THE MOON AS A SPECTRAL CALIBRATION STANDARD ENABLED BY LUNAR SAMPLES: THE CLEMENTINE EXAMPLE

Carlé M. Pieters, Dept. Geological Sciences, Brown University, Providence, RI 02912.

Spectral calibration of Clementine data rely on the Apollo 16 site and laboratory measurements of mature soil 62231. The process produces calibrated spectral reflectance factors.

What color is the Moon? A reflectance spectrum is essentially a measure of how much radiation incident on a surface (solar radiation) is reflected and how much is absorbed at each wavelength. To the eye the Moon is gray-white, but to photoelectric instruments it is various shades of red, that is, exhibiting an increase in brightness with wavelength. In the near-infrared there are absorptions diagnostic of minerals superimposed on the Moon's redness. For the Moon, and other rocky bodies such as asteroids, most of the detectable absorptions arise from ferrous iron in various crystallographic sites. The wavelength, shape, and strength of these absorptions identify the minerals present, and allow their abundances to be estimated.

To accurately measure these diagnostic mineral absorptions with remote detectors requires not only a quality instrument, but also excellent electronic calibration and either direct measurement of the light source (the sun), or a proxy, or a well known reference standard illuminated by the same light source. In the laboratory a white reference such as halon is used (or commercial Spectralon), which in turn has been extensively calibrated relative to a known radiance.

In space, or at the telescope, a separate reference must be found to mimic solar radiation and to eliminate instrumental and atmospheric effects. Radiation from stars to a first order follow a black body spectral curve with multiple emission and absorption lines superimposed. Because stellar lines vary with spectral type and very few stars are really solar-like, it is actually quite difficult to use stars as spectral standards.

The Moon is a nearby atmosphere-less body that reflects solar radiation. Because the Moon's surface itself does not change with time (at least within our lifetimes), it provides an excellent reference standard. The calibration challenge then reduces to identifying an area on the Moon whose measurable properties are exceptionally well known. The return of lunar samples allows their properties to be measured accurately in earth-based laboratories. Since the samples were collected from known areas on the surface of the Moon, carefully selected samples can be used to represent the properties of that area.

For Clementine data, the Apollo 16 site was chosen as a calibration target because it is a relatively homogeneous area with no nearby units of a significantly different material. Since all remote data are acquired as bidirectional reflectance, we use i=30°, e=0° as the standard geometry. The calibration steps used and the assumptions made are discussed briefly below.

The absolute spectral calibration procedures for Clementine data include the following steps (see **Table 1** for an estimation of errors):

a. Selection of Apollo 16 site calibration standard target: a 12x33 pixel area to the west of the landing site free of crater rays.

b. Selection of mature soil representative of the Apollo 16 site: 62231.

c. Obtain bidirectional spectral reflectance measurement of 62231, $R_{62231}(\lambda,i,e)$, at standard geometry (i = 30, e = 0):

   c1. Measure brightness of 62231 relative to Halon: $B_{62231}(\lambda,30,0)$

   c2. Obtain/derive correction for Halon reference standard: $R_h(\lambda)$

   c3. $R_{62231}(\lambda,30,0)=B_{62231}(\lambda,30,0)*R_h(\lambda)$

   An average spectrum is shown in **Fig. 1**.

d. Translate 62231 laboratory spectrum into Clementine 5-filter spectrum to obtain Apollo 16 "ground truth" data for Clementine filters: $R_{62231C}(\lambda, 30,0)$

d1. Obtain effective Clementine filter transmission curves, $F(\lambda)$

d11. Measure the transmission curve of each filter: $f(\lambda)$

d12. Estimate the solar spectrum: $S(\lambda)$

d13. Estimate detector sensitivity: $D(\lambda)$

d14. $F(\lambda)=f(\lambda)*S(\lambda)*D(\lambda)*\text{normalization}$

d2. $R_{62231C}(\lambda, 30,0)=R_{62231}(\lambda, 30, 0) * F(\lambda)$

Clementine filters are shown in **Fig. 2** and reflectance values are listed in **Table 2**.

e. Correct Clementine DN values for all gain, offset, and flat field corrections (including row, column and temperature dependent variables) [1, 2]: $DN_{Clem}(\lambda,i,e)$

f. Photometrically calibrate Clementine DN values to i=30, e=0 [1] (the Moon is redder at larger phase angles): $DN_{PClem}(\lambda,30,0)= DN_{Clem}(\lambda,i,e)*Cphot(\lambda,i, e)$

g. Derive spectral calibration correction factor $Cr(\lambda)$ using the laboratory data for soil 62231 and the Clementine calibrated DN measurement of the Apollo 16 site: $Cr(\lambda)=R_{62231C}(\lambda,30,0)/DN_{PClemAp16}(\lambda,30,0)$

h. Derive absolute Clementine *reflectance factor#* data $R(\lambda, 30, 0)$ for any lunar area: $R(\lambda, 30, 0) = DN_{PClem}(\lambda,30,0)*Cr(\lambda)$

