4-1-2011

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Recommended Citation

Everett, Addison E. and Syrstad, E. A., "A Time-of-Flight Mass Spectrometer for Upper Atmospheric Measurements" (2011). Intermountain Graduate Research Symposium. *Graduate Student Posters.* Paper 33.
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A Time-of-Flight Mass Spectrometer for Upper Atmospheric Measurements

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Research Objectives and Goals

- Design a time-or-flight mass spectrometer (TOF-MS) for fast, ultra-sensitive measurements of charged and neutral particles in the Mesosphere / Lower Thermosphere (MLT)
- Develop a simple, inexpensive vacuum pumping system to allow for mass spectrometer operation at low altitudes and high pressures characteristic of the MLT
- Demonstrate acceptable microchannel plate (MCP) detector performance at high pressures (low millitorr range)

Background

Although the MLT is home to many interesting and important phenomena, it is also perhaps the least understood region of the earth's atmosphere owing to the difficulty of accessing this region for *in-situ* measurements. In fact, the only method of direct access to the MLT is via high-speed sounding rockets for brief periods of at most a few minutes. Species of interest range from individual atoms (several amu) to smoke and dust particles (several thousand amu). The high duty cycle required to spatially resolve thin layers combined with the wide mass range to be measured point toward TOF-MS as the desired measurement technique. However, due to its dependence on high voltages and microchannel plate (MCP) detectors, TOF-MS has rarely been applied in the MLT where ambient pressures reach into the millitorr range.

We present a novel, compact mass spectrometer design using a getter based vacuum pumping system and pressure-tolerant MCP to allow operation in the MLT.

TOF-MS Design

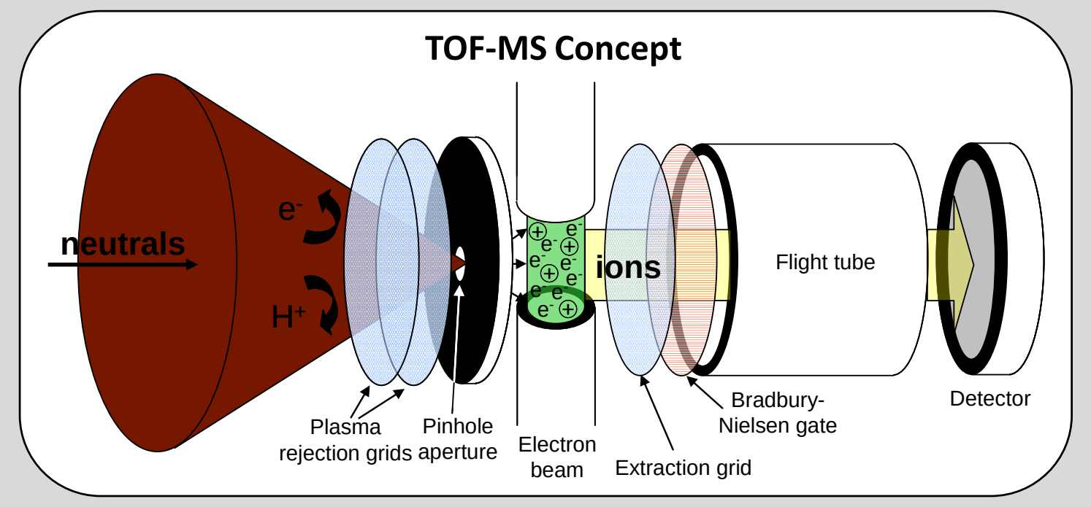
All mass spectrometric methods attempt to separate particles according to their mass-to-charge (m/z) ratio. TOF-MS achieves mass separation by accelerating particles to a uniform kinetic energy and measuring the time it takes different particles to transit a field-free drift region. The basic principle of TOF-MS is expressed in the equation below:

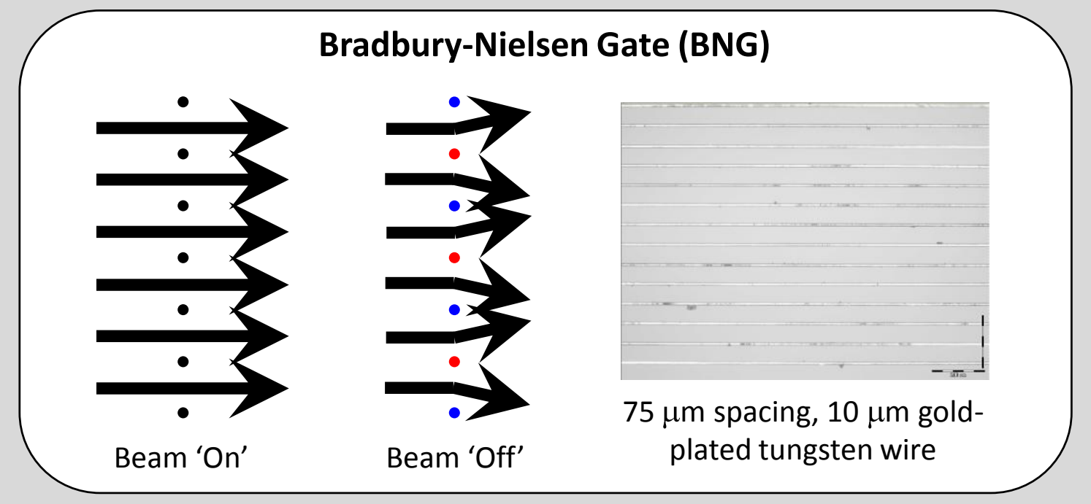
$$t = d\sqrt{\frac{m}{2KE}}$$

For a given kinetic energy (KE), a particle of mass m will travel a drift distance d in time t. This transit time, t, will be the same for particles of a given mass, with heavier particles taking longer than lighter particles to travel the drift distance.
The major TOF-MS design features and their benefits are:

