

A Compact High-Resolution Ion & Neutral Time-Of-Flight Mass Spectrometer for Advanced Space Applications

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ABSTRACT

We present the design, development, and testing of four novel, compact, high-precision Time-Of-Flight (TOF) Mass Spectrometers (MS) for integration with the next generation of space flight platforms. These MS instruments are capable of sampling both ions and neutral elements and are designed to integrate with a variety of space flight vehicles, including sounding rockets and small satellites (ESPA & 12U CubeSats or larger). One of the four flight instruments has been prototyped as a sounding rocket payload with a SWAP of approximately ~8 kg, and ~15 W using a 12-bit 3.2Gs/s analog-to-digital converter data acquisition system (With a Time to Digital Converter (TDC), 10-15 W possible), and a size of ~61 x 27 x 9 centimeters (volume: ~14800 cm³). The TOF-MS instrument has a demonstrated resolving power at full width, half maximum (FWHM) of better than 3500 (modeling predicts 5000), and a mass capability of 2u to 1500u. This instrument has undergone relevant laboratory testing and TRL advancement and will be demonstrated at the Neutral Beam facilities in Berne, Switzerland. The TOF-MS analyzer incorporates two separate ion sources. For neutrals, an improved three-stage Wiley-McLaren electron ionization source (EI) with a space charge trapping capacity at low gas densities. For ions, a Bradbury-Nielson (BN) comb shutter is used. Both sources are axially aligned with common focusing elements, and the measurement of ions and neutrals can be interleaved or measured independently. The mass analyzer consists of a field-free drift region, two electrostatic, two-stage ion reflectrons (ion mirrors), and a microchannel plate detector (MCP). To improve the mass resolution, while maintaining a small form factor, the ion path is folded into a W-configuration using a triple reflection principle between two electrostatic ion mirrors. This style of MS design offers several advantages, including Full spectrum sampling (~100 kHz), Fellget's multiplex advantage, high precision isotope sampling, nearly unlimited mass range depending on input voltage, and a relatively low noise floor. This TOF-MS will serve as a compact, high-precision instrument for the next generation of advanced space missions, including atmospheric sounding, VLEO satellites, and in-situ chemistry sampling of asteroids or planetary bodies.

INTRODUCTION

Mass spectrometers have a long history in Earth and Space Science dating back to before the Apollo program in the 1960-1970s. On planetary missions, the two Viking landers in 1976 and the Galileo probe mass spectrometer to Jupiter². More recently, the Phoenix lander on Mars positively identified the presence of water on the polar regions of the red planet and mass spectrometers have been used to identify and characterize organic molecules in the Saturnian system on the Cassini mission and at Comet 67P/Churyumov-Gerasimenko where the Rosetta mission employed four mass spectrometers to study the comet's composition. Results from these missions reveal the powerful benefits of mass spectrometry, along with the challenges of this sensitive *in-situ* technique to increase scientific understanding of diverse terrestrial

and extraterrestrial environments, including biosignature detection, to a new level.

Here, We describe four mass spectrometer systems designed by the Southwest Research Institute to study diverse environments using the time-of-flight (TOF) principle for mass analysis. In addition, we will discuss the design, application, and perspective mission of the Mass Spectrometry of the Turbopause (MSTR) Cryogenically cooled TOF-MS instrument.

The time-of-flight design principle was chosen over other designs, (quadrupole, ion trap, magnetic sector) for its superior mass resolution, high sensitivity, high mass range, and the measurement of the entire mass range in each extraction pulse. The need for high-speed data

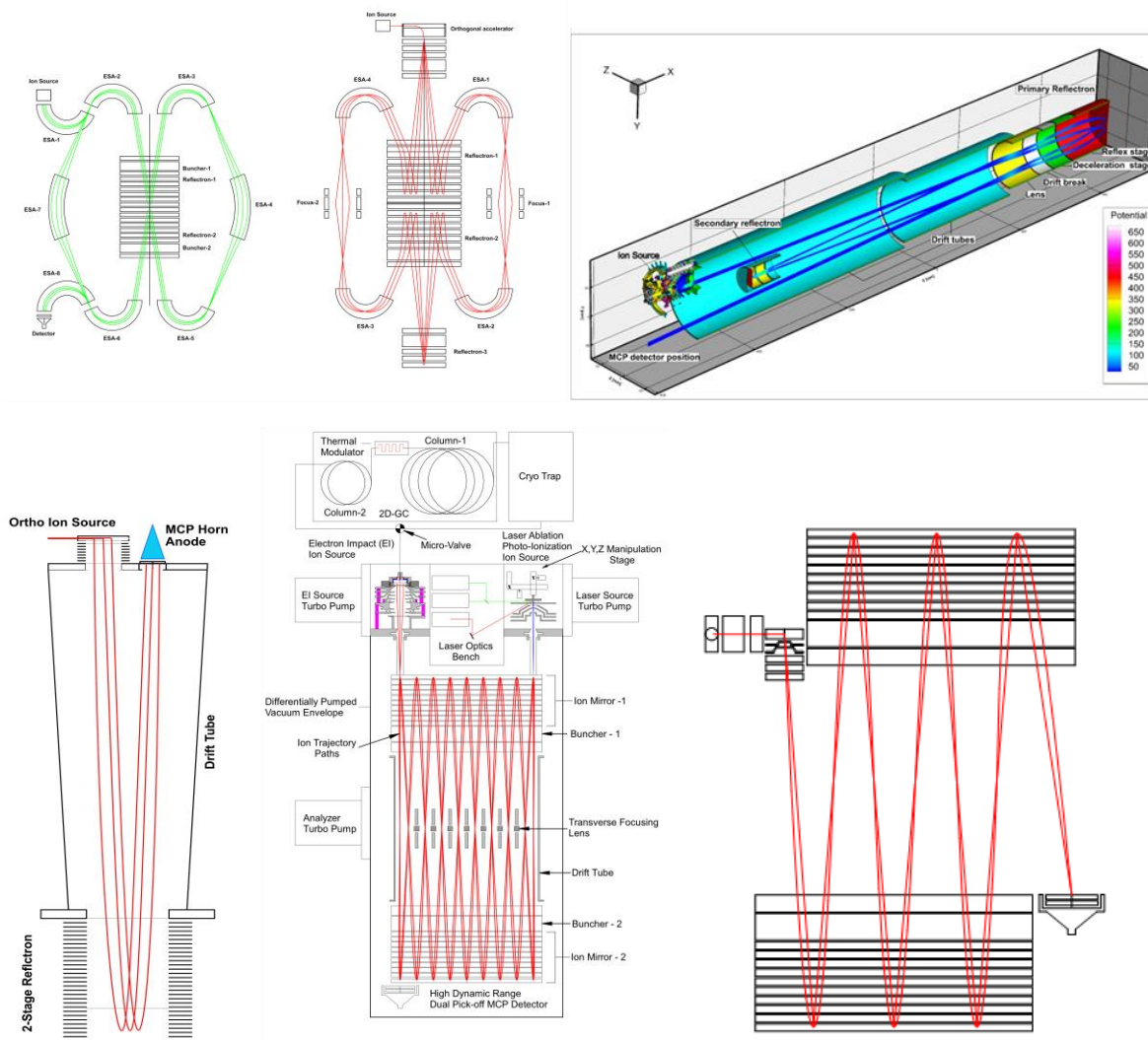


Figure 1. Various ion optical arrangement studied to design a small high- resolution mass spectrometer

