

SIMULATED PERFORMANCE OF A MSL-GENERATION APXS IN A LUNAR SETTING. S. J. VanBommel¹, R. Gellert², and J. Gross³, ¹Washington University in St. Louis, St. Louis, MO, USA; ²University of Guelph, Guelph, ON, Canada; ³Rutgers University, New Brunswick, NJ, USA.

Introduction: Since the landing of Mars Pathfinder and the *Sojourner* rover with its Alpha Proton X-ray Spectrometer [1], X-ray spectroscopy has been integral to the scientific payloads of mobile robotic platforms on Mars. The Mars Science Laboratory (MSL) rover *Curiosity* is equipped with an Alpha Particle X-ray Spectrometer (APXS) [2], built on the heritage of an earlier iteration that flew with the twin Mars Exploration Rovers (MER) *Spirit* and *Opportunity* [3, 4]; the ancestry of these instruments is closely tied to the lunar Surveyor probes [5, 6, 7]. While the APXS uses complementary particle-induced X-ray emission (PIXE) and X-ray fluorescence (XRF) through the utilization of ²⁴⁴Cm sources, recent robotic exploration of the Moon has only once utilized an X-ray spectrometer for in situ compositional analyses of lunar materials with a MER-like APXS clone flying on the Chang'e 3 mission's rover, though it utilized only XRF [8].

Recently, space agencies (e.g., NASA, CSA) have announced a renewed focus on lunar exploration, including a plan for human landings as part of the Artemis program [9]. The Artemis program also includes a Commercial Lunar Payload Services (CLPS) initiative, which aims to deliver science payloads to the lunar surface in cooperation commercial partners. One such announced CLPS mission is the VIPER lunar rover [10], landing in the lunar South Pole region prior to the return of human boots.

Here we present simulations of the capabilities of a MSL-like APXS instrument in a lunar environment to demonstrate likely conservative capabilities of a purpose-built APXS for the Moon. The performance estimates are based on the MSL design and the MSL calibration samples. The MSL APXS includes technology that predates 2010 and an architecture specifically optimized for Mars. Improvements to the results presented herein are likely possible primarily through advancements in detector technology and a design specifically tailored for the Moon.

Method: The ACES (APXS Characterization by Empirical Simulation) software package [11] permits the simulation of an APXS spectrum for a user-defined composition and environment. This enables one to explore many aspects of instrument performance, such as trace element detection capabilities as a function of experimental conditions [12], without the need for extensive and time-consuming laboratory experiments. While the current version (1.0a) is based on the MSL

APXS instrument and calibration sample suite, work is ongoing to enable similar capabilities with the MER generation APXS instrument [13].

ACES program development and characterization is described in detail by [11]. The authors utilized a suite of Mars measurements, spanning a wide array of experimental conditions, in combination with pre-flight calibration data to first train and then later verify the program's accuracy. Figure 1 demonstrates how the ACES routine can accurately predict an APXS spectrum, in this case the composition and experimental conditions observed on Mars were utilized as inputs for the generation of the predicted spectrum. Accuracy has also been demonstrated across the range of measurement conditions observed on Mars, include experiments with the rover specifically executed to fully characterize the flight performance of the instrument.

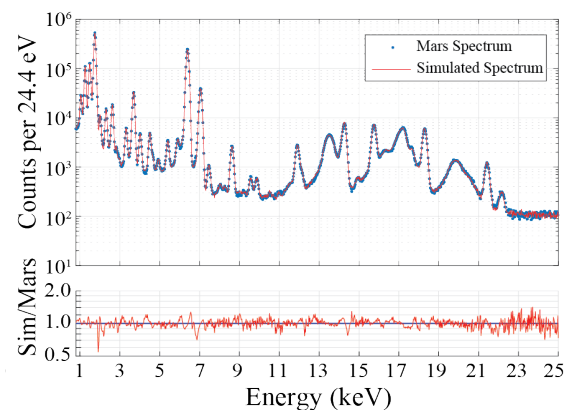


Figure 1: Comparison of Mars spectrum (blue points) and simulated ACES spectrum (red line) for the Mars target Ekwir_1_postbrush (residual below). The simulated spectrum was generated for the determined composition of the target, and the observed experimental conditions (5.5 hours, contact, -35°C) [11].

