Miniature combination Mössbauer and X-ray fluorescence spectrometer for planetary geochemistry

Principal Investigator: Valerie Scott Kristof (389); Co-Investigators: Douglas Dawson (386), Laura Kerber (322), Jeff Delaune (347), Brent Fultz (California Institute of Technology)

Program: FY21 R&TD Topics **Strategic Focus Area: Remote/In Situ/Life Detection Sensors and Instruments**

Objectives

Our overarching project goal is to demonstrate dual-operation of the envisioned combination Mössbauer/XRF spectrometer. Mössbauer and X-ray fluorescence (XRF) spectrometries offer an opportunity to combine two fundamental analytical techniques into a single, miniaturized, dual-mode instrument. These traditionally standalone instruments are key technologies in the geochemist's toolbox and share exploitable technological similarities. XRF delivers simple, non-destructive, bulk analysis of rock and mineral elemental composition, while MS offers detailed mineralogical information about the oxidation state and chemical bonding environment of iron atoms in a sample. Versions of XRF have flown on nearly every major in situ planetary mission, and MS has also delivered key science findings about mineralogy in the Solar System. Notably, MS has never flown without an accompanying XRF instrument — elemental information is vital to deciphering the complex spectra collected with Mössbauer techniques. There is not a compact, bulk analysis, dual-mode instrument readily available to upcoming size-, mass-, and power-constrained missions.

Task Objectives

1) Successful demonstration of piezoelectrically-actuated Mossbauer spectrometer showing <8% Mossbauer peak distortions.

2) Successful demonstration of harvesting Mossbauer signals using a silicon drift detector (SDD) resulting in spectra with <8% distortions.

3) Successful collection of XRF spectra with <100 ppm trace element detection.

Background

Despite the flight heritage of the techniques, there is not a compact, bulk analysis, dual-mode instrument readily available to upcoming size-, mass-, and power-constrained missions. Multiple iterations of the Alpha Particle X-ray Spectrometer (APXS) have flown — on Mars Pathfinder (1997), the Mars Exploration Rovers (MER, 2004-2019), and the Mars Science Laboratory (MSL, 2012-present), playing a crucial role in some of the most exciting Mars discoveries. The MER rovers Mössbauer spectrometers likewise helped in mineral identification and characterized of the redox state and alteration history of rocks and soils on Mars. Previous missions relied on international partnerships for both XRF and Mössbauer spectrometers, yet readily-available instruments for flight covering either technique is not certain. While instruments such as Mars2020's PIXL or APL's AXRS instrument offer XRF, they use power-hungry thermionic X-ray tubes, and may not fit within the constraints of many smaller missions. This dual-mode instrument will be significantly lower mass and power than two individual instruments, largely due to leveraging a small piezoelectric actuator for Mössbauer instead of the traditional electromagnetic drives.

Significance/Benefits to JPL and NASA

Mössbauer (MS) and X-ray fluorescence (XRF) spectrometries are routine techniques in geochemistry laboratories. Currently, NASA missions in need of either low size, mass, and power (SMAP) XRF or MS instruments must acquire individual instruments from foreign entities or build a custom instrument. Having flown by most of the Solar System's terrestrial targets, there is an observed shift to landed missions, which are inherently mass constrained. By combining two techniques, this development will provide a low-SMAP option for key geochemistry instrumentation for future NASA missions. As NASA makes way for smaller scale missions, readily available, low SMAP instruments to deliver routine science will become more valuable. Individuals from 347, 322, 152, and Caltech have expressed interest in this type of instrument, highlighting that, despite the heritage of these techniques, there is inherent difficulty in acquiring either instrument, particularly for SMAP- and cost-constrained missions. While the focus of this project is on the demonstration of a dual-mode instrument concept, the developments proposed here would allow for straight-forward design modifications to generate standalone instruments as well. The successful development of a small combination XRF/Mössbauer spectrometer built in-house at JPL would have many opportunities for infusion into flight.

National Aeronautics and Space Administration

Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

www.nasa.gov

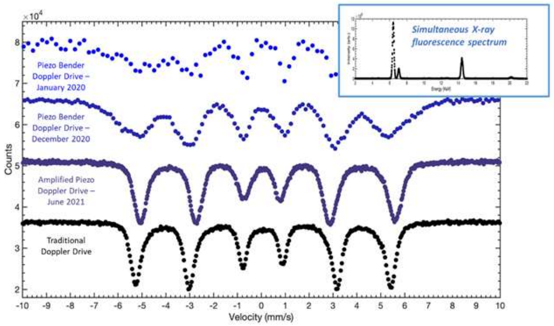

Figure 1. Representative piezo-driven Mössbauer spectra as compared to a traditional Doppler drive. The current piezoelectric drive (June 2021) is nearing the performance of the much larger electromagnetic Doppler drive. Inset shows the XRF spectrum that is collected simultaneously.

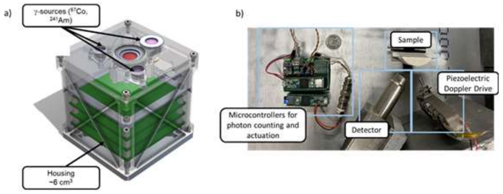

Figure 2. The operation of the complete combination instrument concept shown in the CAD model in (a) has been demonstrated in the lab (b) with miniaturized components that have a clear path to flight.