acquisition, once considered a limitation for a TOF-MS instrument, has now been largely overcome with the availability of high-speed (4-GSps) analog-to-digital converters (ADC's) with up to 14-bit vertical resolution with radiation tolerances greater than ~300 KRad. The science requirements for measurement of species evolving for example, vents of Saturn's moon Enceladus, or Jupiter's moon Europa with a tenuous exosphere require mass spectrometers on spacecraft with fly-by velocities even as low as 4 km/sec to have sufficient spatial resolution to map the position potential hydrothermal vents. At the same time, the measuring requirements for high mass range and sensitivities in the parts-per-million to parts-per-billion at high mass resolution are required for compounds of geochemical and biological importance. A high dynamic range is also essential in these applications to correctly measure the

relative intensities of weak and intense peaks simultaneously. This is vital in the analysis of mass spectra and for example in the precise estimation of isotopic abundances where measurement of variations from the natural abundances provides a powerful tool for investigating terrestrial and extra-terrestrial processes that influence the abundances.

New, modern time-of-flight mass spectrometers are inherently well suited for these types of measurements⁵ due to their high speed, large mass range, and large apertures (geometric factor) employing storage ion sources where ions are accumulated during the time-of-

flight measurement for a significant improvement in sensitivities and duty cycle.

Requirements for New Advanced Instrument Design

- Spatial resolution: The ability to make science measurements from a moving platform on short time scales (sounding rockets, asteroids, comet flyby measurements).
- High sensitivity for measuring a tenuous exosphere.
- High mass accuracy and resolution using mass defects to determine empirical formulas of unknown compounds.
- High mass resolution to resolve isotopologues, and minor isotopes.

The four time-of-flight mass spectrometers systems described here have a common data acquisition system based on an analog-to-digital converter (ADC) on a flight-qualified data acquisition processor (DAP) operating between 1.6 GSps in low power mode to 3.2 GSps with interleaving at a 12-bit vertical resolution up to 7 kHz rates (7000 spectra/sec). All four instruments operate at a minimum resolution of $R = T/2 \Delta T \sim 1000$ to over 200,000 for MASPEX, a multi-pass time-of-flight mass spectrometer, and a mass range above 1000u. To maintain this high resolution, all four instruments employ a folded optical path, effectively extending the flight time in the same physical volume while maintaining a relatively small footprint and pumping volume. Three of the instruments (V-TOF, W-TOF, and MASPEX) are fitted with a flight-qualified electron ionization ion storage source developed for the Europa-Clipper MASPEX instrument while the fourth instrument Zz-TOF can accommodate the storage source, as well as an orthogonal source or combination of both. Early development, more than 20 years ago, in our laboratory took into consideration several possible folded optical paths and ion-optical arrangements that would maximize mass resolution and sensitivity while constraining the size and volume required for a practical flight instrument. Some of these early design concepts are shown schematically above in Figure 1.

Of the many possible instrument designs, we have concentrated on ion optical designs that give us the highest mass resolution, sensitivity, and mass range. This design decision is based in part on our experience gained, and lessons learned as the science lead institution for the Cassini orbiter mass spectrometer and its flybys of the Saturnian moons Titan and Enceladus where the lack of mass resolution and mass range was a limiting factor in the science investigation.

MASPEX: Mass Spectrometer for Planetary Exploration

Mass Spectrometer for Planetary Exploration (MASPEX-EUROPA) is a high-resolution time-of-flight mass spectrometer selected by NASA to fly on board the Europa-Clipper orbiter to explore Jupiter's moon Europa². The mass spectrometer has been under development since 2002^{3,4} with a launch planned for August 2024. The instrument has been ruggedized for the tough radiation environment of Jupiter and will analyze the composition of Europa's surface while in orbit by flying through Europa's tenuous atmosphere.

The MASPEX mass spectrometer employs a coaxial multi-reflection ion path principle thereby extending the flight path and mass resolving power. Resolution of well over 50,000 can be achieved with high ion transmission. The spectrometer is fitted with a storage ion source to enhance its sensitivity, and a Faraday cup and gas calibration system are used to measure absolute gas densities. A cryogenic trapping system for low-abundance species during a fly-by of Europa further enhances the instrument's dynamic range. An integrated ion gauge is used to ensure safe operating pressures. The instrument's high resolution and high sensitivity allow the unambiguous measurements of the isotopes of many small volatile molecules with high mass measurement precision. The MASPEX instrument is shown in Figure 2 below, along with the extraction, injection, trapping, and detection operational concept on the right-hand panel.

MASPEX: Operating Principles

MASPEX generates ions by electron ionization in a field-free region defined by two parallel high transmission grids (13.3 mm diameter separated by 2.38 mm gap) held at ground potential. Electrons are nominally accelerated to 70 eV and focused as a narrow sheet across the ion volume by a beam-defining slit (5 mm long and 0.38 mm high). Electron paths follow tight helical trajectories resulting from two collimating magnets held in attraction parallel to the electron beam path before the application of the extraction pulse. The helical electron path increases the ion-electron