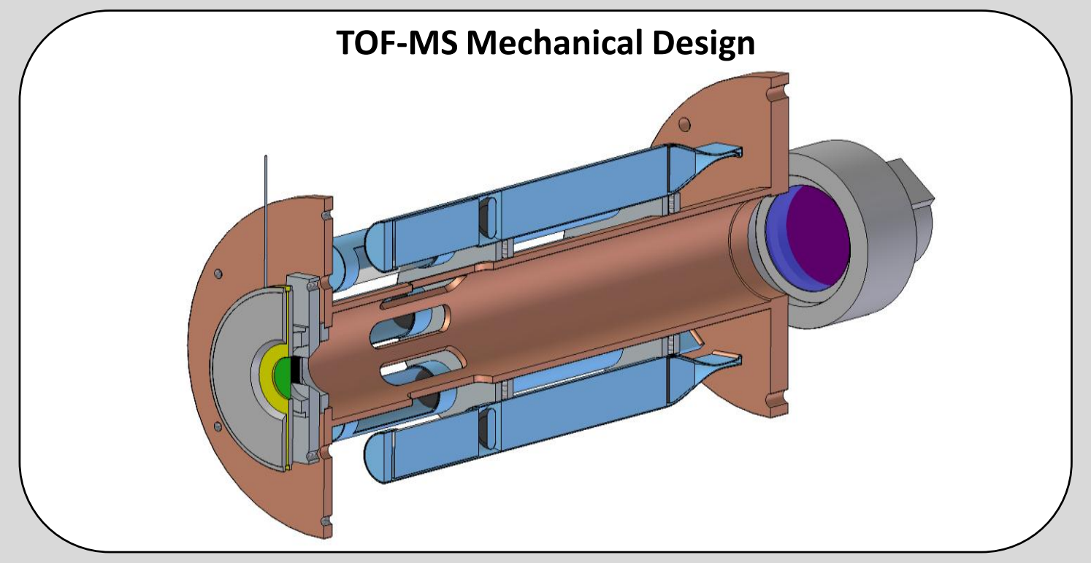
- **Pinhole sampling aperture:** the diameter is tailored to the specific application and is designed to maximize TOF-MS sensitivity while minimizing atmospheric gas load (50µm to 2mm)
- **Ionizer** (neutral TOF-MS only): electron beam / sheet located near aperture to convert incoming neutrals to ions via electron impact
- **Acceleration mesh:** draws ions into the TOF-MS generating a focused ion beam and accelerates them to a uniform kinetic energy (~200 eV)
- **Bradbury-Nielsen Gate (BNG):** modulates ion beam; generates start pulses with extremely well-defined temporal characteristics (>25 ns pulse width, <5 ns rise time) using low voltages (<±20 V)
- **Drift tube:** field-free region where ions separate according to their m/z values—heavier ions travel slower than light ions
- **MCP detector** (Photonis): pulse-counting ion detection with high gain (10^7) and very narrow pulses (350 ps FWHM); previously demonstrated operation at pressures up to 10^{-2} torr
- **Pulse-processing electronics:** amplifies, digitizes, and counts MCP pulses with high temporal precision (100 ps) and at high count rates (up to 1GHz)
- **Barium getter tubes** (Alvatec): evacuate TOF-MS interior to allow operation of the high-voltage MCP and meet the mean free path requirements

The TOF-MS can be operated in either conventional or Hadamard Transform (HT) mode. Conventional TOF mode has a low duty cycle (up to ~5%) but offers very accurate number density measurements, suitable for measurement of standard atmospheric species. HT mode offers a very high duty cycle (50%), but with less accurate number density measurements. HT mode is particularly well suited for measurements of thin metal and dust layers. Both modes offer high mass resolution.