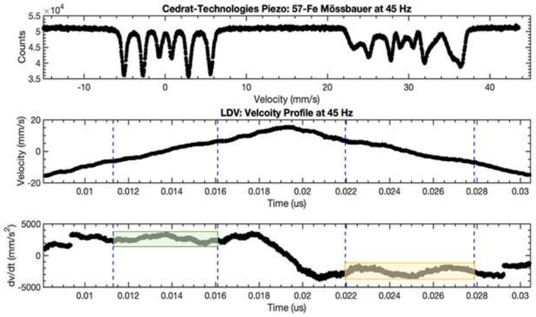

Figure 3. Plots represent the Mössbauer spectrum (top), the measured velocity profile using laser Doppler velocimetry of the piezoelectric actuator (middle), and the calculated acceleration of the piezoelectric actuator.

PI/Task Mgr Contact
Email: Valerie.J.Scott@jpl.nasa.gov

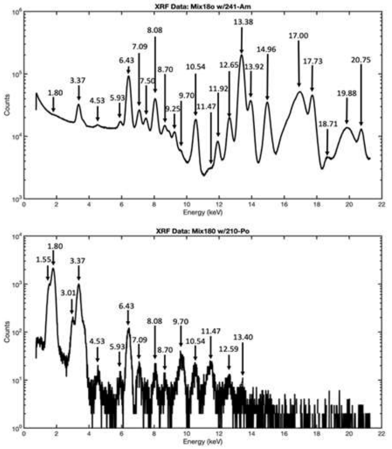

Figure 4. XRF spectra generated of the same geological sample using different radioactive excitation sources - 241Am (gamma source) and 210Po (alpha source). The gamma source is stronger, so can generate high S/N in a shorter time, and gives the ability to detect heavier elements via other transitions, but does not excite lighter elements with high efficiency and also shows elastic scattering of photons which can complicate the spectrum. The alpha source is weaker (because of handling challenges) and takes longer to collect, but the spectrum is easier to interpret because of only exciting K□ transitions. Source selection will depend on the exact science requirements for a given mission.

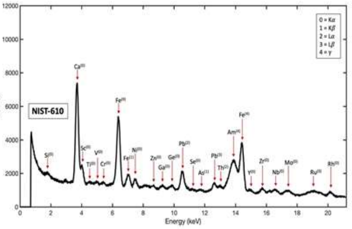

Figure 5. Elemental detection levels to 100s of ppm were shown using ^{59}Co and ^{241}Am gamma sources. ^{59}Co is needed for the Mössbauer operation, but can complicate quantification of Fe.

Approach and Results

Traditional Mössbauer spectrometers utilize bulky electromagnetic Doppler drives to sweep the spectral window. To reduce the mass and power requirements, a piezoelectric Doppler drive is being used. Preliminary Mössbauer build and characterization are being done collaboratively at Caltech with Scott, Fultz, and two graduate students (Pedro Guzman and Cullen Quine). Vast improvements in the quality of the generated spectrum have been observed over the past year's efforts (**Figure 1**).

Methods to harvest Mössbauer data using a Silicon Drift Detector (SDD) have been under investigation. The team has been successful in showing that this is possible, and specific electronics design elements are being considered to minimize size, mass, and power requirements while minimize development time, leveraging flight heritage designs where possible. Mössbauer photons can be detected efficiently with the detector, the signal of which is amplified by a commercial pre-amplifier. These detection event signals are sent to a microcontroller equipped with custom code capable of providing the necessary pulse processing for both XRF and Mössbauer operations simultaneously (**Figure 1, inset**). The microcontroller sorts them by arrival time into 1024 data channels of the spectrum. The data channel advances from 0 to 1023 at a cycle rate of 300 Hz (~3 microseconds), slightly above the frequency of operation of the piezoelectric Doppler drive. A clock pulse advances the data channel, and a second microcontroller synchronizes the waveform sent to the Doppler drive. These two microcontrollers replace the function of a larger, more complex FPGA, offering significant size, mass, and power savings over the traditional method (**Figure 2**).

Mössbauer function characterization is an on-going effort. The Doppler drive has been characterized with Laser Doppler Velocimetry (LDV), which has helped with understanding what is being observed in the spectra as well as offering a path to improving the spectra by applying corrections based on the actual measured velocity profile (**Figure 3**).

Other more minor efforts surround the XRF functionality. We are running experiments to determine the differences in the quality of spectra generated using different sources, such as ^{241}Am (as a closed gamma source) and ^{210}Po (as a weak alpha source) (**Figure 4**). We have also demonstrated detection levels to 100s of ppm using a NIST standard (**Figure 5**). Soon we expect to test the Mössbauer operation in the presence of the other radiation sources to see if there is a degradation in the quality of the spectrum. If the other sources used for XRF interfere with the Mössbauer spectrum quality, either a door must be incorporated to separate the different functions or an X-ray tube can be used to enable turning the XRF source off. To this end, a CNT-based X-ray tube is being designed via simulations with components available from Moxtek.

In Year 2, we will continue Mössbauer/XRF operation optimization and begin testing well-characterized geological samples available from Caltech's GPS. Using as much flight heritage components as possible, we intend to map out a clear path for flight electronics, and get a preliminary mechanical design.

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