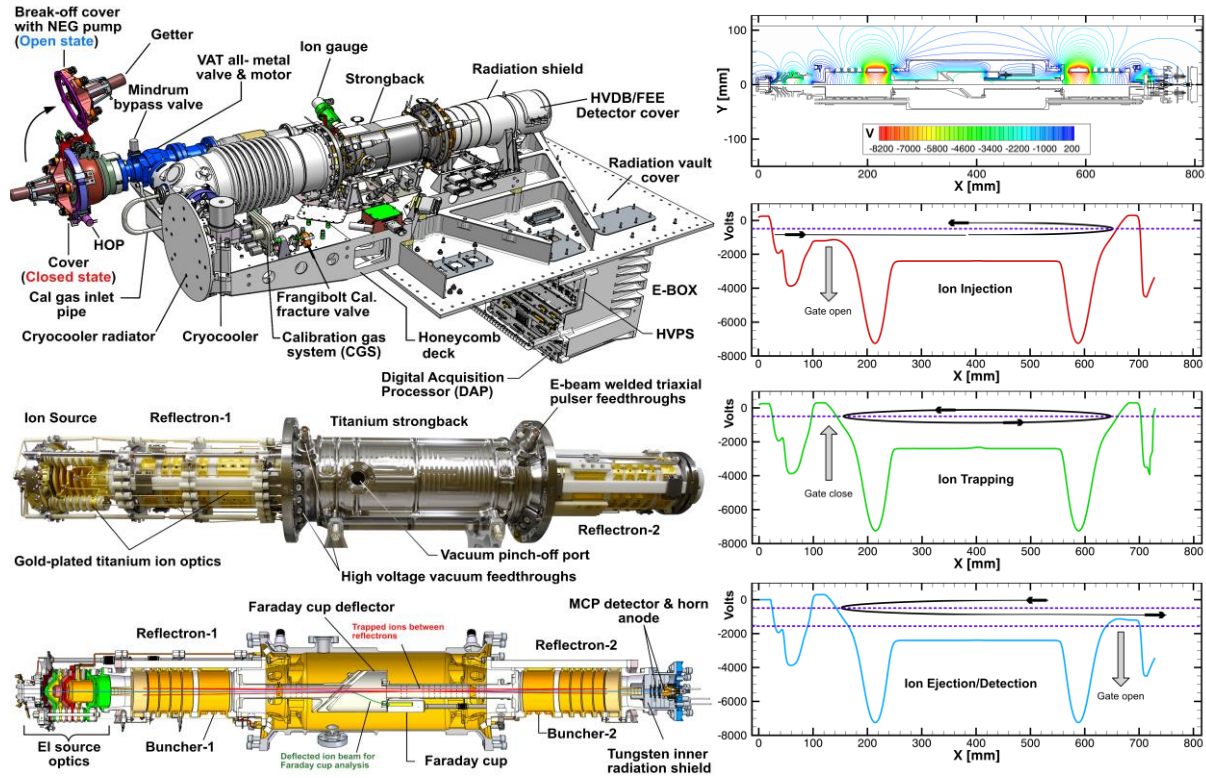


Figure 2. MASPEX-Europa ion optics and operating principles. Potential diagram on the right shows the operation sequence for extraction, injection, trapping and detection.

interaction time to improve ionization efficiency and generates a weak space-charge potential well that stores ions between extractions improving source sensitivity. To generate a time-of-flight mass spectrum, ions are bunched and accelerated into narrow packets along the time-of-flight direction that are dispersed in time according to their mass-to-charge ratio based on the time-of-flight equation.

Where,

$$t = \left(\frac{m}{2qES} \right)^{1/2} \times (2s + L)$$

- t = The time of flight
- m = the mass.
- E = the electric field between pusher and extractor
- s = grid separation distance.
- q_e = elementary charge
- L = drift length

To extract the ions into the TOF analyzer, we apply two, fast (~ 5 ns rise-time for 3 μ s), push/pull pulses to energize the pusher grid with a positive voltage ($\sim +400$ V) and extractor grid with a negative voltage (~ -150 V) pulse. These pulses are delivered by a set of GANFET-based switching pulsers applied to the pair of grids whose gap defines the ion volume. The high electric field (> 100 V/mm) generated during extraction imparts an acceleration to the ions out of the ion volume of constant energy per charge. Two accelerating electrodes just after the extractor grids provide a second and third extraction electric field region whose ratio to the electric field produced by the pusher-extractor combination defines the position of the first-time focus plane. Ions leaving the accelerators then pass through a set of lens elements used to focus and inject the ions into the mass analyzer. See Figure 2 bottom left. The analyzer section of the mass spectrometer comprises two reflectrons (ion mirrors) in a coaxial arrangement separated by a field-free drift tube region. This arrangement of electrodes artificially extends the ion flight path to an arbitrarily selected length by reflecting the ion packets back and forth between the reflectrons using a fixed analyzer length. To trap the ions between the reflecting fields, the potential on the back of the first reflectron element is momentarily lowered below the energy of the ion

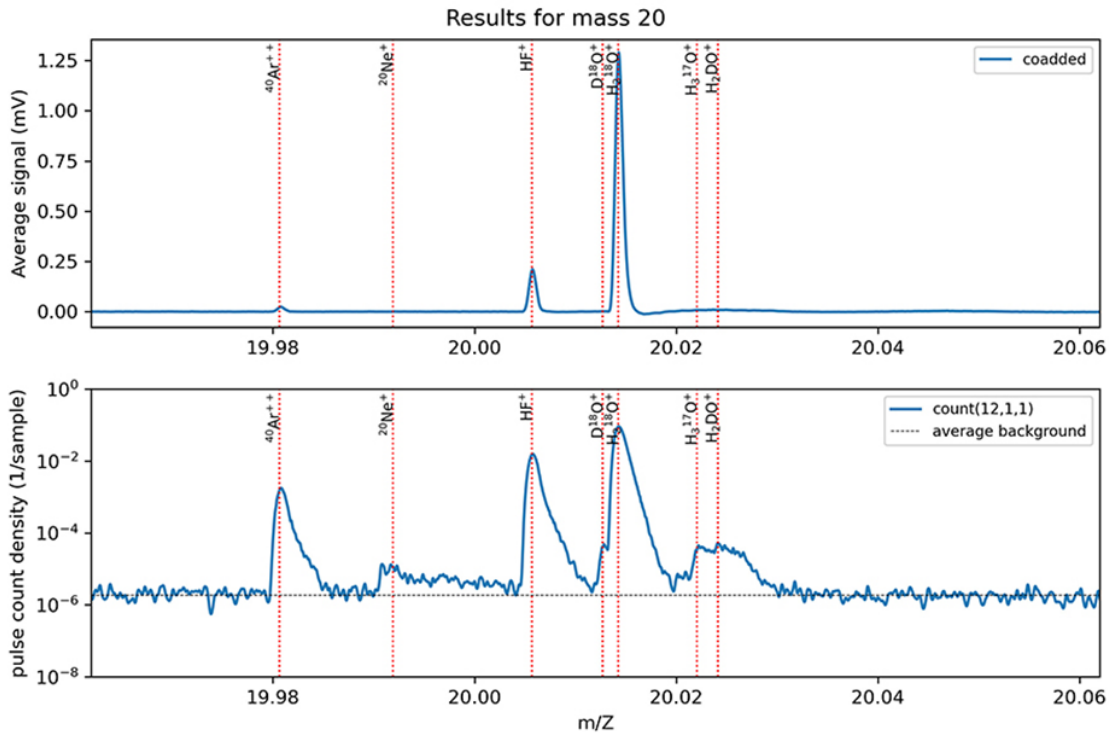


Figure 3. Mass spectrum for ions with $m/z=20$. The top spectrum is the coadded spectrum and the lower spectrum is the count spectrum. The high resolving power allows the accurate mass measurement to identify species based on mass defects.

