Measuring and Interpreting Bidirectional Reflectance Distribution Functions for Apollo Lunar Regolith Samples using the Visible Oxford Space Environment Goniometer. R. J. Curtis[1], T. J. Warren[1], N. E. Bowles[1], K. L. Donaldson Hanna[2], D. A. Paige[3]. [1]Atmospheric, Oceanic and Planetary Physics, Department of Physics, University of Oxford, Oxford, UK (rowan.curtis@physics.ox.ac.uk), [2]Department of Physics, University of Central Florida, Orlando, USA (kerri.donaldsonhanna@ucf.edu), [3]Department of Earth and Space Sciences, University of California, Los Angeles, USA (dap@ucla.mars.edu).

Introduction: An accurate description of how visible light scatters from the lunar surface over a range of viewing angles enables 1) physical properties of the lunar surface to be determined, by comparing remote sensing data and a photometric model [1]—such as the Hapke model [2]—and 2) more accurate light scattering function inputs to be set within thermal models, thus improving the match between modelled lunar surface temperatures and remote sensing measurements from thermal infrared (TIR) instruments such as the Diviner Lunar Radiometer [3], [4].

The Oxford Space Environment Goniometer (OSEG) instrument [5] was designed to provide ground support for remote sensing instruments [6], by measuring TIR emission phase functions under simulated lunar-like conditions. OSEG has recently been modified to measure visible wavelength Bidirectional Reflectance Distribution Functions (BRDFs) in ambient conditions (i.e. Visible-OSEG/VOSEG). These BRDFs are comparable to those taken by the Bloomsburg University Goniometer (BUG) in the E. Foote *et al.* [7] study, which measured BRDFs for Apollo 11 (10084) and Apollo 16 (68810) regolith samples [8]. The initial measurements made by Foote *et al*. were in agreement with the Hapke model [2], except at high reflectance angles, where deviations were suggested to be due to porosity variations. The Hapke model predicts that both porosity and surface roughness affects the BRDF. To investigate this, a new suite of BRDF measurements have been made using VOSEG, of Apollo lunar regolith samples 10084 and 68810 (as used in [7]) with a range of porosity and surface roughness values. This project aims to use the laboratory measured BRDFs 1) to further test the slope angle size-scale and porosity parameterizations within the Hapke model, by measuring a suite of samples with known compositions, slope angles and porosities; and then to create Hapke parameter maps (which describe surface properties) for the lunar surface using data from Diviner's visible channels, and 2) to improve thermal models [9]–[11], by including more accurate visible light scattering functions within them. This is vital for permanently, or partly shadowed lunar polar regions, in particular—and hence, is important for investigating the distribution of ice volatiles, such as water ice, on the lunar surface/subsurface [12], [13].

Visible Oxford Space Environment Goniometer:

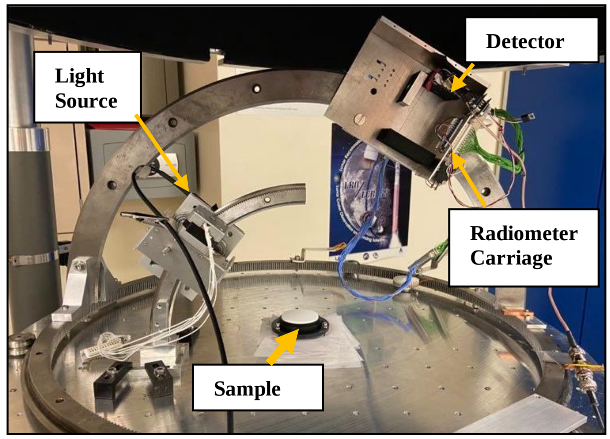

Figure 1: The Visible Oxford Space Environment Goniometer—measuring White Spectralon—with major parts labelled.

VOSEG is an automated three-axis goniometer, which allows variation of incidence, emission and azimuthal angles. A range of viewing geometries are possible: $\leq 60^0$ incidence, $\leq 70^0$ reflectance and down to $\sim 4^0$ phase angles (full instrument details given in [14], [5]). Figure 2 shows an example of VOSEG measurements of White Spectralon [15] (a well-characterised, commercial fluoropolymer), which are in agreement with BUG (within VOSEG's measured uncertainty).

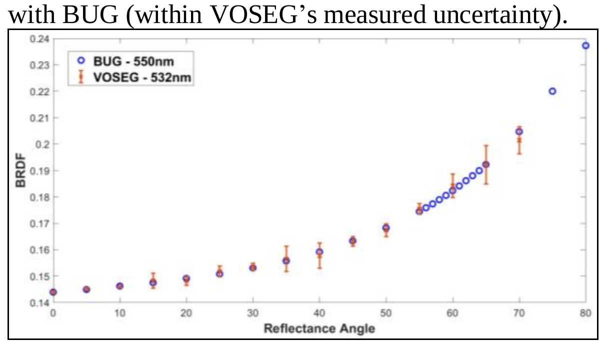

Figure 2: Bidirectional Reflectance Distribution Function measurements of White Spectralon, comparing BUG to VOSEG for 60° incidence angle, in the Principle Plane (180° azimuthal angle).

