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Miniature MEMS Mass Spectrometer for Space Applications

Abstract: The article describes a miniature mass spectrometer made at the Wroclaw University of Science and Technology in cooperation with Creotech Instruments for of the European Space Agency. It was manufactured by the use of MEMS technology (micro-electro-mechanical systems) combined with precise 3D printing. It is one of the smallest gas composition analyzers (the measuring head is 2×2×10 cm^3 and weighs only 120 grams) that can be used in space applications. Its operating parameters are not much worse than for the classic, much larger counterparts (resolution reaches 100 and mass range up to 400 AMU).

Keywords: Mass spectrometry; MEMS technology; Gas composition analysis

Introduction

Space exploration inherently involves studying the physicochemical properties of extraterrestrial celestial bodies. Analyzing the composition of gas mixtures and solids (dust, rocks, etc.) is crucial here. These analyses can be performed in two ways. The first involves bringing extraterrestrial samples collected by astronauts or space vehicles back to Earth for analysis. The second deploys analytical instruments in space, often as part of landers or extraterrestrial robots exploring space bodies such as the Moon or Mars.

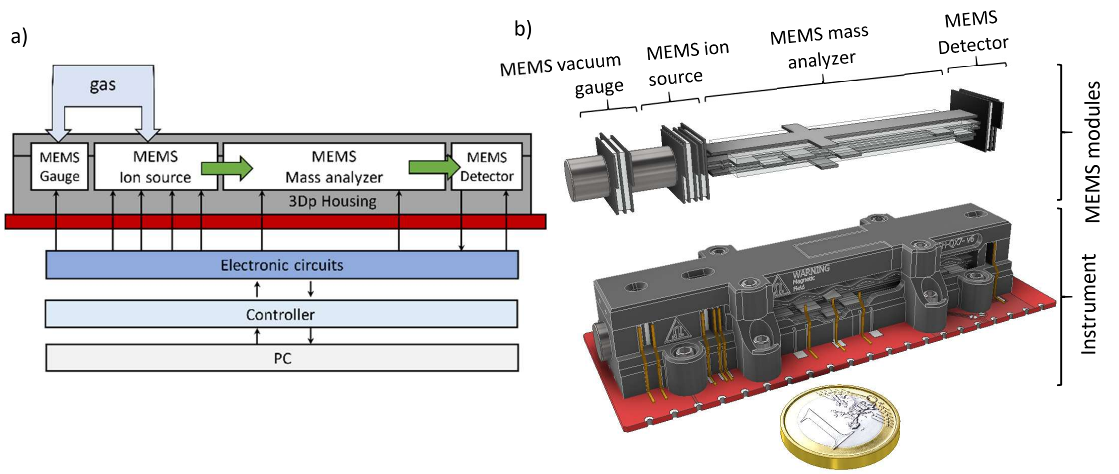
New concepts for exploring celestial bodies using very small platforms demand the development of compact, mechanically robust (including shock- and vibration-resistant) analytical instruments.

To address these trends, the European Space Agency (ESA) announced a call to design a miniature mass spectrometer [1]. Mass spectrometry is a fundamental analytical technique in which a sample is ionized, and the resulting ions are separated based on their mass-to-charge ratio. This highly sensitive method is widely used on Earth, primarily in specialized laboratories. Mass spectrometers have been sent into space before [2], [3], [4], but they remain relatively large instruments weighing tens of kilograms, significantly increasing mission costs and limiting applications.

The chance for miniaturizing mass spectrometers has been seen in the application of MEMS (microelectromechanical systems) technology [5]. Such a device was developed as part of the mentioned ESA project at Wroclaw University of Science and Technology [6].