TOF-MS Concept

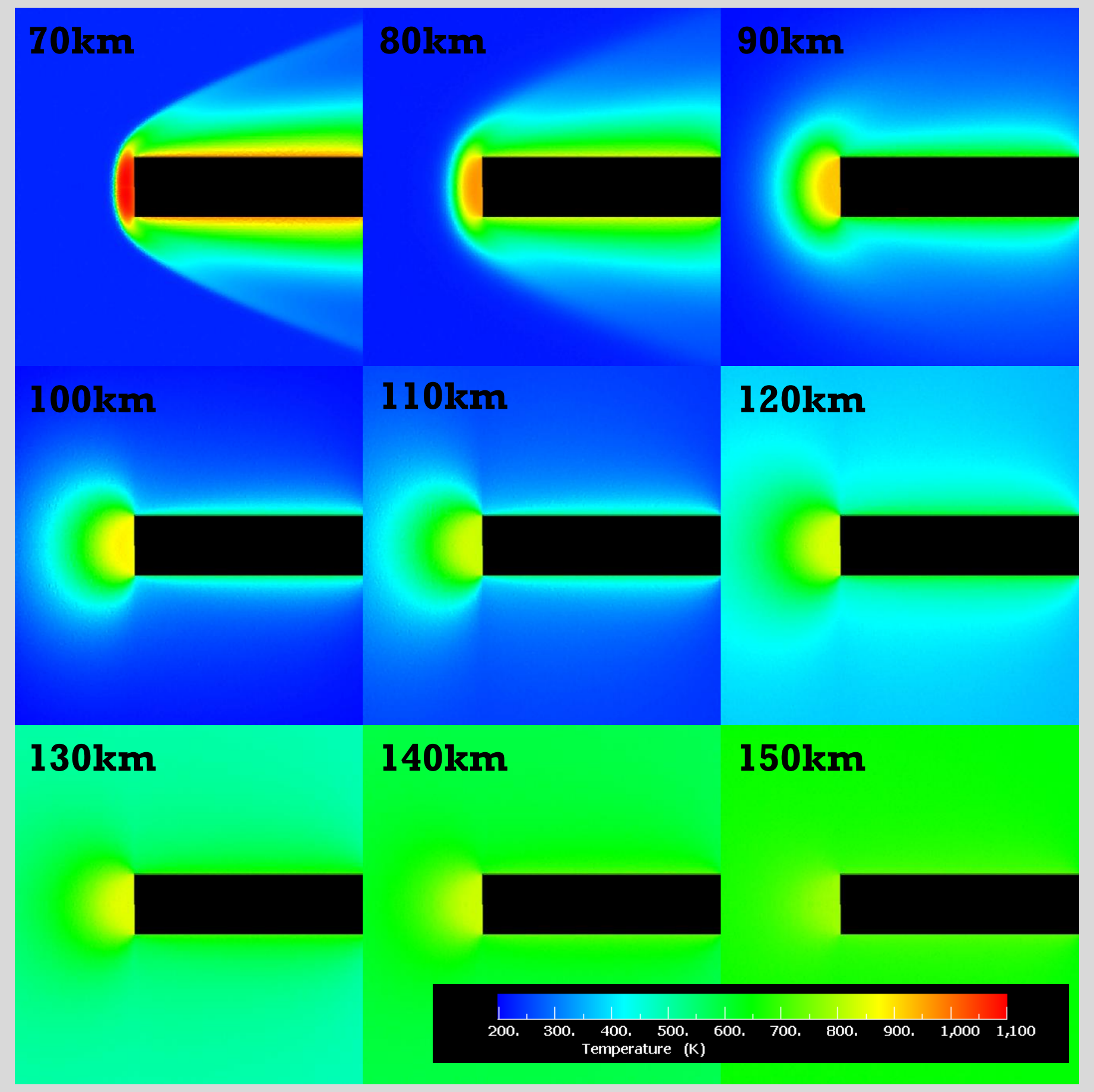

Bradbury-Nielsen Gate (BNG)

