



Suitcase TOF: A Man-Portable Time-of-Flight Mass Spectrometer

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The need for man-portable analytical instrumentation to detect and identify potential chemical and biological hazards in the environment is growing as the number of natural and man-made threats increases. To that end, APL has been developing the Suitcase TOF, a small suitcase-sized Time-of-Flight Mass Spectrometer, and testing it extensively on known chemical and biological agents. This article introduces the reader to TOF mass spectrometry, describes the features of the Suitcase TOF that make it portable and rugged, and touches on the results of agent testing. Application areas include first-responder and special operations spot checks, clinical medicine, medical research, infrastructure and environmental monitoring, law enforcement, and military troop protection.

INTRODUCTION

The mass spectrometer is a powerful analytical device that has the capability of detecting a wide range of chemical and biological substances. Mass spectrometry is a method of measuring the masses and fragmentation patterns of those substances to determine the composition of the original sample. Coupled with the soft ionization technique called Matrix-Assisted Laser Desorption and Ionization (MALDI),¹ the Time-of-Flight Mass Spectrometer (TOFMS) can measure very large, intact molecules. For example, biological toxins with masses greater than 50 kDa have been readily detected in our portable MALDI TOFMS.

The ability to deploy mass spectrometers for the field detection of chemical and biological threats has been hindered by the size, weight, and power requirements of

typical instruments. APL has been developing a small suitcase-sized TOFMS^{2,3} that has undergone extensive testing on known chemical and biological agents. This article gives an overview of the components of the Suitcase TOF and their operation, presents encouraging results of field testing on actual agents, and touches on future improvements toward fielding a man-portable TOF instrument.

INSTRUMENT DESCRIPTION AND OPERATION

The Suitcase TOFMS (Fig. 1) has four major subsystems—the vacuum system, optical system, source/analyzer, and electronics/data system—each with unique and innovative features.⁴

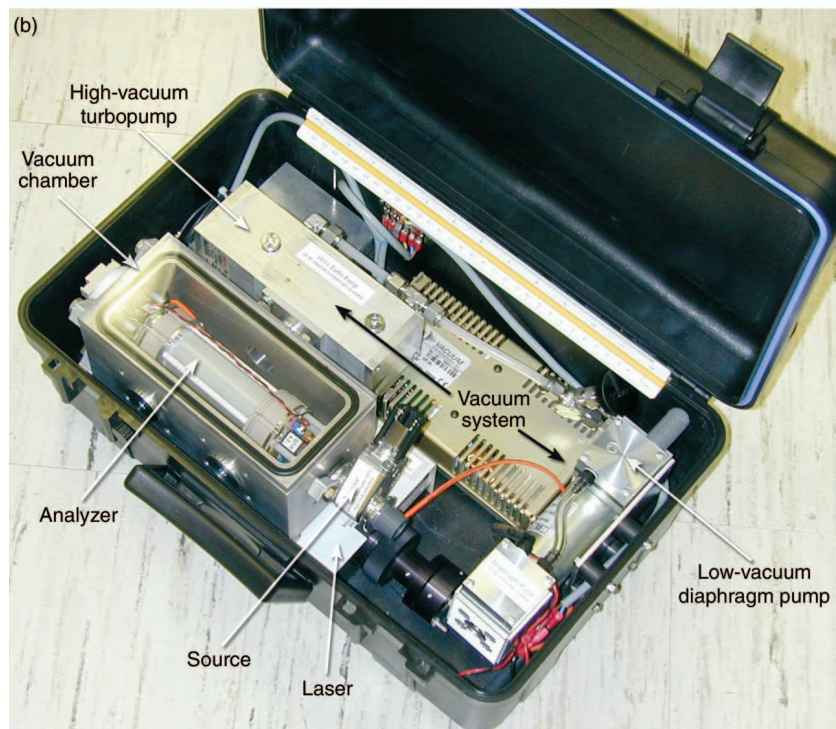
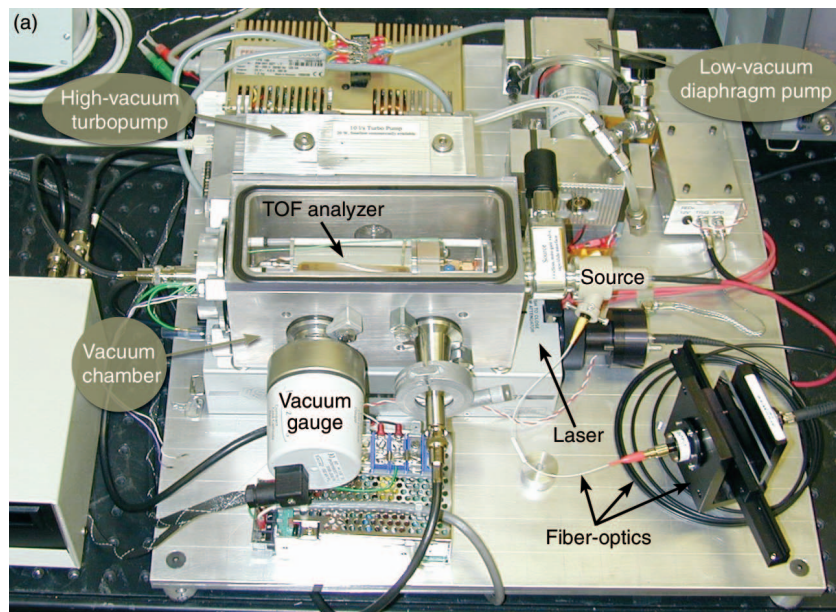