With the ability to control composition and experimental conditions, rapid (sub-second) simulations can generate spectra as if they were observed on Mars, which can then be fed into analytical tools used to analyze flight spectra (i.e., [4]). In the case of [12], this permitted the authors to explore the precise quantification limit (PQL), the concentration where $\leq 10\%$ precision error is achieved, of select trace elements across a range of scenarios. The results have served to better guide tactical rover plans in addition to providing measurement-specific upper bounds on the concentra-

tion of these trace elements when not detected. The work has also enabled a means whereby lower concentrations of trace elements can be quantified with confidence.

To simulate and subsequently analyze lunar spectra, subtle changes needed to be made to the ACES 1.0a script. Specifically, as lunar measurements would be conducted in a vacuum, attenuation modeling of X-ray quanta by a ~10 mbar (primarily CO₂) atmosphere is not required. For the purposes of this study, all atmospheric effects were disabled in the ACES routine. The analysis routine, used to aid derivation of PQLs, is unaltered from its Mars-centric form. However, atmospheric effects primarily affect low-Z (atomic number) elements, decreasing rapidly as Z increases, thus affecting primarily Na. The magnitude of the (predominantly linear) spectral background is anticipated to differ on the Moon from what has been observed on Mars. However, for the purposes of this preliminary study, it was left unchanged. The composition was fixed to that of the Apollo 12 returned sample 12009, an olivine basalt [14, 15]. Composition plays a role in matrix attenuation and thus PQL derivation. Resolution and sample proximity were fixed to ideal (i.e., effective duration = measurement duration [11]).

Results: The results of this study are summarized in Table 1. For a composition similar to lunar sample 12009, all major oxides outside of Na, are quantifiable to high precision in under 1 hour. Trace elements require longer measurement times to precisely quantify.

The integration of modern (detector) technology and overall instrument design changes aimed to optimize for the lunar surface will only improve the capabilities. Ongoing mineralogical deconvolution work with MER and MSL APXS data will furthermore benefit the possible future application of an APXS on the Moon.

One should note that several elements are typically found in larger abundance on Mars, and thus the calibration approach used in ACES v1.0a was not optimized for very low concentrations in some elements. However, even with this caveat in mind, the demonstrated ability to carry out precise in situ measurements of bulk rock compositions on the Moon will yield crucial information for future landing site selections and furthermore help constrain the complex geology of unexplored lunar regions. Given the accuracy and high precision of the APXS, combined with the PQLs reported in Table 1, the results demonstrate that even a MSL generation APXS would be a suitable in situ chemical analysis instrument for future lunar missions.

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Lunar Sample: 12009 ^[14,15]		Effective Duration	
		1 hour	12 hours
Major Oxides (wt%)		PQL (µg/g)	
SiO ₂	45.03	10000	10000
TiO ₂	2.90	600	100
Al ₂ O ₃	8.59	4000	200
Cr ₂ O ₃	0.55	1000	400
FeO	21.03	100	<100
MnO	0.28	2000	800
MgO	11.55	7000	5000
CaO	9.42	200	<100
Na ₂ O	0.23	7000	5000
K ₂ O	0.06	200	<100
P ₂ O ₅	0.07	400	100
SO ₃	0.06	200	<100
Trace Elements (µg/g)		PQL (µg/g)	
Co	49	~400-500 ^[12]	
Ni	52	150	60
Sr	85	200	90
Rb	1	300	150
Y	38	110	40
Cu	14	120	30
Zn	4	110	20
Ga	5	70	25
Ge	1	80	25

Table 1: Simulated sensitivity (PQLs) for the MSL APXS in a lunar environment when analyzing an Apollo 12 lunar olivine basalt (12009) composition [14, 15] for the effective durations noted at an ideal resolution.