75 µm spacing, 10 µm gold-plated tungsten wire

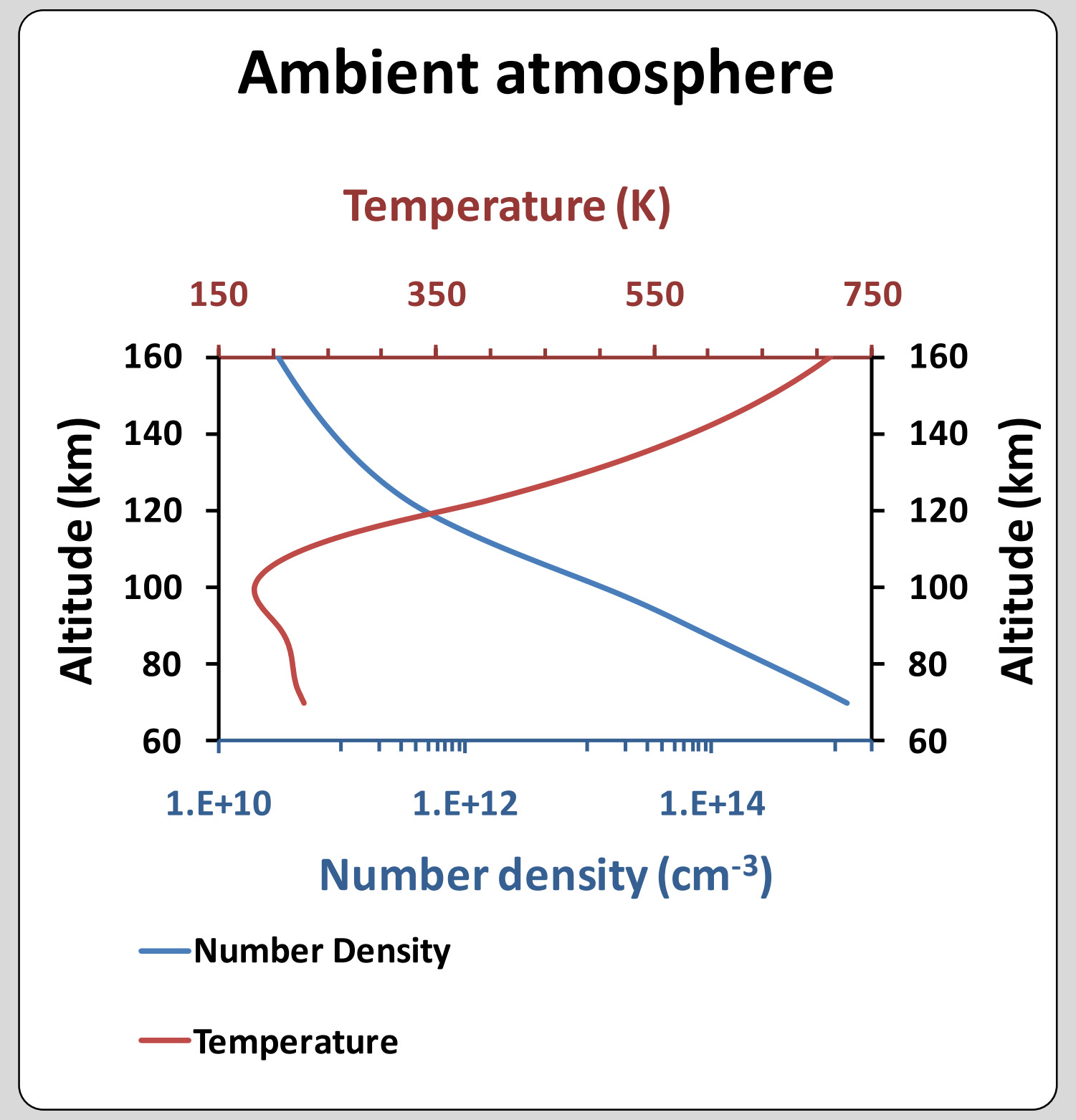

TOF-MS Mechanical Design

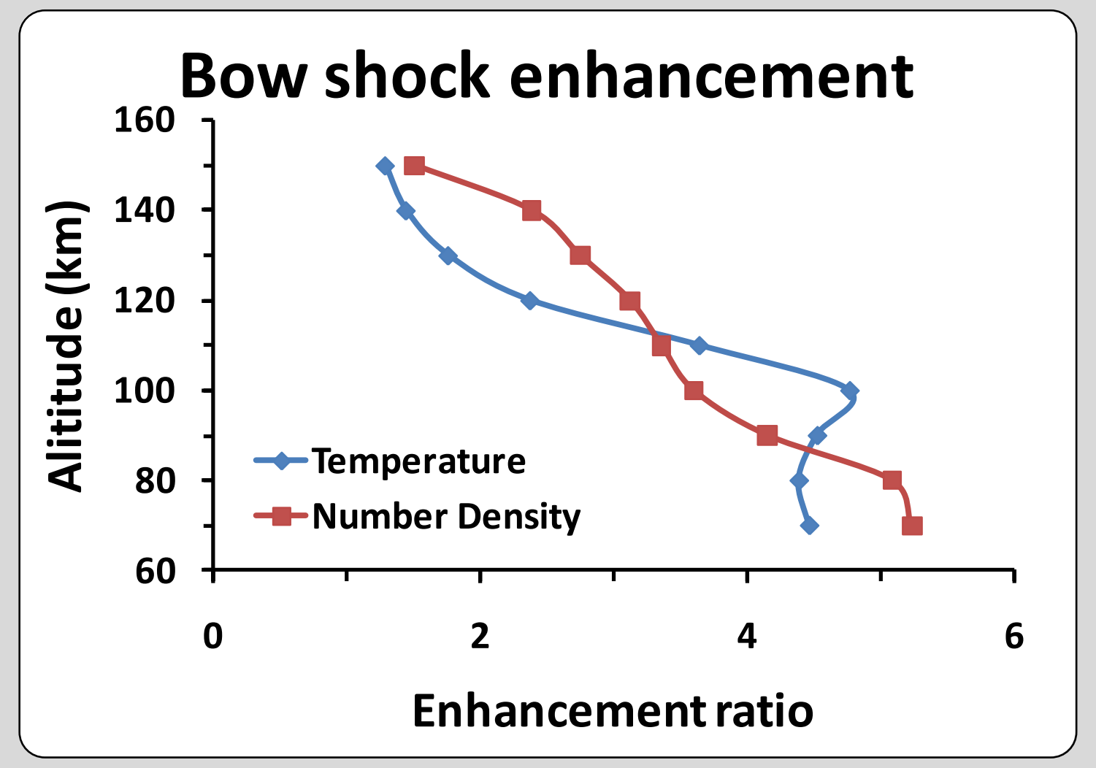
Gas Flow Simulations

A bow shock forms in front of a sounding rocket as it flies through the atmosphere. In order to study the effects of the bow shock on the TOF-MS, gas flow simulations were conducted using the Direct Simulation Monte Carlo (DSMC) technique. Of particular interest are the density and temperature enhancements of the bow shock that would occur on a sounding rocket flight through the MLT region to an altitude of 160km.



