**Introduction:** The bidirectional reflectance function (BRDF) of terrestrial and planetary materials is of use for (a) correcting satellite or lander images for variations in illumination and viewing geometry [1], (b) inferring the subpixel-scale physical condition of the surface [2], and (c) synthesizing realistic views of planetary objects and terrain [3]. We have designed and built a system capable of measuring the full BRDF of samples in broadband wavelengths. Sample characteristics are fully documented by physical descriptions, high resolution digital color photographs, and spectral reflectance measurements.

**Photometric Goniometer:** We briefly describe the physical make-up of the goniometer which is illustrated in Figure 1.

**Light Source.** The light source is a 100W quartz-tungsten-halogen (QTH) bulb and is powered by a stable, radiometric grade power supply. The output light is chopped and filtered by broadband (50nm FWHM) interference filters in the 400-1000nm range. In practice, most of filters employed match the center wavelength of standard optical filters used by the astronomical community. The filtered light is focused onto a fiber-optic bundle, which ends at the top of the shorter goniometer arm with a 16mm diameter lens assembly. The collimated output is directed onto the sample ~60cm below. Samples are limited in size to ~40mm diameter.

**Detector.** A calibrated silicon detector is mounted at the end of the second, longer arm (~90cm) of the goniometer. It is electronically "locked" to the chopper motor on the source, which greatly reduces noise and allows the equipment to work even under ambient lighting conditions. The detector is spectrally sensitive from 200nm-1100 nm. All measurements are ratioed to the light scattered by a certified standard of diffuse reflectance "hood" which contains a diffused tungsten filament illuminator. The scattered light is collected by a fiber-optic cable and routed into the spectrograph. The spectrograph measures the reflectance from 400-1100nm with a spectral resolution of ~2-5nm, depending upon the slit size in place. All measurements are ratioed to the Spectralon™ standard.

**Mechanical components.** Three stepper motor stages, each independently controlled by computer software, are used to position the light source and detector in incidence, emission, and azimuth. The incidence angle can be varied from 0-75°, emission angle from 0° to 80°, and azimuth angle from 0-180°. This allows one-half of the upper scattering hemisphere to be completely covered, which is mirror symmetric with the other half (across the principal plane). The symmetry is checked by measuring selected points on the mirrored half-hemisphere. The minimum phase angle is ~2°, allowing the majority of the opposition surge to be measured. The entire measurement process is automated using a PC and Labview™ software. A sequence of motions in incidence, emission, and azimuth angles are preprogrammed. The stepper motors move the appropriate axis, stop, and allow the detector to register and record the reflectance at that geometry. A single measurement takes between 5-15 s, depending upon the angular movement required between measurement points. An entire scattering half-hemisphere (at a single incidence angle) takes between 30-45 minutes with an average spacing of ~0.03 sr between measurement points, and ~0.001 sr near opposition and the specular point.

**Camera System:** A separate camera system employs a high-resolution color CCD camera and close-focus zoom lens to image samples prior to measurement of their BRDF. Field-of-view (FOV) for the system ranges from ~70mm to 8mm, with corresponding resolutions of up to ~50 line-pair/mm (~20um). The purpose of the camera is two-fold: (1) digitally document, at high spatial resolution, all samples measured, and (2) using offset photographs, provide a means for viewing samples in stereo and measuring their surface roughness.

**Spectrograph:** A separate spectrographic system consists of a single fixed-grating spectrograph with a linear CCD detector. The sample (up to 40mm in diameter) is placed under a reflectance "hood" which contains a diffused tungsten filament illuminator. The scattered light is collected by a fiber-optic cable and routed into the spectrograph. The spectrograph measures the reflectance from 400-1100nm with a spectral resolution of ~2-5nm, depending upon the slit size in place. All measurements are ratioed to the Spectralon™ standard.

**Applications:** The B.U.G. Lab system was designed to investigate the full BRDF scattering properties of planetary analog materials at a range of optical wavelengths. Current work is focusing on validating current scattering models [2] over a wide range of viewing and illumination geometries and testing the wavelength independence of the Hapke roughness parameter [2,4,5]. Future work includes measuring the BRDF of planetary analog materials such as meteorites (asteroids) and palagonite (Mars), and lunar samples.


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Fig. 1. Goniometer shown in "parked" position (i=0, e=0). The longer arm holds the silicon detector. The shorter arm terminates with a fiber-optic lens assembly that puts a near-collimated beam on the sample (hidden behind the black panel).