A LOW-COST, PRECISE 3D-PRINTED SPECTROGONIOMETER FOR STUDYING REFLECTANCE PHOTOMETRY. J. K. Ando\textsuperscript{1,2} and S. Li\textsuperscript{1}, \textsuperscript{1}University of Hawai‘i at Mānoa, Hawaii Institute of Geophysics and Planetology, \textsuperscript{2}jkando@hawaii.edu

Introduction: Laboratory spectroscopy of planetary materials is essential to analyze and contextualize remote sensing spectra. Measuring a material’s photometric parameters (e.g., the phase function in Hapke’s model)\textsuperscript{[1]} involves taking multiple spectra of a sample at different phase angles, requiring precise positioning for accurate measurements\textsuperscript{[2]}. With a traditional goniometer stage, it is difficult and time consuming to position the spectrometer’s sensor optical fiber to accurately measure a small sample.

We use 3D-printing to create a highly modular, precise, and low-cost goniometry setup compatible with a Malvern ASD FieldSpec 4 VIS-NIR spectrometer. This enables measurements of materials between phase angles of 15° and 130° in the principal plane of observation (no azimuth angle).

Design: The goniometer consists of a base with locations to mount modular optical fiber positioners for the ASD4 sensor fiber and, optionally, an illuminator fiber light (Fig. 1). A larger illuminator lamp can also be used. The base is compact, and mounts to a standard optical bench (Fig. 1). Trays can slot laterally into the base, enabling the quick exchange of Spectralon calibration targets and samples under the fiber. The full base is compact, measuring 118 mm by 80 mm.

Sensor fiber positioners are procedurally generated using a Python script in Autodesk Fusion 360. The ideal position of an optical fiber relative to a sample is determined as a function of the fiber’s field of view $\beta$, its emittance angle $\epsilon$, and the desired semi-major axis of the sensed area $a$ (Fig 2). This allows for mm-scale precision that is extremely difficult to achieve with a traditional goniometer, especially at high emittance angles. For an experiment with illuminator light incident at -55°, we fabricate fiber positioners with $\epsilon$ from -45° to 60°, in increments of 5° (Fig. 2).

Additional positioners from 55° to 75° are designed by hand for use with the 5° foreoptic lens and pistol grip available for the ASD4. These high phase positioners mount directly to the optical bench. Shadowing and physical space restrictions that become a limiting factor at low phase angles ($\epsilon<45^\circ$), while it becomes no longer possible to sense entirely within the cup at high emittance angles ($\epsilon>75^\circ$). To ensure stability, an additional piece can be used to clamp each fiber positioner down.

We 3D print our files in black PLA, although any dark and rigid material would be suitable. We recommend printing the base and fiber positioners at 100% infill, as low infill parts can warp after prolonged exposure to a high power (e.g., 70 W) illuminator lamp. We estimate a material cost of <$20 to fabricate all parts to these specifications.

In addition to the benchtop setup, we have a miniaturized version designed to fit inside a liquid nitrogen dewar, enabling photometric measurements of...
ices. Due to space limitations within the dewar, only angles between 15° and 105° can be measured reliably.

**Example Measurements:** As a test, we use this experimental set-up to measure the Hapke phase parameters of the Colorado School of Mines Lunar Highland simulant (CSM-LH1). We set the ASD Illuminator lamp at an angle of -55°, and measure phase angles from 10° to 130°. We take five measurements of the sample at each angle, with the cup rotated between each measurement.

We use Markov Chain Monte Carlo via the emcee package in Python to fit the following Hapke model parameters: the Henyey-Greenstein phase parameters $b$ (amplitude) and $c$ (scattering direction), the single-scattering albedo $\omega$, and shadow hiding opposition effect (SHOE) amplitude $B_{s0}$ and angular width parameter $h_s$. For $b$ and $c$, we use a Gaussian prior to constrain the fit to the hockey stick relation that is observed in many different kinds of materials [3].

**Results:** The collected data and fit are shown in Figure 3, with corresponding fit parameters in Table 1.

**Discussion:** We find that this experimental set-up allows for well-constrained laboratory measurements of $b$, $c$, and $\omega$. The other parameters $B_{s0}$ and $h_s$, related to the opposition effect, are poorly constrained.

The opposition effect is a significant enhancement in reflectance at zero phase, and is typically negligible for angles $> 20°$ [1]. We cannot measure phase angles low enough to measure it with certainty. This limitation stems from the ASD fibers themselves rather than the 3D printed stage; at phase angles $< 10°$, the sensor fiber’s own shadow intersects its viewing area of the sample, leading to inaccurate measurements.

**Data Availability:** Updated .stl files for 3D printing your own stage are available at https://github.com/jordankando/spectroscopy-stage.

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![Figure 2: 3D printed positioners from -45° to 60°. Each part’s base measures 30mmx30mm. Positive angles (high phase) are found in the back row, while negative angles (low phase) are in the front row.](image)

![Figure 3: Reflectance factor vs. phase angle, as measured for Colorado School of Mines Lunar Highlands Simulant. The orange line is the best-fit Hapke model. Error bars represent 1σ.](image)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Fit Result w/ Uncertainty</th>
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<tbody>
<tr>
<td>$b$</td>
<td>$0.117^{+0.021}_{-0.009}$</td>
</tr>
<tr>
<td>$c$</td>
<td>$1.299^{+0.151}_{-0.214}$</td>
</tr>
<tr>
<td>$\omega$</td>
<td>$0.821^{+0.003}_{-0.004}$</td>
</tr>
<tr>
<td>$B_{s0}$</td>
<td>$0.084^{+0.216}_{-0.062}$</td>
</tr>
<tr>
<td>$h_s$</td>
<td>$0.348^{+1.074}_{-0.324}$</td>
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Table 1: Hapke parameters of CSM-LH1 Simulant, as determined via. MCMC fit. Error bounds represent the 18th and 84th percentile.