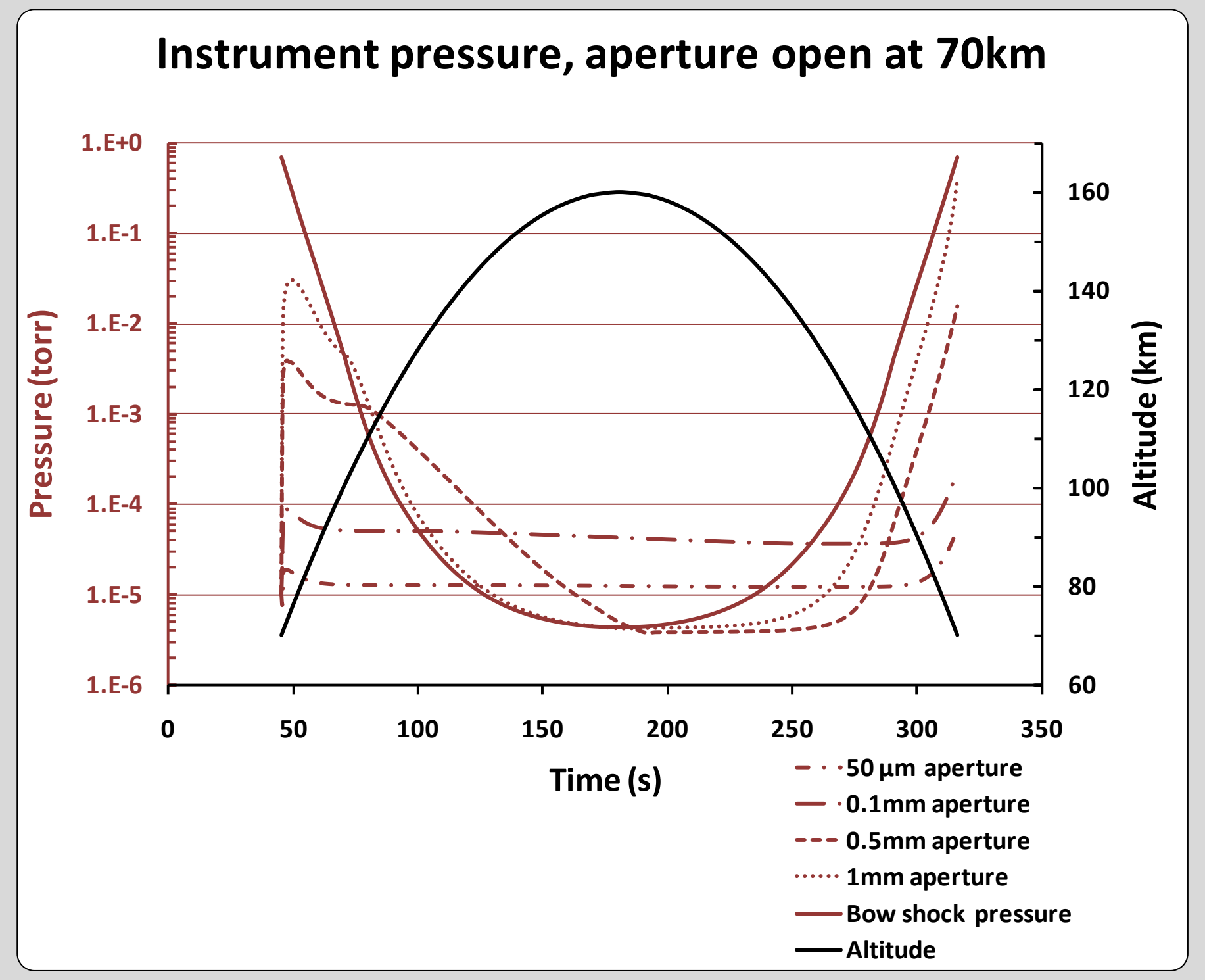
Temperature simulation showing the evolution of the bow shock at 10km intervals from 70-150km, assuming a 160km ballistic trajectory