packets during ion extraction while we maintain the trapping field of the second reflectron element. The injection, trapping, and ejection potentials are switched by a pair of bipolar GANFET based switching pulser units switching between -1100 V during the injection phase and +350 V during the trapping phase in about 30 ns. Once the injected ion packets have cleared the first reflectron element and entered the field-free drift tube, we raise the potential, in approximately 30 ns, of the first reflectron to the trapping potential. Trapping the ions inside between the two gridless two-stage reflectrons. To maintain the ions isochronous and stable trajectories inside the analyzer without losses, two ion bunches have been fitted on each of the reflectrons to provide transverse focusing of the ion packets during multiple reflections (passes) while they generate the required accelerating field for the second stage of the reflectron of the two-stage mirror.

The two-stage reflectrons provide second-order kinetic energy focusing achieved without the use of grids in the analyzer that would reduce transmission to unacceptable levels for ions reflecting back and forth between the ion mirrors. The two electric field regions on MASPEX are generated by control of the field penetration between the

bunchers and the reflectron lens elements. To detect the ions after executing N number of passes, the trapping field of the second reflectron end element is timed to allow ions to leave the analyzer and registered on a fast microchannel plate detector with an impedance-matched conical anode, to match the 50 Ohm termination resistor. The arrangement of the electrodes allows separated mass ions to be brought into time focus at the detector after executing multiple passes in the analyzer extending the mass-resolving power with high ion transmission. The extraction, injection, trapping, and mass analysis are performed at kHz rates to enable the detection of fast-changing composition. The MASPEX resolution $> > 50,000$ however requires high voltage stabilization < 5 ppm for up to 8500 V and precision machining of field-forming electrodes. To accomplish this requirement, several critical high voltage supplies have specialized temperature compensation and voltage stabilization circuitry. MASPEX has the capability of running in several modes. ICE mode enables constant monitoring for ice grain impacts during Europa's closest approach. In this mode, hydrogen is mass analyzed in linear TOF without reflections by delaying energizing the trapping potential of the second reflectron for a short period. This

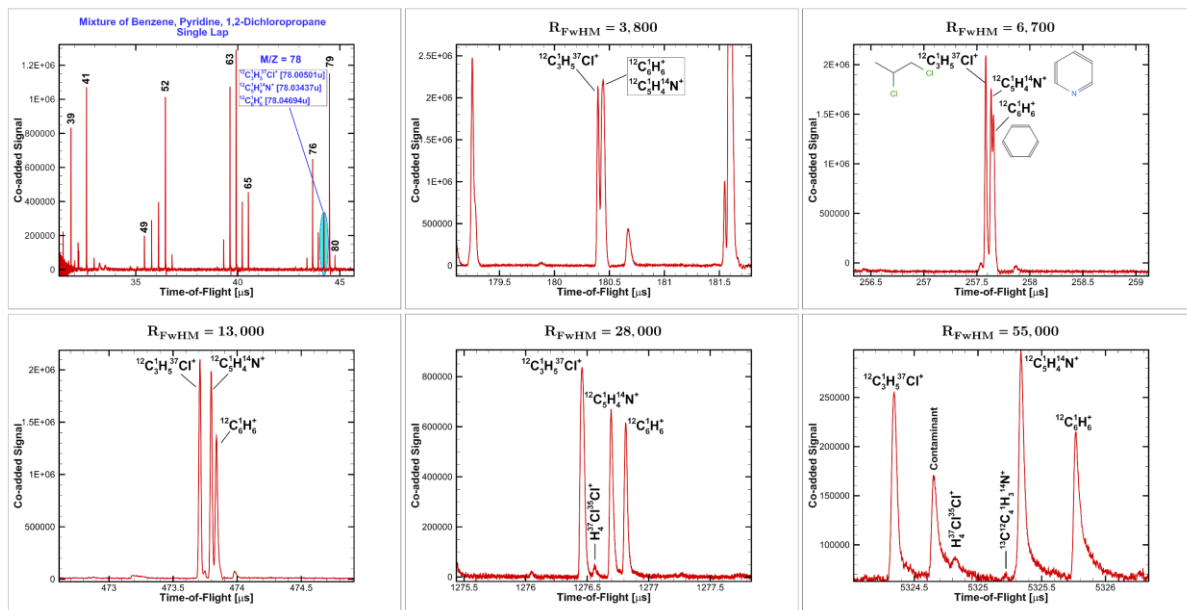


Figure 4. Mixture of benzene, 1,2-dichloropropane and pyridine. The first panel shows a single lap broadband spectra with mass 78 highlighted at an approximate resolution of $t/2\Delta t \sim 1000$ for one pass through the mass analyzer. Notching was used to eliminate most of the unwanted fragment ions from this three component mixture concentrating on the triplet near mass 78. Increasing the lap time to a resolution of $t/2\Delta t = 55,000$, the mass triplet can be fully resolved to baseline.

allows the low mass region of hydrogen and up to helium to pass through before switching on the mirror end cap potential to trapping potential for multi-pass TOF analysis. A trigger is initiated by a sudden change in the hydrogen abundance, at which time the mass spectrometer runs a series of measurements that may include looking for amino acid mass ions. The resolving power of MASPEX is shown in Figures 3 and 4 above. MASPEX is capable of distinguishing small mass differences used to identify compounds with similar masses. Another example of MASPEX's capabilities is shown in Figure 5, where oxygen is isolated with a resolving power of 234,000 with a trapping time of over 15 ms showing the trapping stability of the analyzer.

MASPEX can also filter out unwanted ions such as water peaks that might saturate the detector and isolate ions of interest by notching out unwanted species from the spectrum that may interfere with the analysis by momentarily dropping the potential either the source or detector (notching) removing the ions from the mass analyzer. This cleanup of the spectra greatly simplifies the interpretation of the mass spectra because ions that are not in the targeted mass window can be removed and not registered at the detector.

