF resolution, thus compensating for these observed issues.

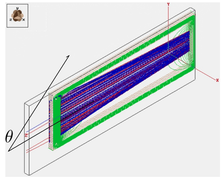
TIGTOF v.2

TIGTOF is being redesigned based on the CREX-2 flight data. We have decided to implement an overall larger geometric factor to provide improved TOF resolution. The curved screens (originally designed to accomodate a large range of ram entrance angles into the instrument's aperture) will be replaced with flat, rectangular ones since the angular field-of-view can be drastically reduced for a TIGTOF that is ram-facing, as will be the case for RENU3. We have also decided to split the walls of the instrument into two (with an outer, grounded wall, and an inner, electrically biased wall), with the inner wall functioning as a modified Einzel lens. This modification will improve the focusing of incident ion trajectories thus allowing for reduced anode capacitance, improved mass resolution, and improved energy resolution.

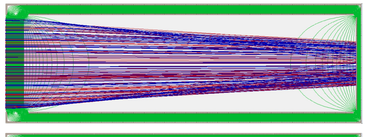


Model Description

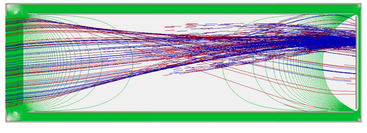




$\theta = 0°$

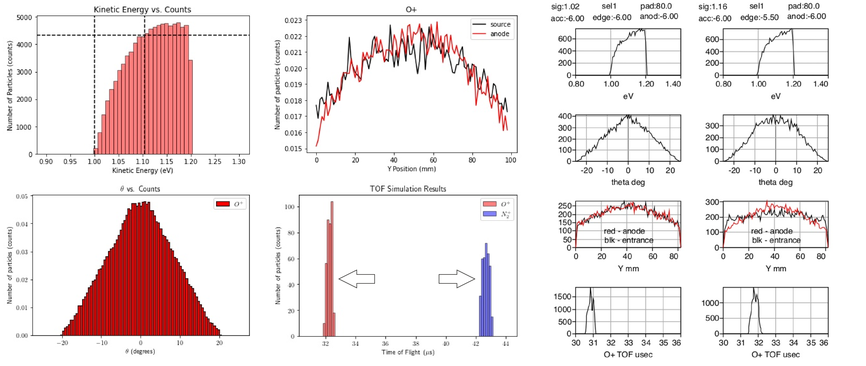


$\theta = 10°$



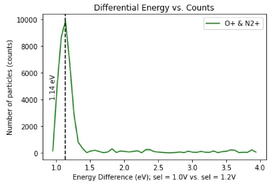
We have been using SIMION to model and simulate TIGTOF v.2's response in order to guide its redesign. This software uses an adaptive "relaxation method" to calculate the electric potential and electric field inside the modeled instrument, and then simulates the trajectories of ions through such an environment. Here, we collapse the 3-D model to 2-D to better visualise the results, and fly two groups of ions through the instrument (top, left & right), using a randomized Monte Carlo method. The trajectories of O+ (16 amu) are shown in red, while those of N2+ (28 amu) are shown in blue. The energies of both ion populations are ~ 1 eV (from the sheath potential), plus ~ 0.1 eV (thermal energy).

Model Results



Example simulation results (SIMION, left, middle; MathPad, right). Our goal is to select the appropriate electrode voltages and anode size to optimize the signal strength, energy resolution, angular response (FOV), and mass resolution (TOF) for the redesigned TIGTOF v.2. We want to demonstrate that the design of TIGTOF v.2 as described here provides the TOF resolution necessary to distinguish between O+ and N2+. This can be determined by seeing if there is an appreciable (> 2 microseconds, limited by the timing of the electronics) difference between the TOF peaks of O+ and N2+ from these simulated results. For each configuration, the separation between the TOF peaks is ~ 10 microseconds. The number of counts decreases appreciably after ~ +/- 10 degrees (above, left, right). The angular distributions for O+ and N2+ are comparable, and are symmetric in theta and phi for the 3-D simulated cases.

Geometric Factor



$$\mathcal{G}_{v.2} = \frac{\Delta A \Delta\theta \Delta\phi \Delta E}{E} \frac{N_{detected}}{N_{source}} \sim \boxed{0.205 \frac{cm^2\, sr\, eV}{eV}}$$

Redesigning TIGTOF v.2 involves the calculation of the resized geometric factor, which depends on multiple parameters. Some are known (e.g. the open area of the aperture, the energy acceptance bandpass, and the number of particles flown), while others must be determined through simulation (e.g. theta, phi, the characteristic energy, and the number of particles detected). In particular, by virtue of the TOF method, the calculation of the characterisitc energy requires the differential energy be accounted for (left).

Summary & Future Work

TIGTOF is being developed at the University of New Hampshire as a low-cost, low-resource instrument designed to examine the role of molecular ions in ion upflow processes, therein providing a proper characterization of the energy budget as input to ionosphere-thermosphere coupling models. A prototype of TIGTOF was flown on the CREX-2 sounding rocket in 2021. Since then, we have been developing an improved instrument based on measured flight data and simulated results. This optimized TIGTOF will be tested and calibrated using Dartmouth College's ELEPHANT plasma chamber (2023), prior to its flight on the Rocket Experiment for Neutral Upwelling (RENU3) sounding rocket (2024). The dimensions and electrode voltages of TIGTOF v.2 have been changed to maximize TOF resolution. Notably, a 10 x 10 cm entrance aperture with a 30 cm length would make TIGTOF v.2 the same size as a 3U cubesat. Since TIGTOF does not use high-voltage and does not require any deployments, its simplicity, compact size, and light weight would make it an ideal cubesat instrument.

Acknowledgments

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