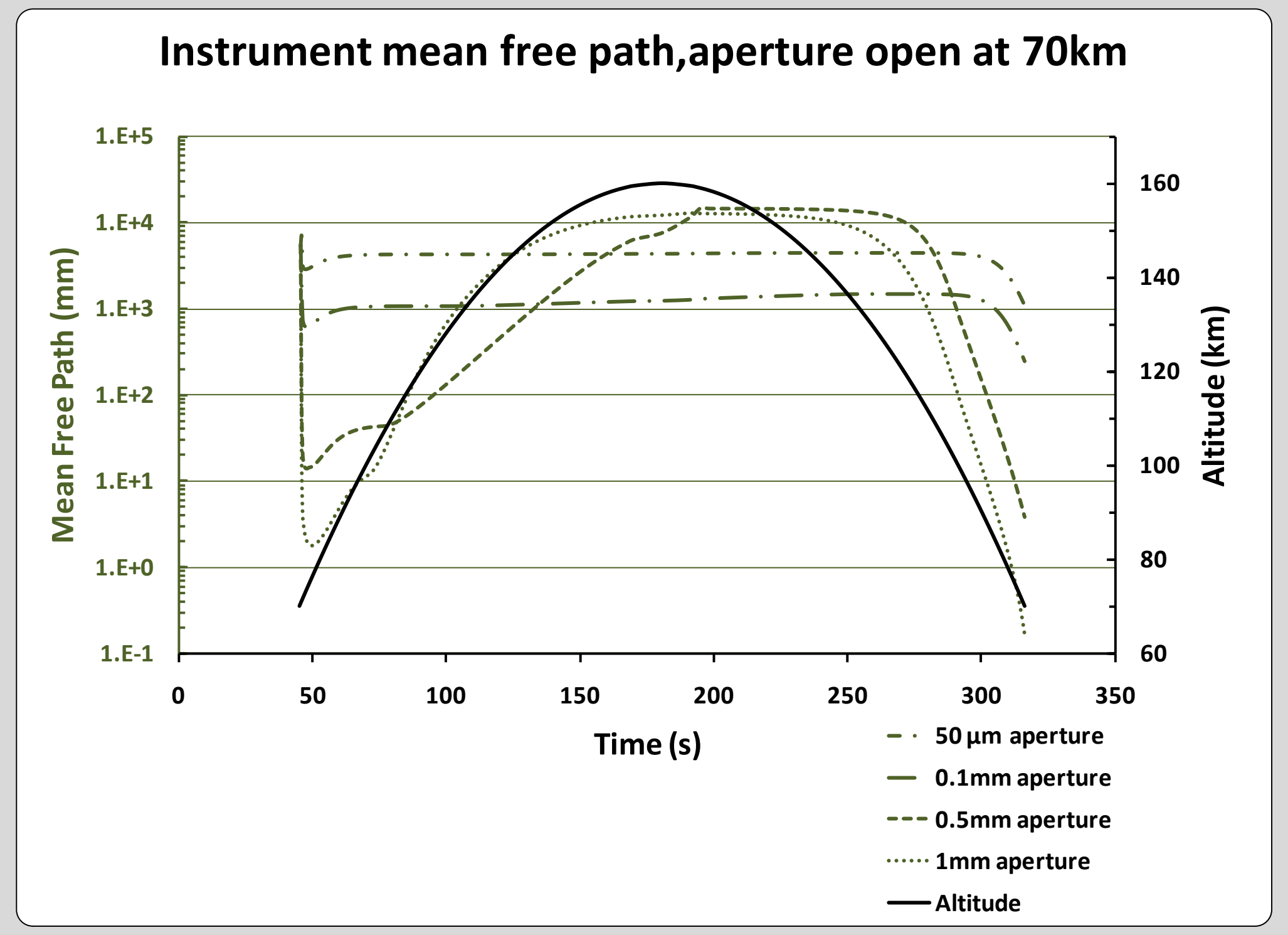

Ambient atmosphere


Bow shock enhancement

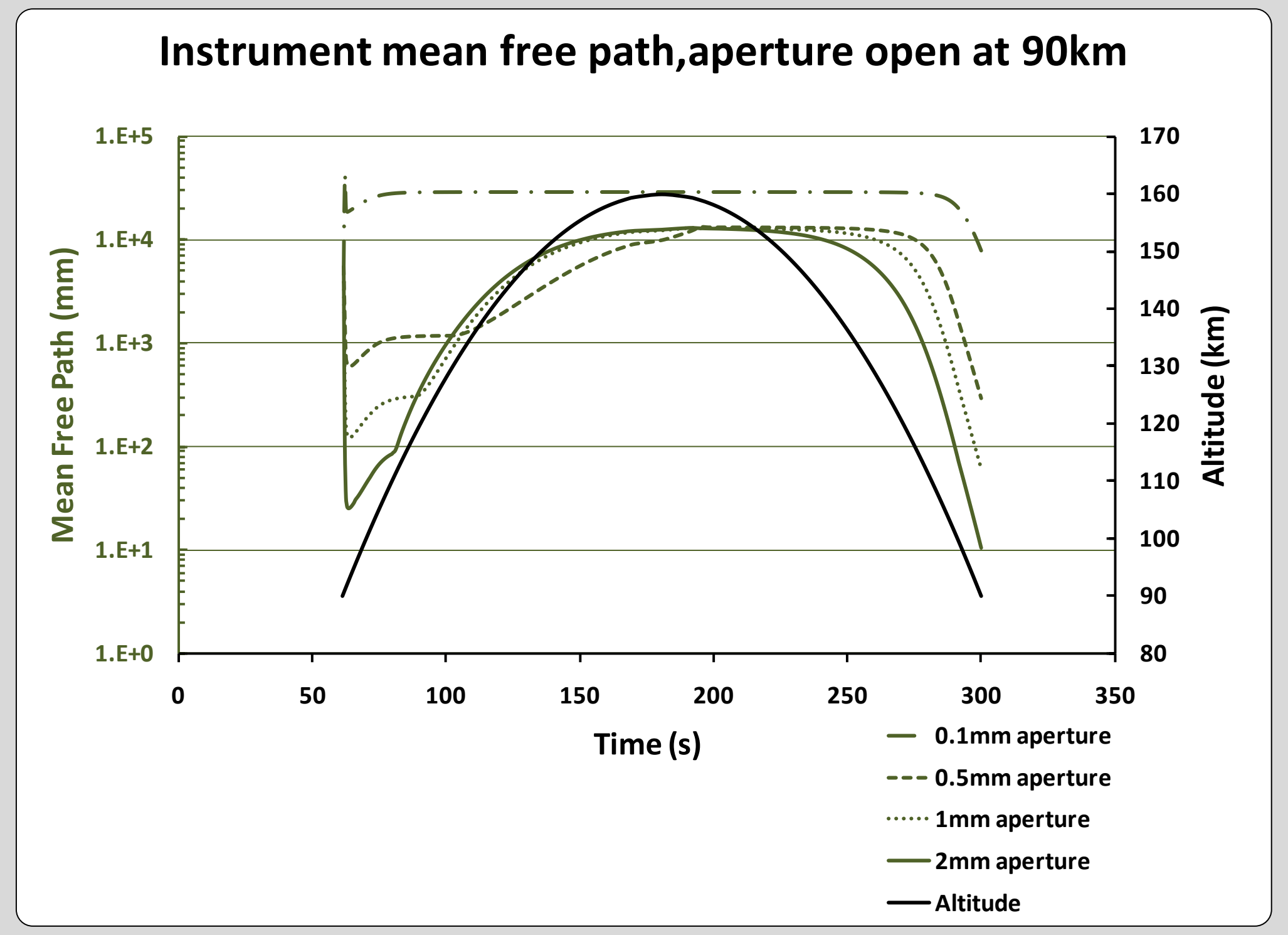
Instrument Pressure and Pumping Modeling

