Development of a compact LIBS instrument for future lunar explorations: a feasibility study using lunar meteorites

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The composition of lunar surface is a fundamental observable for understanding the geology of the Moon. For example, in situ measurements of Mg# on a mineral-by-mineral basis help us understand the differentiation process of the lunar magma ocean, adding information to the Mg# map obtained from the orbit [Ohtake et al., 2012]. Elemental analysis is also important for the future lunar polar missions because it provides possible water detection with its geologic context.

Laser-induced breakdown spectroscopy (LIBS) is a method that enables such spot-by-spot analyses. LIBS analyzes the emission spectra from laser-induced plasma that exhibits a number of emission lines characteristic to individual elements. The laser beam is focused on a sample to ~100 microns, allowing the analysis of individual minerals. In addition, LIBS analysis can be conducted from several meters away in a few minutes and the laser pulses can excavate the surface of a sample up to several millimeters. In fact, LIBS was/will be used on Mars for NASA's Curiosity and Mars 2020 rovers [Reess et al., 2018]. In contrast, no actual measurements have been made on the Moon yet. A previous study for a lunar LIBS revealed that major elements can be measured with the accuracy of several wt% [Lasue et al., 2012]. However, their laboratory study did not focus on the miniaturization of the instrument: they switched three spectrometers with different wavelength ranges; the laser in their research was about 1 m long.

In our study, the entire LIBS components were assembled in a package to be portable. Our LIBS instrument is 35 cm×30 cm×20 cm and ~8 kg including a laser, spectrometer, CCD camera, optics with an automatic focusing function, controllers, breadboard, and enclosure. The instrument has a simple electrical interface, namely 12, 15, and 24-28 VDC power lines and one USB hub for communication.

Using the LIBS package, we constructed a quantitative analysis model for major elements with a goal to achieve the precision sufficient to classify lunar crusts. We conducted a series of experiments as follows: 20 geological standard samples from National Institute of Advanced Industrial Science and Technology (AIST) and United States Geological Survey (USGS) were pressed and located in the vacuum chamber under 3×10-2 Pa, 1 m away from the LIBS components. Laser pulses from a Nd:YAG laser (~30 mJ at 1064 nm) were applied 100 times at 5 spots. Ninety spectra were averaged after correcting dark, continuum emission, and relative sensitivity of the optical system. The corrected data were used to build the models with univariate analysis (UVA) (i.e., calibration curves) and multivariate analysis (Partial Least Squares, PLS). The precision of the model was acquired by the leave-one-out cross validation. Then, the concentrations of major elements (Si, Fe, Al, Mg, Na, Ca, Ti, K) in the lunar mare meteorite NWA479 were predicted (phenocryst and groundmass separately) using the models.

Our quantitative analyses yielded the model prediction precisions better than 1 wt% (Na2O and TiO_2), 2 (CaO and K2O), 3 (FeO), and 8 wt% (SiO_2). We also found that elements with strong emission lines were better predicted by UVA than by PLS: as 6.29 wt% (PLS) vs 3.90 (UVA) wt% for MgO, 1.04 wt% (PLS) vs

0.69 wt% (UVA) for Na_2O. Also, the predicted concentrations of Mg, Al, and Ca in phenocryst (olivine) and groundmass (plagioclase and pyroxene) of the lunar meteorite were distinguished against each other, indicating the possibility of mineral-to-mineral measurements on the Moon. From the calibration activity, we also found that the geological samples with Fe_2O_3> 20 wt% and CaO > 16 wt% are necessary to improve the accuracy of Mg# and An# predictions, because lunar meteorites contain higher $Fe2O_3$ and CaO than typical igneous rocks on the Earth. In addition, we conducted a separate LIBS experiment with the engineering model of the Nd:YAG laser used for Hayabusa-2's LIDAR instrument. The obtained LIBS spectra exhibited a number of emission lines, indicating the feasibility of LIBS measurements with the flight-proven laser. The preliminary results from the lunar meteorite experiment using the compact LIBS instrument suggest the possibility to analyze the composition of minerals quantitatively on the lunar surface.

References

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