Mass resolution and accurate mass measurement are related. For Gaussian TOF peak shapes, mass measuring

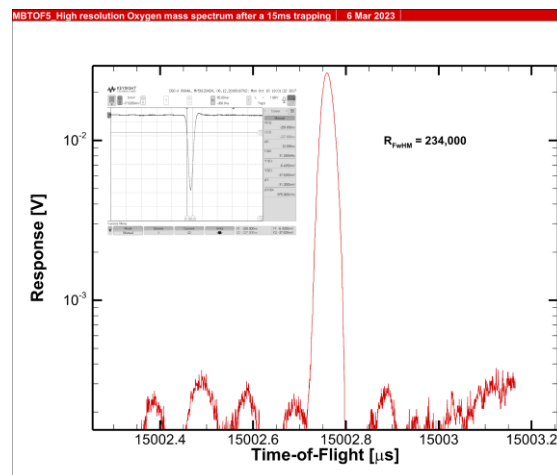


Figure 5. Demonstration of very high resolution of oxygen trapped for 15 ms at a resolving power of $t/2\Delta t = 234,000$. The resolution is limited by power supply stability and the ion energy distribution in the storage ion source.

uncertainty is reduced by higher resolving power R_{FWHM} and the square root of the number of ions

$$\left(\frac{\delta m}{m}\right) * 10^6 [ppm] \approx (2\sqrt{2\ln 2} \cdot (R_{FWHM}) \cdot \sqrt{N_{ions}})^{-1}$$

Where,

$\frac{\delta m}{m}$ is the mass uncertainty in parts-per-million,

R_{FWHM} is the mass resolution at FWHM,

N_{ions} are the number of ions in the source.

The importance of high resolution with accurate mass measurement allows for the unambiguous identification of compounds in a mixed gas phase without prior separation techniques such as gas chromatography.

Zz-TOF

We have developed a small, folded optics high-resolution multi-pass TOF based on a Zig-Zag trajectory. Zz-TOF was developed using internal funds. Unlike MASPEX, the resolution is fixed but the advantages are the observation of the full mass spectrum in a single pass without low mass ions lapping and the need for ion notching as on MASPEX. Other advantages include less complex power supply requirements, only two pulsers for extraction, the ability to use a continuous ion source, the ability to operate at substantially higher pressure using a differentially pumped ion-optical arrangement, and the possibility of using two sources and two detectors either for redundancy or for different ionization techniques (e.g. EI and laser ionization).



Figure 5. Photo of the orthogonal accelerator optics with 4 degree bend. Source provides extraction, acceleration, focusing and deflection.

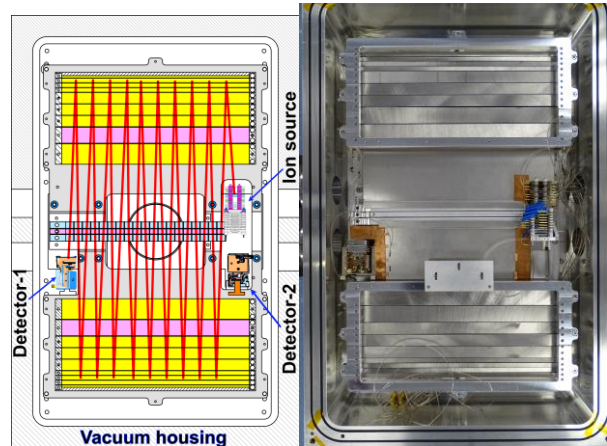


Figure 4. Zz-TOF CAD rendering showing the folded ion ZigZag path in the analyzer. A photograph of the lab prototype is shown on the right with the drift tube shields mounted over the deflection system.

Zz-TOF Operating Principles

The mass spectrometer CAD rendering and photograph are shown in Figure 6. In a Zz-TOF configuration, ions are injected orthogonally into the pulsed accelerator electrode shown as the (ion source) in Figure 7. Ions are then pulsed out, focused as a rectangular beam, and execute a Zigzag path reflecting back and forth through the rectangular gridless reflectron, see Figure 6.

The shape and potential applied to the reflectron ensure that the second-order time focusing of the isochronous packet of ions is focused at the detector plane. To maintain transverse focusing a series of 19 einzel lens elements with a single voltage is used to maintain focus. With exception of the pusher and extractor, all voltages are static and the two reflectrons share identical voltages, to reduce the number of power supplies needed for its operation. In addition to the flight path shown in the in Figure 6 left panel, two small deflectors at the ends of the einzel lens elements can be used to fold back the ion path and intercepted by detector-2. This operational mode doubles the flight path and doubles the resolution of the instrument. The prototype instrument was designed for use with a gas chromatograph for future lander missions using an external ion source that can operate at much higher pressure using a conductance limiting slit. The external ion source was also designed to remove hydrogen or helium ions from entering the mass analyzer by a small magnetic deflection system reducing scattering and noise from the high abundance carrier gas ions that would be transmitted if they are not removed.

MSTR V-TOF & W-TOF Development

The V-TOF and W-TOF instruments, see Figure 8, were developed under the NASA MSTR program, an HFORT grant, funded through the Heliophysics Technology office. The objective of MSTR was initially to develop a V-TOF single reflection mass spectrometer and raise its technical readiness for a potential sounding rocket application to study the Earth's upper turbopause region. This design was later enhanced by introducing an additional reflection stage resulting in a triple reflection to enhance its resolution. The turbopause region of the upper atmosphere between 70 and 120 km is poorly understood and of high scientific value. A time-of-flight mass spectrometer was selected for development due to its extremely fast spectral acquisition (> 5 kHz), high mass range (> 1000), high mass resolution (> 1000), high spatial resolution and high sensitivity (> 0.02 Counts/sec)/(molecules/cm³). The instrument was

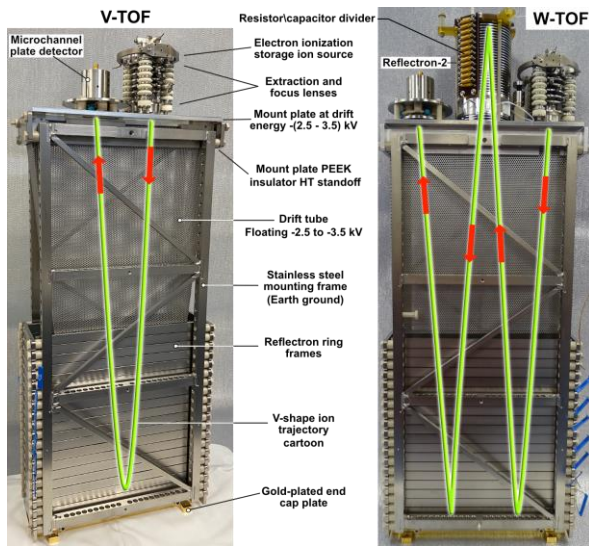


Figure 6. Side-by-side image of V-TOF single reflection and W-TOF triple reflection TOF instruments. W-TOF adds an additional static voltage reflectron to improve the resolving power of the instrument.

designed around the MASPEX TRL9 storage ion source for the analysis of neutrals, a Bradbury-Nielsen gate (BNG) is employed for the analysis of ions Figure 9.