#reflectance factor [3] = reflectance relative to a Lambertian surface under the same illumination. (Same as reflectance coefficient [3] and radiance coefficient [4], but *not* to be confused with radiance factor which is reflectance relative to a Lambertian surface illuminated at i = 0 [3, 4])

Table 1. Estimated Value for Sources of Error:

$B_{62231}(\lambda,30,0)$	1%	repeatability of laboratory measurements (absolute)
$R_h(\lambda)$	<0.5%	accuracy of halon spectral correction (largely NBS)
$f(\lambda)$	N/A	measurement accuracy of filter transmission
$S(\lambda)$	<<1%	black body estimation for solar flux
$D(\lambda)$	N/A	detector responsivity estimation
$DN_{Clem}(\lambda)$	1%	calibrated Clementine DN values [1, 2]
$DN_{ClemAp16}(\lambda)$	<1%	variation within site representing Apollo 16
$Cphot(\lambda,i, e)$	1%	photometric model [1]

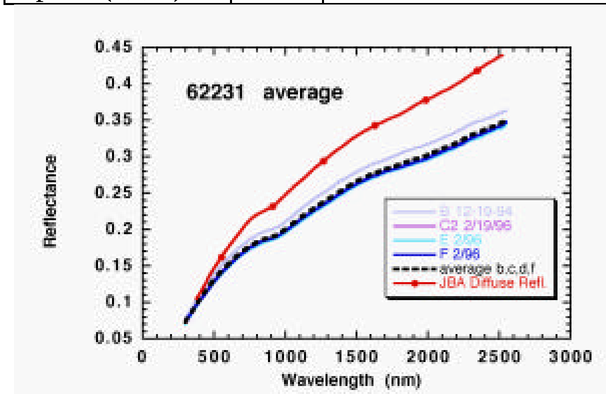

Figure 1. Reflectance spectra for Apollo 16 soil 62231. Several bidirectional spectra taken at i=30°, e=0° are averaged. The previous "diffuse" (directional hemispheric) spectrum by John Adams is shown for comparison.

These calibrations require several assumptions:

1. *A mature soil represents the properties of the site seen remotely under the same viewing conditions*. This appears to be valid as long as regolith has been allowed to develop and there are no nearby fresh craters.
2. *62231 is representative of mature Ap16 soils*. Spectra of several other Apollo 16 soils with comparable maturity all look similar to 62231; deviations are on the same magnitude as repeatability of individual measurements.
3. *Non-Lambertian properties of Halon are insignificant at i=30, e=0*. Any deviation would be a small scalar correction.
4. *The detector response properties used in calibration are invariant over the two month period of measurements*. There is no guarantee that this is true, but no systematic month-to-month variations are detected that are not photometric errors.
5. *Contribution from Clementine scattered light is compensated through in-flight*

measurements and calibration procedures. There is also no guarantee that this is true, but no effects of scattered light have been able to be demonstrated in spectral analyses.

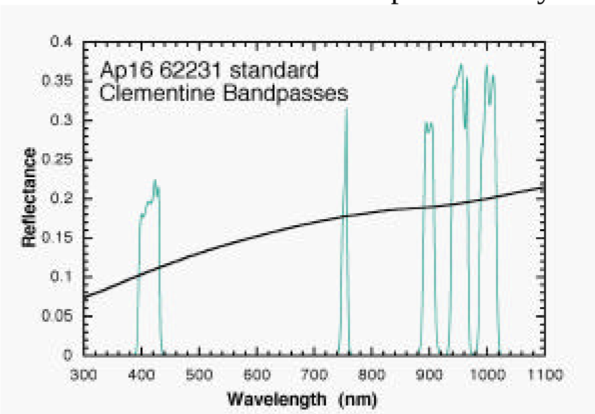

Figure 2. Average bidirectional spectrum for 62231 used as a calibration standard. UVVIS Clementine bandpasses are superimposed.

Table 2. Spectrum for Apollo 16 soil 62231 resampled at Clementine UVVIS wavelengths. These values are used in the final USGS Clementine mosaicks.

Effective Wavelength (nm)	$R_{62231C}(\lambda, 30,0)$
414.9	0.1077
753.3	0.1776
898.8	0.1893
951.5	0.1941
1000.4	0.2004

References: [1] McEwen (1996) LPSC27, 841; McEwen et al.(1998) LPSC29, #1466.[2] Pieters et al. (1996) www.planetary.brown.edu/ clementine/calibration.html. [3] Hapke B. (1993) Cambridge Univ. Press [4] Hapke B. (1981)*JGR. 86,* 3039.