Sample Physical Property Variation Study: The methodology for studying how porosity and surface roughness variation affects BRDF is as follows:

Firstly, Apollo 11 and 16 samples are prepared in three compaction states—for the porosity study, and in two surface roughness states—for the surface roughness study. Secondly, a non-contact surface profiler is used 1) to measure the rms slope angles of the samples at various size-scales [16], and 2) to determine the porosities of the samples. For Apollo 11, the three prepared samples have filling factors (related to porosity [2]) of 0.45±0.01, 0.41±0.01 and 0.29±0.01. For Apollo 16, the filling factors are 0.55±0.01, 0.49±0.01 and 0.28±0.02. The associated density increases over the range of sample compactions is 54±2% for the Apollo 11 sample, and 105±4% for the Apollo 16 sample. These are in accordance with those measured for the Apollo core samples –i.e. between ~1,100kgm^{-3} and ~1,800kgm^{-3}: a 64% increase [11]. Figure 3 shows measured rms slope angles for this study's Apollo samples, and compares them to slope angles determined for in-situ lunar regolith, from the 1999 Shepard and Helfenstein study [16].

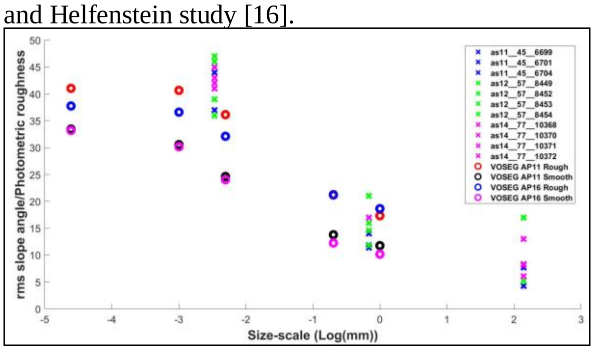

Figure 3: Lunar regolith rms slope angles for the Apollo 11 (10084) and 16 (68810) samples measured by VOSEG (circles), compared to slope angles determined for regions of the lunar surface in the 1999 Shepard and Helfenstein stereo-photogrammetry study (crosses), over various size-scales (from 10µm to 1mm, for VOSEG; and 85µm to 8.5mm, for Shepard and Helfenstein (1999)). As12-XX_XXXX in the legend refers to Apollo 12 image, XX_XXXX etc. [16].

Finally, BRDFs for each of the Apollo samples are measured over 0-70^0 reflectance angles at 0-60^0 incidence angles, for 0^0, 45^0, 90^0, 135^0 and 180^0 azimuthal angles. The BRDF study has been completed using VOSEG's 532nm ThorLabs CPS532 laser setup, and data is currently being measured using the Bentham IL1 Broadband light source setup. These measurements will be applicable to narrow-band remote sensing data, such as in the 2014 Sato *et al.* study [1], or to broadband data such as from Diviner [17].

Conclusions and Future Work: A new library of BRDF measurements are currently being measured for well-characterised Apollo samples with known surface roughness profiles and porosity values. The laboratory measured BRDFs are for samples with known compositions, porosities and slope angle values. This reduces the number of free parameters when fitting the Hapke model [2]. Initial results show the Hapke model does capture the BRDF dependence on surface roughness and porosity. An example of fitting the Hapke model to two BRDFs measured by VOSEG (and compared to BUG) is shown in Figure 4, for the rough and smooth Apollo 11 samples. These initial results suggest the appropriate size-scale for the Hapke slope angle parameterization is 500µm.

Once the BRDF dataset is complete, future work will be required 1) to further test the Hapke model's porosity and surface roughness parameterizations (i.e. investigate the size-scale of the Hapke slope angle), and to produce Hapke parameter maps for regions of the lunar surface, by comparing the laboratory BRDF data to visible off-nadir data taken by Diviner's broadband visible channels. And 2) to include accurate visible scattering inputs within thermophysical models to test how realistic scattering affects predicted surface temperatures, and thermally-derived thermophysical properties for the lunar surface.

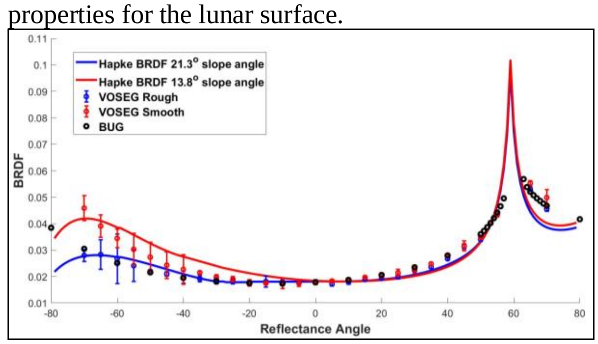

Figure 4: BRDFs measured by VOSEG for rough and smooth Apollo 11 (10084) samples (red/blue circles), compared to data taken in the E. Foote et al. *study (black crosses), and Hapke BRDFs for 13.8^0 and 21.3^0 slope angle values—which correspond to the 500µm size-scale for the Apollo 11 samples—at 60^0 incidence, in the Principal Plane. Hapke parameters: w=0.25, b=0.22, hs=0.02; ϕ=0.29±0.02 and 0.32±0.02 (as measured)* [7].

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