Figure 1. Suitcase TOF (a) in the breadboard configuration for testing and (b) packaged in a small Pelican case for demonstration purposes (data system not shown).

Vacuum System

The vacuum system consists of a 52-in.³ coffin-type chamber machined from a block of aluminum with a clear Lexan top and multiple polymer O-ring sealed vacuum ports (ISO-KF) machined into its walls. A Pfeiffer combination turbomolecular/drag pump (model TPD011) is used to evacuate the chamber into the low 10^{-6} torr range. With a pumping speed of 10 L/s and a mass of 2.5 kg, the Pfeiffer pump is the smallest one of its kind that

is commercially available. This type of combination pump can exhaust into the relatively low vacuum of a diaphragm pump. A KnF-Neuberger diaphragm pump (Model N84.4ANDC) capable of operating at 1.5 torr and 4.8 L/min is used in this application. The chamber pressure is measured with a Pfeiffer wide-range vacuum gauge (combination Pirani/cold-cathode gauge).

Optical System

The optical system of a typical MALDI TOFMS is designed to deliver a series of short ultraviolet (UV) laser pulses to the source region of the TOF analyzer. The sample to be analyzed is co-deposited with a UV-absorbing substance (matrix) onto a probe and inserted into the source of the analyzer at the focal point of the optical system. The laser energy is absorbed by the matrix and transferred to the analyte. Both analyte and matrix molecules are desorbed, ionized, and accelerated into the TOF analyzer.

Standard optical components (lenses and windows) are used in nearly all commercial and custom TOF mass spectrometers. In contrast, the APL Suitcase TOF uses fiber-optics to deliver the energy from a pulsed nitrogen laser featuring a small, sealed plasma cartridge (LSI Model VSL-337, 140 μ J per pulse, 5-ns pulse width, 337-nm wavelength, and 1- to 20-Hz pulse rate). This pulsed nitrogen laser is also the smallest and lightest commercially available one that will work in this application.

Fiber-optic components simplify the optical mounts and increase the overall ruggedness of the instrument. The light is coupled into a 200- μ m core UV fiber, transmitted to a U-bracket (OzOptics Model UB-01), collimated and launched across the air gap of the U-bracket through a linear-wedge neutral-density filter, and then coupled back into a second 200- μ m core UV fiber. The linear-wedge 0–2 optical-density filter is used to attenuate the laser energy delivered to the sample. A small lens pigtailed to the end of the second fiber focuses the light (1 \times magnification at 1 cm) through a vacuum window and onto

the center of the sample probe. A simple sliding gimbal mount is used to align the beam and set the spot size at the sample. Finally, a fast photodiode mounted near the exit aperture of the laser detects scattered light to be used as the start trigger for the TOF measurement.