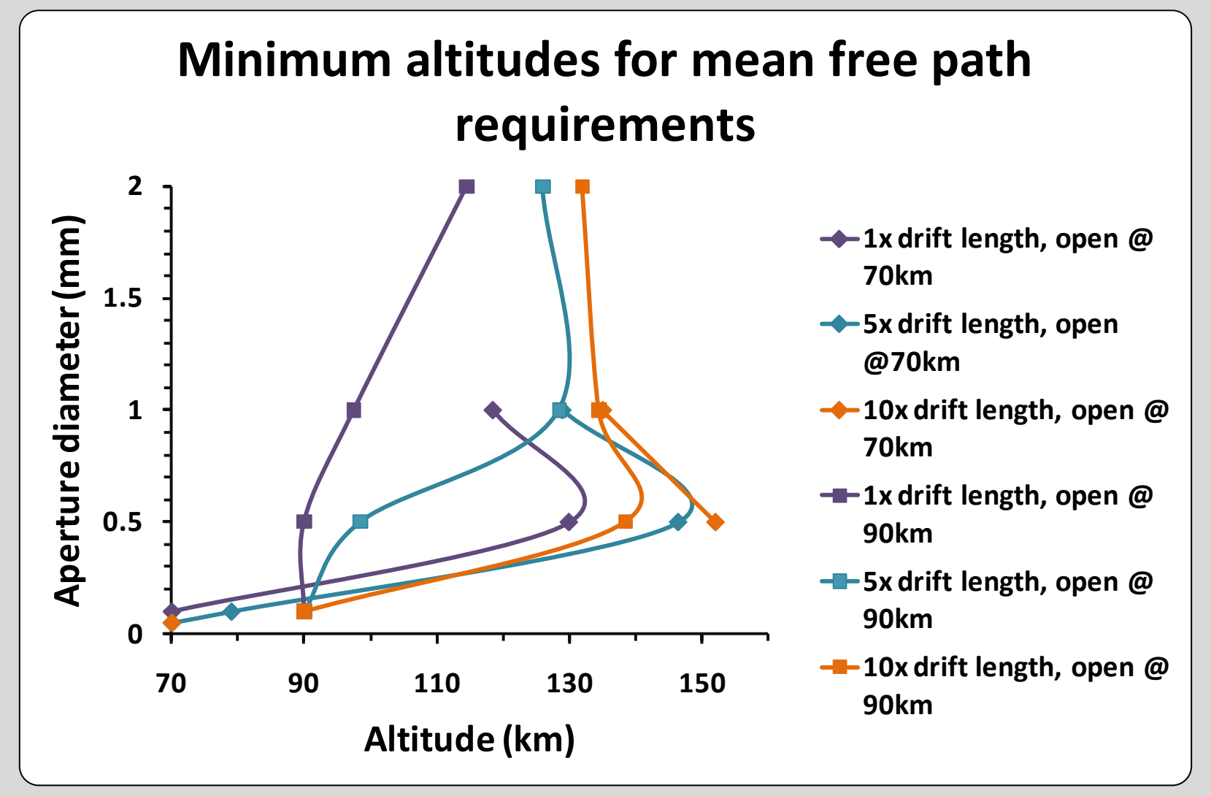
Results from the gas flow simulations discussed above were used as inputs to gas flow models to study conditions inside the instrument. Standard gas flow equations were applied to model the mean free path inside the instrument for a variety of aperture sizes, rocket velocities, and aperture-open altitudes. The graphs in this section were generated for velocities consistent with a 160km ballistic apogee.


Instrument pressure, aperture open at 70km


Instrument mean free path,aperture open at 70km

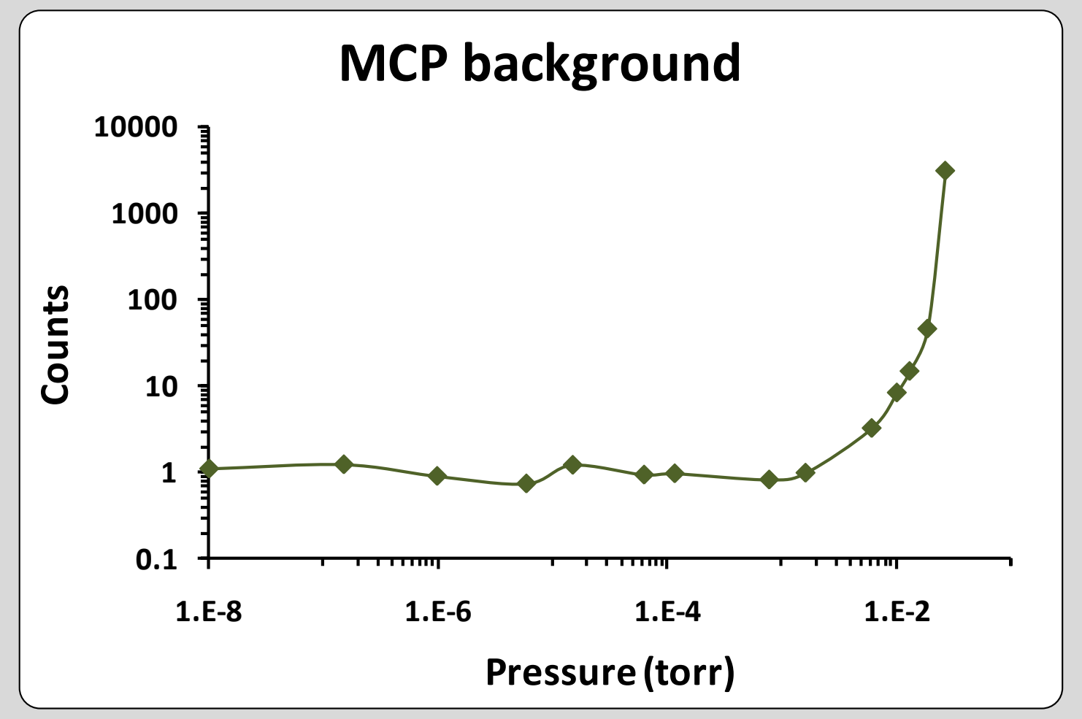
Instrument Pressure and Pumping Modeling, continued