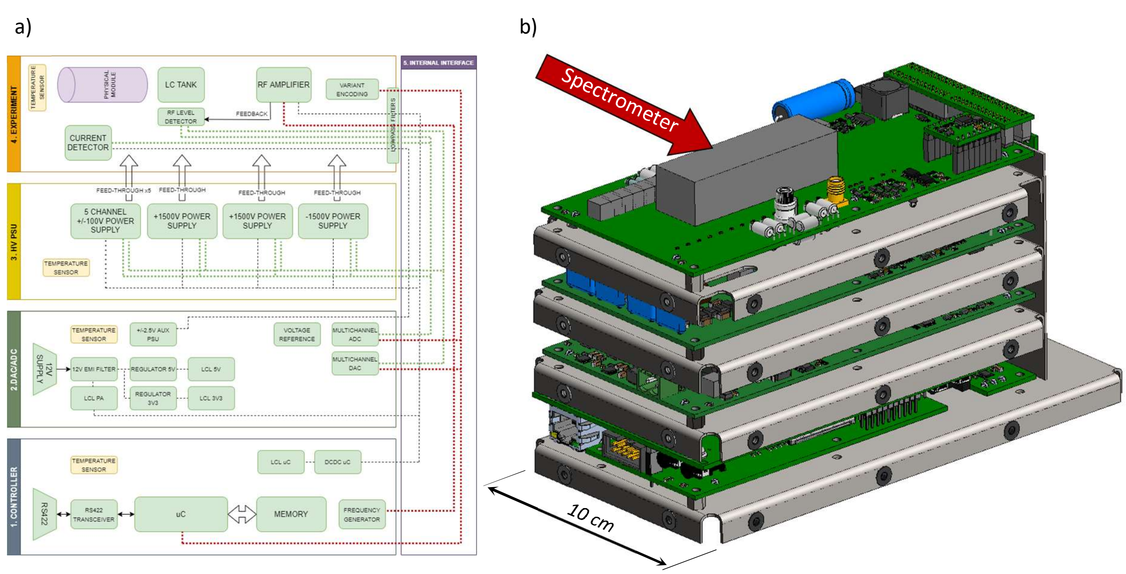
Materials and Methods

The miniature mass spectrometer developed by our team, in collaboration with Creotech Instruments, comprises a glow discharge ion source, a quadrupole ion mass analyzer, a Faraday cup detector, and an ionization vacuum gauge (Fig. **1**). All key components are made of silicon and glass using microengineering techniques. These components are integrated into a 3D-printed housing that aligns them and ensures mechanical robustness. The housing also allows for the replacement of individual components (e.g., various types of mass analyzers) to adapt to different operating conditions. The complete instrument head measures 2×2×10 cm³ and weighs only 120 grams, significantly less than traditional devices.



1. Block diagram of the miniature mass spectrometer (a) and instrument visualization (b)

The spectrometer requires a complex electronic system to power and control its operation. This system includes high-voltage modules, a high-frequency resonant generator, and a highly precise ion current meter (Fig. **2**). All these modules are implemented as several integrated PCBs occupying approximately 2 U of volume (2 dm³).



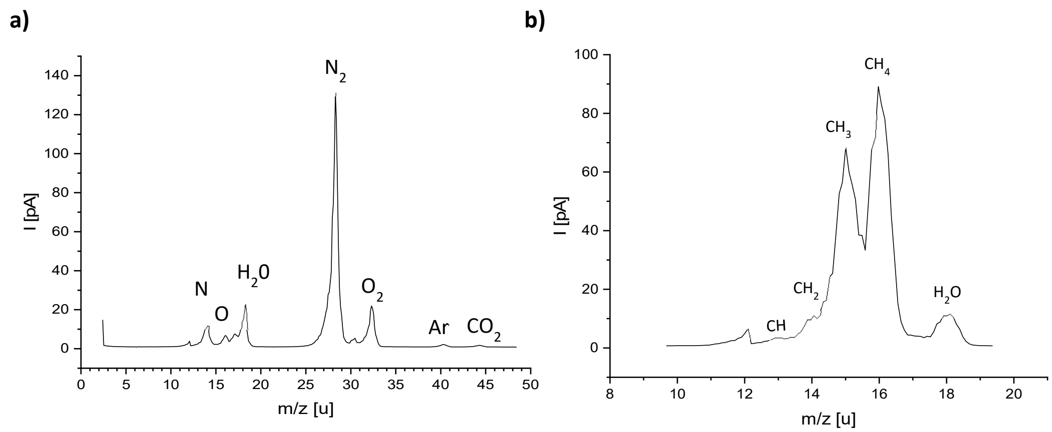
2. Electronic system of the instrument: a) block diagram, b) visualization of the instrument including the mass spectrometer and electronics; design and implementation by Creotech Instruments

In the spectrometer, gases are ionized via glow discharge. The ions are formed into a beam and directed toward the analyzer. The quadrupole mass analyzer selects ions in a varying electric field generated between four parallel rods. The detector captures and counts the ions, while the pressure sensor monitors process conditions.