Source/Analyzer

The heart of the Suitcase TOF is the source/analyzer. Many of the unique features alluded to earlier are incorporated into this subsystem and are described briefly here (a detailed description can be found in Ref. 4).

First, a short introduction to TOF mass analyzers is instructive. Conceptually, a linear TOFMS, as shown in Fig. 2a, is very simple.⁵ Analyte and matrix ions formed in the electric field of the source region are all accelerated to the same kinetic energy. A flat sample plate held at a high voltage (≈ 10 kV) separated by a small distance from an extraction grid at ground potential typically defines a source. After exiting the source, the ions drift in a field-free region until they strike a detector. Because all the ions have the same kinetic energy, a more massive or heavier ion will have lower velocity than a less massive or lighter ion. The velocity v and TOF t of the ions are related to their mass m by the following equations:

$$v = \left(\frac{2zeEs}{m} \right)^{1/2}, \quad (1)$$

and

$$t = \left(\frac{m}{2zeEs} \right)^{1/2} D, \quad (2)$$

where z is the number of charges (e) on the ion, E is the electric field in the source region of width s , and D is the length of the drift region.

In a simple linear analyzer, the initial energy, temporal, and spatial distributions of ions in the source lead to peak spreading at the detector. One method of correcting the initial energy distribution and decreasing the peak width is to use a “reflectron,”⁶ a retarding electric field that reflects the ions back along their original path to strike a detector placed at the ions’ spatial focus. Ions of the same mass but with slightly more energy enter the reflectron first, penetrate slightly deeper, and exit later than less energetic ions. As they approach the detector, the more energetic ions catch up with slower ones and come into a spatial focus at the detector. This is illustrated in Fig. 2b. The reflectron increases signal resolution, defined as $(t/2\Delta t)$, by correcting for the initial energy spread (decreasing Δt) and increasing the effective drift length of the analyzer (increasing t). An ion detector can be placed to the side of the original ion path or a detector with a center hole can be placed coaxially with the original ion path so that the ions pass through the center of the detector, are reflected by the

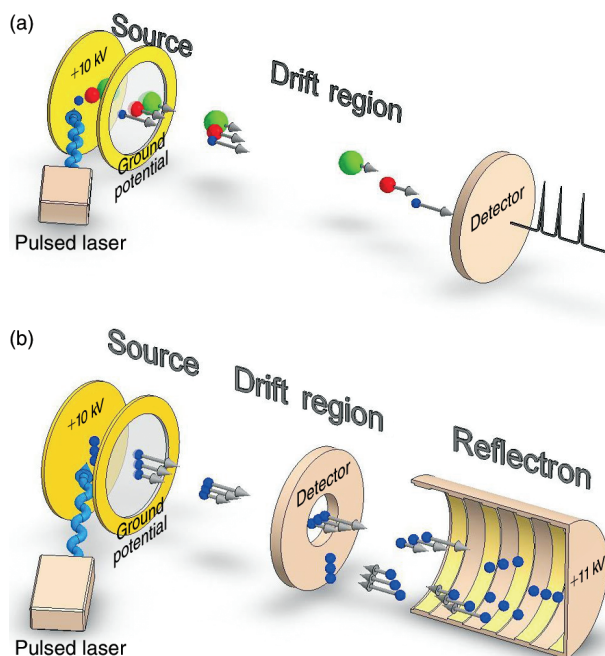


Figure 2. Schematic of (a) a simple linear TOFMS illustrating how ions separate in time owing to their differences in mass and (b) a reflectron TOFMS illustrating the energy-focusing effect on a packet of single-mass ions with small differences in kinetic energy. (Ions are on the vertical plane.)

ion mirror, and then are accelerated back toward the active face of the detector.