V-TOF & W-TOF Operating Principles

Both V-TOF and W-TOF operation is similar using the same extraction principle. In neutral mode, gas molecules enter through the cryogenic bow shock reducer and through the energized BNG gate to prevent ions from entering the mass spectrometer ion source. See Figure 9 and 10, Ions are created between the pusher and

extraction gridded electrodes kept at earth ground by the ionizing electron beam. Ions are extracted into the analyzer by a fast rise-time (5ns) push-pull pulse of 3us duration to extract the ions out of the ionization region into the acceleration and focusing region of the ion source. The application of the extraction pulse can be varied between 1 Hz to more than 5 kHz for fast data acquisition. In ion mode, the electron beam is gated off and the BNG is pulsed to rapidly gate ions through the opening of the storage source which is not pulsed in this mode of operation, but the lens focusing elements are employed to focus the gated ions into the mass analyzer.

Mass spectra acquired with W-TOF show the improved resolution over V-TOF separating ions near the argon mass region (see figure 11 below). The top panel shows spectra in red using the V-TOF configuration. The spectra shown in blue were acquired in the W-TOF configuration clearly showing improved mass separation. The higher resolution allows higher mass measuring precision to identify unknown species in the mass spectrum. The undershoot seen is due to some

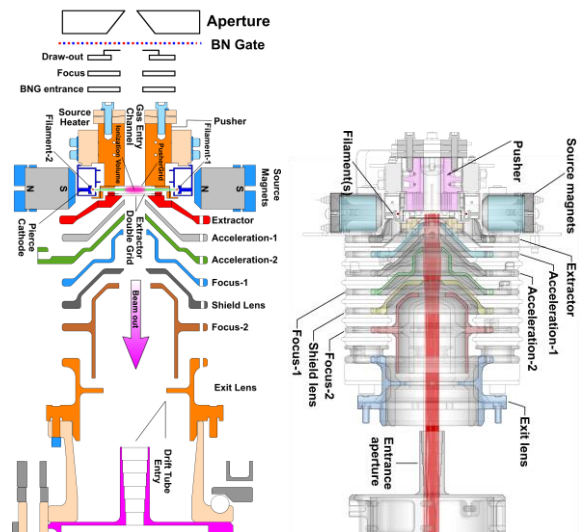


Figure 7. Left, Ion BNG and neutral storage ion source used on V-TOF and W-TOF mass spectrometers. Right, Charged optical ray trace of the ion source. Ions extracted from the source are shown in red.

impedance mismatch of the signal to the data acquisition system. Figure 12, shows the spectra of a leaked-in mixture of noble gases in addition to background ions from water and air. A zoomed-in view of Krypton, and one of xenon, Figure 13, shows the performance of the W-TOF in detecting all the major, as well as the minor, stable isotopes of those two gases consistent with

accepted isotope abundances. Additional fragmentation patterns are being evaluated for compounds of interest for a proposed flight mission to the turbopause region. These fragmentation patterns will be used to calibrate the instrument against the National

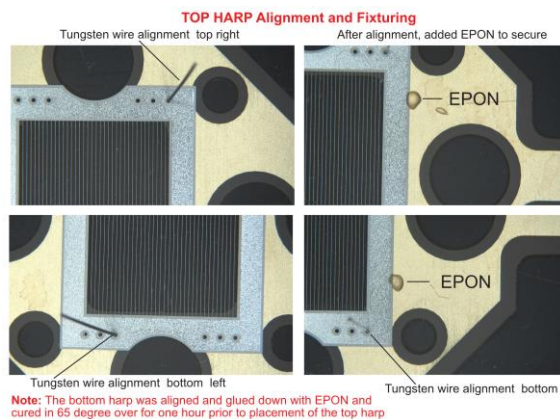


Figure 9. Photograph of BNG gate assembly of two interleaved BNG electroformend harps. Equal but opposite voltages are applied to each interleaved harp to block the ion transmission. When gated off, ions pass through the harps and enter the mass analyzer. The gating is applied at about 2 kHz.

Institute of Standards (NIST) mass spectral database using search algorithms.

The MSTR Program

The underlying physics of the upper atmosphere's turbopause region (80 to 120 km), is one of the most important, yet poorly measured and least understood topics in aeronomy today. With increasing altitude, it is seen that the photochemistry and dynamics in this region of the atmosphere are complicated by its transition from a fully mixed state to a state of diffusive equilibrium. With, even small variations in the composition and dynamics of this region having profound effects on the global and regional climatological behavior of the thermosphere-ionosphere system. The study of this region is complicated by the relative difficulty of accessing VLEO, the Turbopause region is too low for satellite missions and simultaneously too high for traditional flights or weather balloons. Therefore, sounding rocket missions are required. To address these issues, we propose to make the first ever simultaneous composition measurements of O, O₂, N₂, NO, CO₂, H₂O, O₃, and Ar spanning the 80 to 120 km altitude region with a rocket flight as part of the Cryogenic Mass Spectrometry of the Turbopause Region (CMSTR). The CMSTR payload will consist of the V or W-TOF MS instruments described above and feature a cooled

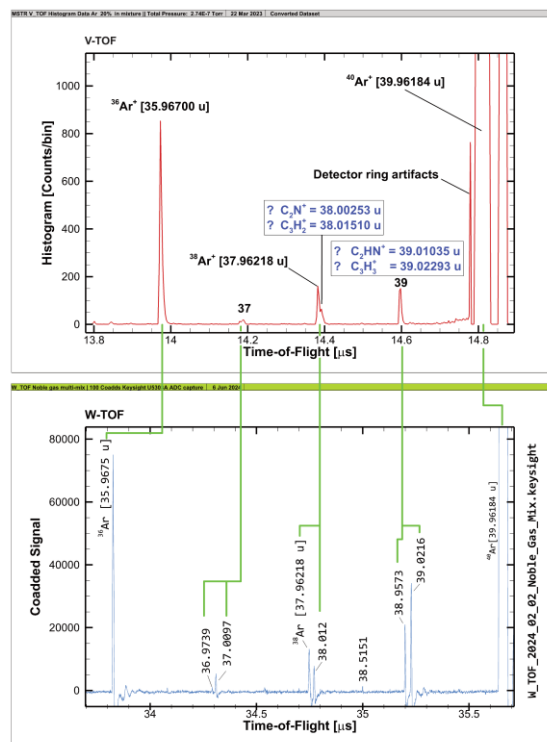


Figure 8. Mass spectra acquired near argon isotopes. The top panel was acquired in the V-TOF configuration while the bottom panel and spectra were acquired in the W-TOF configuration with improvement in mass resolution.

nosecone to collapse the bow-shock produced during supersonic flight.