Results

The performance of the spectrometer were tested using standard and artificial gas mixtures. The mass spectrum recorded for air (Fig. **3a**) shows distinct peaks corresponding to nitrogen, oxygen, and other elements present in the atmosphere. Notably, the spectrum also displayed traces of water vapor and environmental contaminants. The data demonstrated the system's ability to separate and identify various components in the sample, even those with similar masses.

Methane, another important gas for space research as a potential indicator of life on other planets, was also analyzed. The spectrum (Fig. **3b**) showed a primary methane peak and peaks resulting from its fragmentation (CH_3, CH_2, CH), closely resembling spectra generated by commercial devices. The presence of water and carbon-containing gases was also evident in this spectrum.



3. Acquired mass spectra: a) for air, b) for methane

The key parameters of the instrument are summarized in Table **1**. The quadrupole analyzer with an electrode spacing of 1.75 mm has a mass range of 1–80 atomic mass units (amu) and a resolution of up to 100. This is sufficient for detecting most gases in the Earth's atmosphere, on space stations, or on planets and other solar system objects. A quadrupole analyzer with an electrode spacing of 1.05 mm offers a much broader mass range (up to 400 amu) for detecting organic molecules, though with reduced resolution (~50). The spectrometer achieves a detection limit of 10^{-8} hPa partial pressure. Using a microchannel plate (MCP) improves its sensitivity by at least several hundred times.

The instrument underwent rigorous mechanical and thermal tests (TVAC), confirming its resistance to sinusoidal vibrations up to 10 g at frequencies from 5 to 150 Hz, random vibrations from 20 to 2000 Hz with an ASD of 0.05 g^2/Hz, and shocks up to 600 g. The spectrometer operates directly in a high vacuum environment and a wide temperature range from -40 to 50 °C. Short- and long-term stability was also demonstrated.

Tab. 1. Summary Table: Instrument Parameters

	Value	Units
Instrument size	2×2×10	cm^3
Instrument weight	120	g
Ion source	**MEMS GD**	
Voltage range	500 :: 1200	V
Operating pressure	10^{-6} :: 10^{-2}	hPa
Mass analyzer	**MEMS Quadrupole**	
Electrode size r_0	0.8/0.5	mm
Analyzer length	70	mm
RF signal frequency	6.6	MHz
RF signal Amplitude	<600	V_{pp}
Mass range	1-80/1–400	u
Resolution	100/50 (FWHM)	
Detector	**MEMS FC**	
Electron multiplier	MCP (optional)	
Ion currents	10 fA :: 5 nA (without MCP)	
Prototype size	**1.5**	**U**
Prototype weight	**1.0**	**kg**
Power consumption	**15**	**W**

Conclusion

The miniature mass spectrometer developed at Wroclaw University of Science and Technology is one of the smallest analytical instruments in the World capable of being sent into space. It meets all ESA requirements while offering performance comparable to commercial devices used in specialized Earth-based laboratories. Its compact size enables deployment on very small vehicles, robots, or drones to collect data directly in targeted locations, without the costly and cumbersome need to return samples to Earth.

This versatile device can be adapted for various tasks, including monitoring the atmosphere inside space crafts (e.g., ISS) and habitats, analyzing the composition of laser-evaporated asteroid, lunar, or Martian rocks (space mining), and performing elemental gas analysis in low Earth orbit (space weather analysis or climate change assessment). Its existence paves the way for small-scale space missions, where larger, heavier instruments would be impractical.

Additionally, the spectrometer has numerous terrestrial applications, ranging from stationary uses like monitoring industrial processes to mobile applications such as deploying it on drones to detect hazardous materials or monitor greenhouse gases in industrial and energy sectors.

Acknowledgments

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Source materials

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