A reflectron with a linearly increasing potential (constant electric field) corrects ion energy spreads to first order. Deviating from the linear potentials typically used in commercial instruments to a slightly curved potential can create higher-order corrections.^{7,8}

APL’s Suitcase TOF analyzer is a miniature, nonlinear reflectron TOF with a very efficient gridless focusing source and unique detectors that produce very clean signals. Fine-mesh metallic grids are employed in most mass spectrometers to establish boundaries between regions of differing electric fields. For example, the high electric field of the source region is typically separated from the field-free drift region by a grid. In our Suitcase TOF, we have eliminated all but one grid, which is located a few millimeters from the detector. The gridless focusing source uses a very small three-element electrostatic lens to extract the ions with a high field (≈ 5 kV/mm) and then slow them down and focus them for maximum transmission through the center of the detector and into the reflectron.

Typical reflectrons are built by stacking many thin metal elements onto insulating rods and applying the reflector potentials with a resistor network. We have simplified and ruggedized the reflectron by defining the electrode structure on a flexible circuit board material, rolling it around a mandrel, and encasing it in a fiberglass cylinder.⁹ A surface-mount resistor

network is soldered to pads on the end of the flexible circuit board.

Finally, the analyzer uses a custom microchannel plate (MCP) detector assembly with a novel anode structure that drastically reduces the signal ringing that is often associated with coaxial detectors. A small polished pin replaces the standard disk-shaped anode to collect the pulse of electrons generated by the stack of MCPs. A reduction in the stray capacitance significantly improves the impedance match between the anode and the 50- Ω transmission line, resulting in much less ambient electrical noise coupling into the line and virtually no signal ringing.

Electronics/Data System

The current version of the Suitcase TOF uses a mix of commercial and custom electronics to control the instrument and collect the data. Five high-voltage power supply modules are used to manually control the source, reflectron, and detector voltages. A full-size LeCroy oscilloscope (Model 9354, 500-MHz analog

bandwidth, 500 megasamples/s) digitizes the TOF signal and averages between 10 and 100 individual shots to produce one TOF mass spectrum. A very small laptop computer (Panasonic Tough Book) running a National Instruments LabView program downloads the data from the oscilloscope and then processes, formats, stores, and presents the mass spectra. Efforts at greatly reducing the size, weight, power, and packaging of the electronics are being addressed in the next prototype.

TEST RESULTS

After a brief testing period at APL, the Suitcase TOF was moved to the Edgewood Area of the Aberdeen Proving Ground (APG), where scientists from the U.S. Army Soldier and Biological Chemical Command began testing on an assortment of biological toxins and chemical agents. First, a series of biological toxins ranging in mass from a few hundred daltons to over 60 kDa were run in parallel on the Suitcase TOF and one of APG's commercial TOFMS (Fig. 3). All but a few compounds were