Science Objectives

The CMSTR mission targets the NASA Heliophysics roadmap and hopes to:

- Determine the dynamics and coupling of Earth's magnetosphere, ionosphere, and upper atmosphere and their response to solar and terrestrial inputs.
- Address the poorly understood turbulent diffusion and transport processes in the lower thermosphere and the need for more extensive in-situ observations of the neutral dynamics the region.
- Enable the first modern measurements of O, O₂, N₂, NO, CO₂, H₂O, and Ar volume densities as a function of altitude from ~80 to 120 km.
- Compare in-situ measured CO₂ profiles with those retrieved by IR radiometry

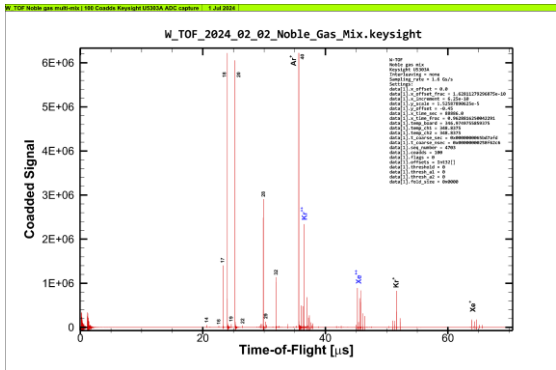


Figure 11. W-TOF spectra for a noble gas mixture showing the isotopes of neon, argon, krypton and xenon and their double and triple charge states.

- Measure the NO transport across the turbopause, and the magnitude of energetic particle precipitation (EPP).

Proposed Flight Mission

The CMSTR rocket flight will ideally launch from a high-latitude range, such as Poker Flats in Alaska. Launch dates should be near the polar winter and coincide with LIDAR and orbital sounding measurements if possible. After launch the rocket will climb past 70 km at which point the outer nosecone will be ejected. At ~75 km, the TOF vacuum seal will release and the TOF-spectrometer will begin sampling the atmosphere. Between 75 and 80 km the bow shock-reducing nosecone will manage the ram thermal. Mass spectrometry measurement of the atmospheric species of interest will take place between 80 & 120 km. At an apogee of 140 km, the sounding rocket will level out and begin its descent. The downward trajectory will focus on the measurement of ions, utilizing the BN gate. Past 60 km on the descent, the CMSTR instrument will turn off and the payload recover parachute will open for a planned full recovery of the payload S-band telemetry will be maintained with command throughout the mission. Key data will be processed onboard and downlinked along with health/housekeeping data. Back up of the raw & processed data will be stored onboard in crash hardened data storage. Figure 14 below details the operational concept for the MSTR sounding rocket flight.

Cooled nosecone

CMSTR features a multifunctional nosecone, which serves as a bow shock reducer, cooled heat exchanger, and closed ion source chamber. Modern, advanced 3D printing technologies will be used to fabricate the nosecone with the supercritical helium coolant channels

directly embedded within the structure. This integrated approach will greatly improve the thermal performance of the bow shock reducer by minimizing thermal resistance paths. Material selection is critical, with GRCOP-42 superalloy forming the primary nosecone material. A critical aspect of this design is the overall size and surface area of the nosecone. The ram heating effect of a supersonic rocket is substantial and increases nearly linearly with the total exposed surface area. The current design requirements state that the outer surface of the nose cone cannot exceed 30 K at altitudes above 70 km, which can be accomplished by pre-cooling the nosecone prior to launch and by maximizing the coolant flow during the peak ram heating period. This increased flow rate of coolant must be balanced against the total available coolant volume as a design trade. To reduce the total required volume of Helium, an outer nosecone will be fitted to the sounding rocket, which will absorb a substantial sum of the ram heating up to an altitude of ~70 km. This outer nosecone will be jettisoned, eliminating the majority of the absorbed heat. Ultimately, the outer walls of the nosecone will be

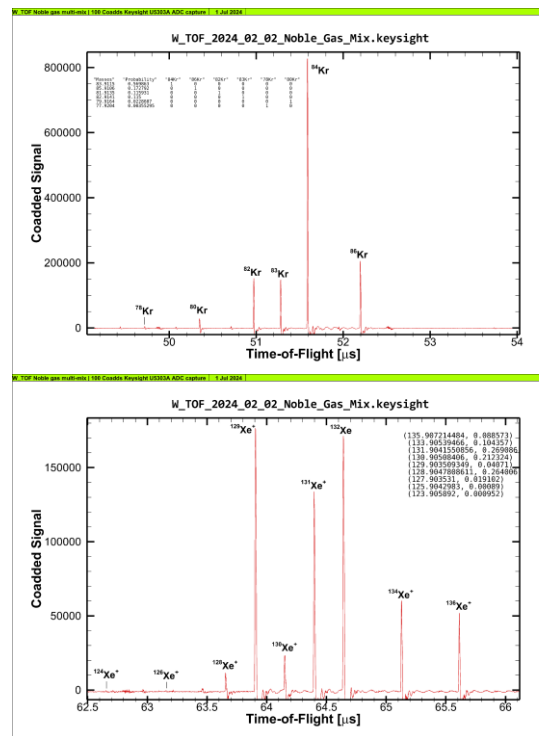


Figure 10. Krypton and xenon isotopes acquired using a noble gas mixture in the W-TOF configuration.

maintained at temperatures below 20 K. A low outgassing Teflon shield surrounding the cooled ion source will serve to thermally isolate the system from the payload support structure and vacuum cover release.