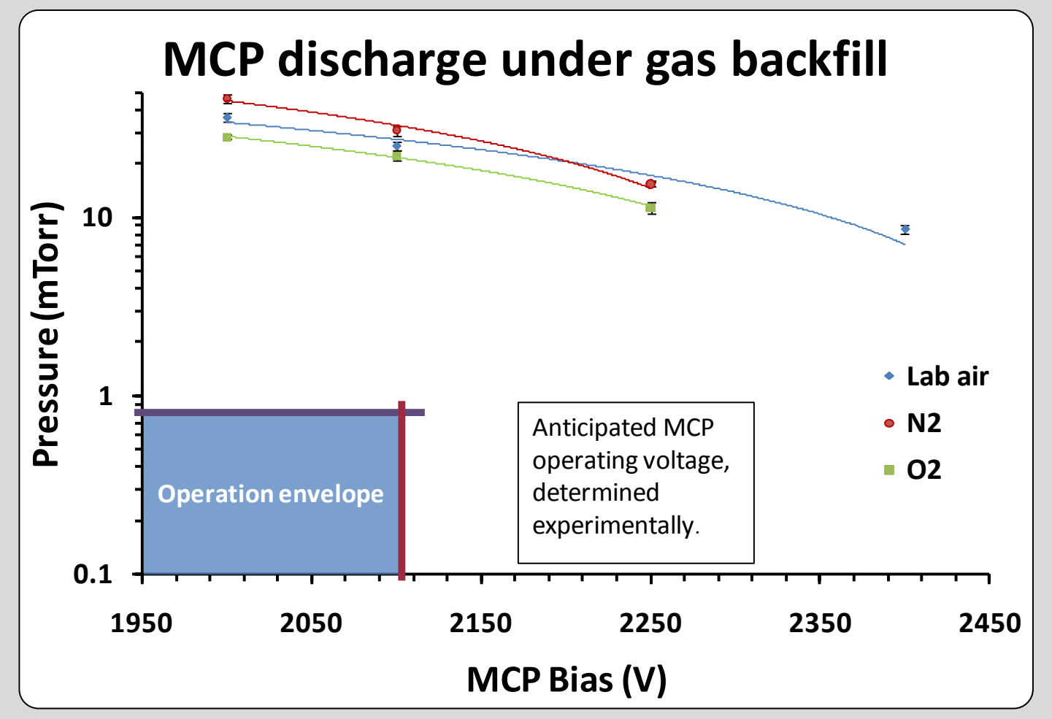

Instrument mean free path,aperture open at 90km


Minimum altitudes for mean free path requirements

The relationship between aperture size, opening altitude and mean free path is complex. The minimum altitude at which certain instrument mean free path lengths are achieved is shown above. Small aperture sizes are necessary in order to limit the amount of gas entering the instrument at low altitudes. The instrument pressure, and hence mean free path, are determined by three main factors: aperture size, aperture open altitude, and getter tube pumping characteristics. To minimize collisions between particles in the instrument and therefore maximize instrument performance, a mean free path of at least 10x the drift length is critical. Future work will determine experimentally the pumping speed and capacity of the barium getter tubes. The information gained from these experiments will then be used to more accurately model the instrument pressure and mean free path.

MCP High-Pressure Testing


MCP background


MCP discharge under gas backfill

High pressure operation of an MCP was demonstrated by backfilling a vacuum chamber with various gases including N_2, O_2, Ar, He, and ambient lab air. MCP discharge pressures were recorded and are plotted in the figure to the far right. Note that all discharges occurred at pressures well above the expected operating pressures of the instrument. The figure above ("MCP background") shows MCP background counts at increasing pressures under an N_2 atmosphere, at a potential of -1900V. These experiments suggest that an MCP can be successfully deployed in the MLT.

Conclusions

The simulations and experiments presented in this poster show the possibility of operating a simple TOF mass spectrometer in the MLT. Rigorous simulations and modeling of gas flow and vacuum pumping show that necessary mean free path requirements can be met at altitudes as low as 70km. Experiments involving MCP operation at high gas pressures have shown that an MCP can be safely operated in the mesosphere. Specifically, these results show that:

- Mean free path requirements necessary for successful TOF measurements of the MLT can be achieved.
- MCP operation has been demonstrated at elevated pressures reaching into the mTorr and even tens of mTorr range.
- A simple inexpensive vacuum pumping system capable of achieving and maintaining acceptable pressure in a TOF instrument has been simulated.

Acknowledgments

This work has been supported by NASA grant # NNX09AH97G. We would also like to acknowledge Dr. Charles Swenson, Scott Schicker, and Ben Sampson for input, lab help and many interesting and thought-provoking conversations. DSMC gas flow simulations were conducted using the DS2V program version 4.5.06, from Professor Graeme Bird.