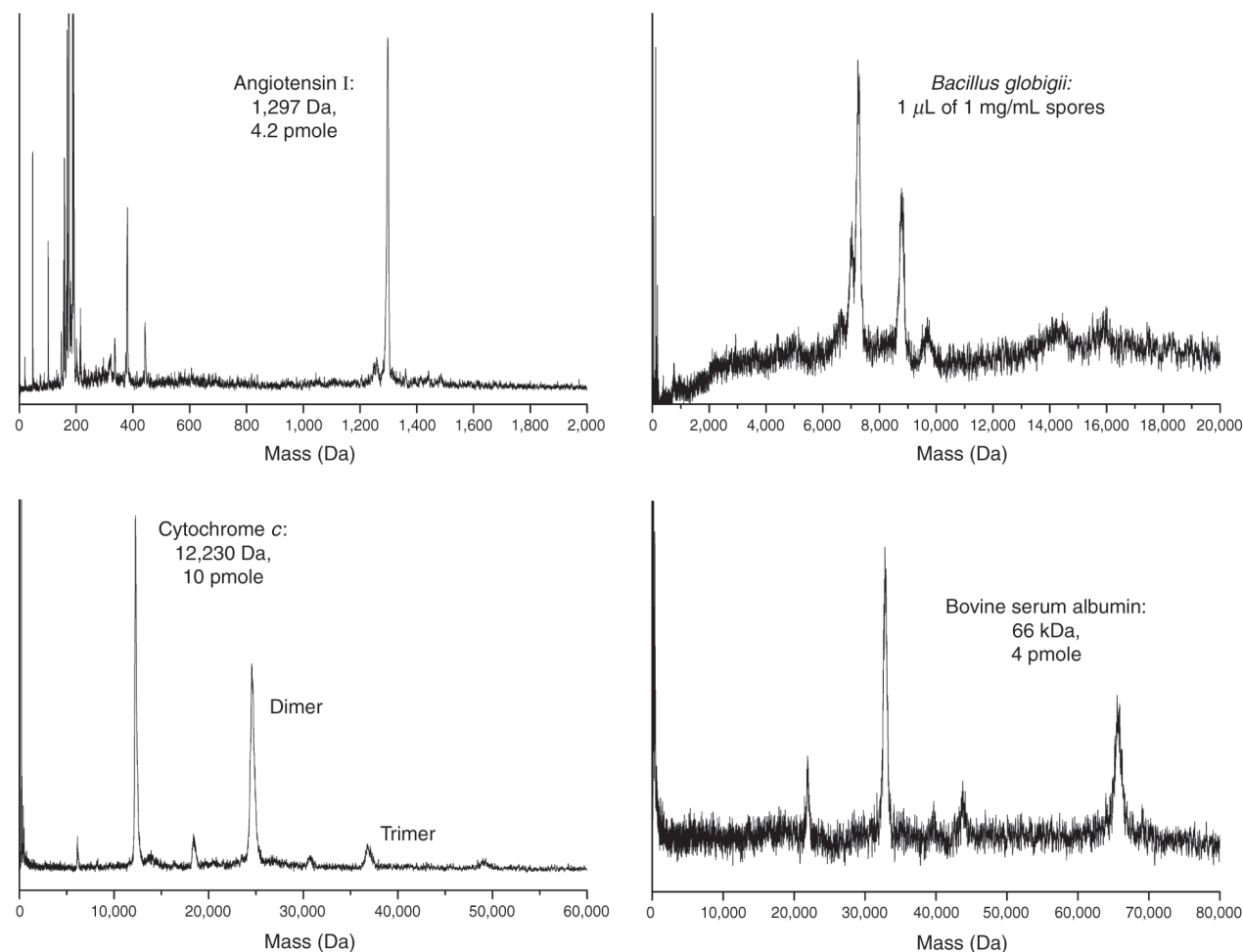


Figure 3. A few representative spectra of calibration compounds covering the same mass range as those tested at the Aberdeen Proving Ground.

successfully detected on both instruments with very encouraging results. The reason why others were not detected on either instrument can likely be attributed to problems related to the sample and not to the instruments. The commercial TOF generally has better sensitivity and signal resolution because of its high-voltage pulsed extraction, longer flight tube, and other parameters that can be optimized. Overall, however, the Suitcase TOF did quite well in comparison. For some of the very high mass compounds, the Suitcase TOF equaled the performance of the commercial TOF in resolution and sensitivity.

The Suitcase TOF was then moved to another APG facility for further testing on a series of chemical weapons agents. Every compound tested was detected at levels comparable to APG's standard analytical techniques for these agents. As of this writing, the Suitcase TOF is undergoing further biological testing at a third APG facility with encouraging results.

CONCLUSION

The Suitcase TOF was designed for a first-responder type of application in which a small instrument must be easily transportable to a remote location for testing of a suspect material. A "person in the loop" is also envisioned for this instrument—a minimally trained individual who can perform a simple sample workup with a disposable test kit, move the sample into the instrument, and start the analysis sequence. Test kits can be developed for solid, liquid, and gaseous samples so that a result can be obtained within a few minutes.

The need for analytical instrumentation in the field to detect and identify potential chemical and biological threats continues to grow. We have demonstrated that a miniature man-portable TOFMS can fill a number of needs. Test results to date have exceeded our expectations and those of our APG collaborators, and testing will continue on an expanding range of compounds.

Inputs from our colleagues and collaborators have resulted in numerous improvements that are currently being built into the next prototype. Enhanced optics, electronics, detectors, and other features will improve the performance of the Suitcase TOF, and continued reduction in size, weight, and power will improve its portability, leading eventually to a very powerful and simple-to-use battery-powered instrument.

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