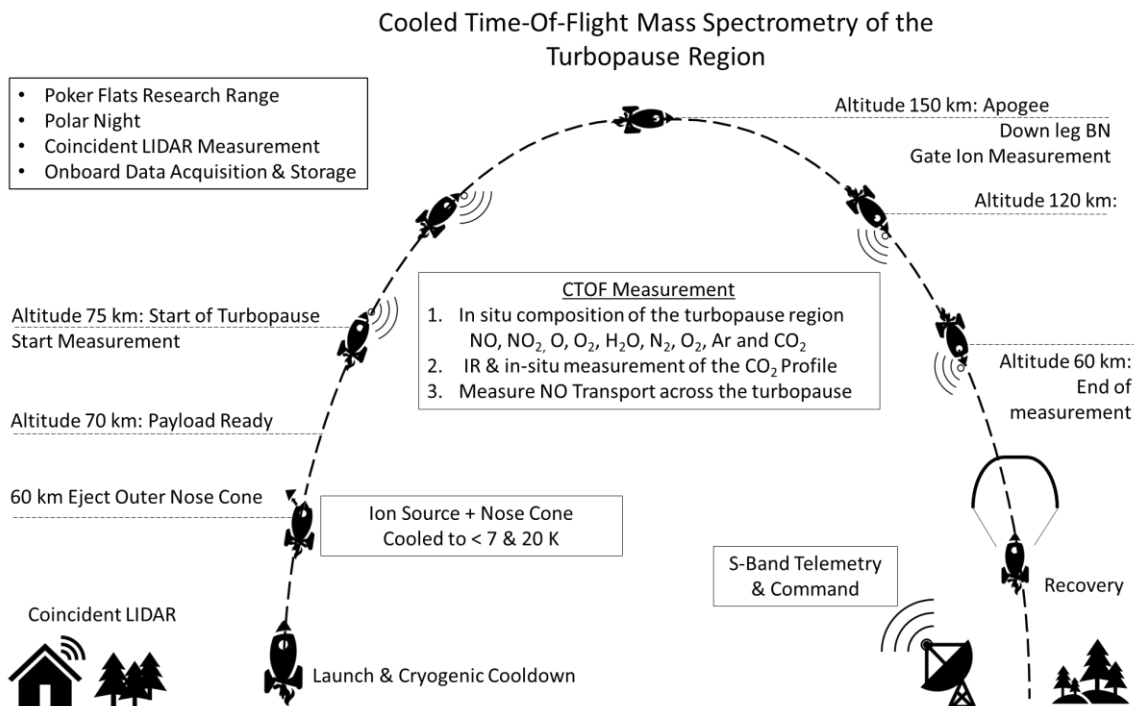


Figure 14. CMSTR flight concept.

This will prevent trace gases from leaking into the system around the ion beam and limit the thermal parasitics to the cooled ion source. The MSTR nosecone is critical to sample high density neutrals and ions under free-flow conditions. If MSTR were to be utilized in a vacuum environment, than a nosecone would be unnecessary. Figure 15, details the basic cryogenic system design for the CMSTR sounding rocket.

Conclusions

Time of flight mass spectrometry is a critical and groundbreaking topic of research with numerous applications in aerospace. In this paper, we present an overview of several novel TOF-MS payloads, with a special emphasis on the V & W-TOF configurations developed under the MSTR program. MSTR is a compact (low SWAP) and versatile ion and neutral time-of-flight mass spectrometer. MSTR is capable of high resolution, >3000, with large mass numbers. The MSTR instrument is ideal for integration with a wide variety of flight vehicles, including sounding rockets, Small Satellites, and CubeSats.

Acknowledgments

The V & W TOF instruments are currently under development by the Southwest Research Institute and Orion Space Solutions. The MSTR program is supported by NASA and the Heliophysics Technology office

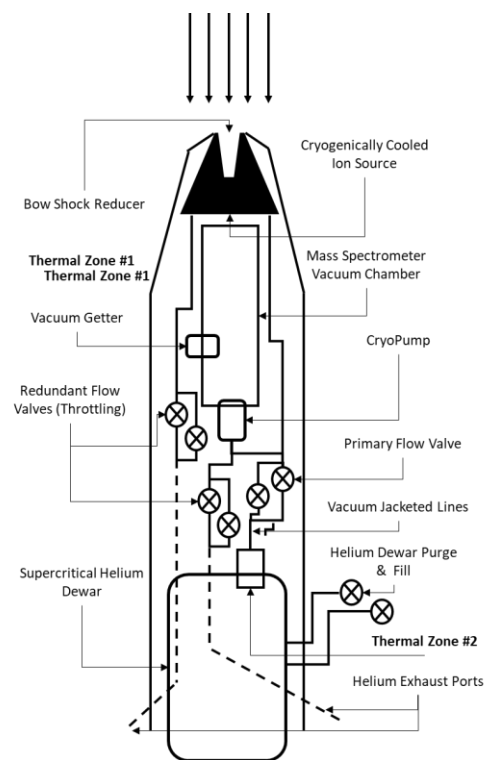


Figure 15. MSTR cryogenic system design.

through an HFORT grant. We would like to thank Kyle McAllen and NASA for their support of this program.

References

- [1] Niemann, H. B., Harpold, D. N., Atreya, S. K., Carignan, G. R., Hunten, D. M., & Owen, T. C. (n.d.). *GALILEO PROBE MASS SPECTROMETER EXPERIMENT*.
- [2] Waite, J. H., Burch, J. L., Brockwell, T. G., Young, D. T., Miller, G. P., Persyn, S. C., Stone, J. M., Wilson, P., Miller, K. E., Glein, C. R., Perryman, R. S., McGrath, M. A., Bolton, S. J., McKinnon, W. B., Mousis, O., Sephton, M. A., Shock, E. L., Choukroun, M., Teolis, B. D., ... Siegmund, O. H. W. (2024). MASPEX-Europa: The Europa Clipper Neutral Gas Mass Spectrometer Investigation. *Space Science Reviews*, 220(3). <https://doi.org/10.1007/s11214-024-01061-6>
- [3] Miller, G. P., Waite, J. H., & Young, D. T. (n.d.). *A High-Resolution, Multipass Time-of-Flight Mass Spectrometer for Investigation of Elemental, Isotopic and Molecular Compositions*. <https://doi.org/10.1016/0168>
- [4] Hunter, J., Sacks, W. R., Block, B. P., Scherer, S., Chassefiere, E., Berthelier, J.-J., Jambon, A., Dissly, R. W., Nicks, D., Young, D., Miller, G., Beauchamp, P., & Croonquist, A. (2005). *The Mars Analytical Chemistry Experiment*.
- [5] Palmer, P. T., & Limero, T. F. (2001). *FOCUS: FIELD-PORTABLE AND MINIATURE MS Mass Spectrometry in the U.S. Space Program: Past, Present, and Future*. <https://pubs.acs.org/sharingguidelines>