A hybrid method for calculating TiO$_2$ concentrations using Clementine UVVIS data, and verified with Lunar Prospector neutron spectrometer data. J.J. Gillis$^1$, B.L. Jolliff$^1$, R.C. Elphic$^2$, S. Maurice$^3$, W.C. Feldman$^2$, D.J. Lawrence$^2$. 1. Washington University, Department of Earth & Planetary Sciences, St. Louis, MO, 63130, USA; 2. Los Alamos National Laboratory, MS-D466, Los Alamos, NM, 87545, USA; 3. Observatoire Midi-Pyrenees, 14 avenue Edouard Belin, 31400 Toulouse, France. (gillis@levee.wustl.edu)

Algorithms that extract estimates of TiO$_2$ concentrations from Clementine UVVIS data have been developed by [1-5]. Building on that foundation, we present a hybrid algorithm for calculating TiO$_2$ concentrations using the Clementine UVVIS data. This method is termed hybrid because it uses two equations to calculate TiO$_2$ concentrations; the first equation is similar to that of [4] and the second forms a subparallel trend that we apply to locations with “anomalously” low reflectance values and a flat or “blue” continuum. Where applied, the hybrid algorithm predicts lower TiO$_2$ values than the latest TiO$_2$ algorithm described by [4].

The Lunar Prospector neutron spectrometer (LP-NS) data can be used to test these new TiO$_2$ estimates by means of a “delta-sigma-effective” analysis, after the method of [6]. The hybrid method described here yields TiO$_2$ concentrations that, when coupled with the effects of other thermal neutron absorbers, match more closely the observed epithermal-to-thermal neutron ratio data than do the TiO$_2$ concentrations calculated by the algorithm of [4]. Although we do not yet have a petrographic or other theoretical explanation, the important result is that the three data points considered to be anomalous by [2-4] may in fact better represent the majority of lunar basaltic regions, and a calibration using those points yields more accurate TiO$_2$ concentrations for those basaltic regoliths.

Hybrid Method: We calculated global TiO$_2$ concentrations using the “final” calibration of the Clementine UVVIS data by the USGS, Flagstaff [7], and a hybrid method for calculating TiO$_2$ abundance, which combines the method of [4] with one described herein (Fig. 1). The basis for the method of Lucey and coworkers is a correlation between the spectral parameter $\theta_T$, determined using Clementine full resolution (125 m/pixel) images, with the soil composition from each Apollo and Luna landing site and sampling station [2-4]. The premise behind the use of two trends is the observation that the three landing sites with the largest deviation between calculated and actual soil TiO$_2$ content also exhibit the darkest and bluest spectral characteristics compared with the rest of the sample locations used to define the trend (Fig. 2).

For example, Apollo 11, Luna 16, and Luna 24 soils tend to have higher UVVIS ratios than other soils of similar TiO$_2$ concentrations and thus do not fall along the trend defined by Apollo 12, 15, 16, and 17 mare soils (Fig. 1). As a result, their calculated TiO$_2$ values are over predicted by a factor of ~2 (A11) to >4 (L24). The empirical power-law fit to these three data points minimizes the error of each point and prevents negative values.

The decision of which trend to use when calculating TiO$_2$ content is made on the basis of reflectance and continuum slope. The second equation is used to calculate TiO$_2$ abundances when reflectance at 415 nm is <0.66 and the 415/750 ratio >0.6, (inset box Fig. 2). If both these criteria are not met then a calibration similar to [4] is used.

Test of the Method: An independent test of the accuracy of the hybrid equation is made with the LP-NS data [6]. Variations in the epithermal-to-thermal flux...
ratio measurements are the result of compositional differences in lunar surface materials (i.e., the absorption of thermal neutrons is dependent on the thermal-neutron cross section of an element and the concentration of that element). The elements Fe, Ti, and Ca have relatively large cross sections and account for a majority of thermal neutron absorption. In addition, Sm, and Gd have isotopes whose thermal cross sections are 3-4 orders of magnitude larger than Ti, so these elements can be very significant thermal neutron absorbers despite being present in only trace amounts. The accuracy of the TiO$_2$ values, calculated using the hybrid algorithm, can then be assessed by comparing how well the predicted cross sectional absorption area (determined by the mass of Ti in the soil) matches the observed flux ratio of epithermal-to-thermal neutrons by Prospector.

To do this we must account for the combined effects of these elements on the LP-NS flux data. “Sigma effective”, $\Sigma^{*}_{\text{eff}}$, is a sum of the cross sectional areas of each element per gram of material, weighted according to their proportions [6]. The proportions of FeO, TiO$_2$, Ca, Sm, and Gd are estimated from global remote sensing data. FeO, TiO$_2$ (using both the “Lucey method” and the hybrid method) and Ca (approximated from FeO) are estimated using Clementine UVVIS data. The Lunar Prospector Th gamma-ray data are used to approximate concentrations of Sm and Gd, assuming that to a first order, they are present in KREEP-like ratios [Sm=2.86×10$^{-2}$ and Gd=1.17×Sm].

By comparing estimated $\Sigma^{*}_{\text{eff}}$ with the epithermal-to-thermal flux ratio (Fig. 3), the accuracy of the Clementine UVVIS-based TiO$_2$ abundances can be assessed. If FeO, TiO$_2$ and REEs (and inferred CaO abundance) are all properly accounted for, values for $\Sigma^{*}_{\text{eff}}$ would plot ideally along a line (red line on Fig. 3 [8]). Any residuals ($\pm \Delta \Sigma^{*}_{\text{eff}}$) arise from an under- or overestimation of the abundance of the major neutron absorbers in the lunar regolith. Positive residuals from the ideal relationship (i.e., points falling below the ideal line) indicate that additional absorbers are needed and negative residual deviations are caused by an overestimation of the summed concentration of neutron absorbers. As FeO, Sm, and Gd are calculated exactly the same way, and only the algorithm for calculating TiO$_2$ changes. Thus, variations in the positions of data points in Fig. 3 result only from the different methods used to calculate TiO$_2$.

Figure 3 illustrates that the magnitude and frequency of $\pm \Delta \Sigma^{*}_{\text{eff}}$ values estimated using the hybrid equation are significantly less than for the points calculated using the algorithm of [4], suggesting that the TiO$_2$ concentrations estimated by the hybrid method may be more accurate. In addition, we find that the locations where the hybrid equation is applied, using the above criteria, and where the largest $\pm \Delta \Sigma^{*}_{\text{eff}}$ values occur, using the method of [4] to estimate TiO$_2$, overlap one another. These areas include western O. Procellarum, southern M. Serenitatis, M. Tranquillitatis, M. Fecunditatis, M. Smythii, and M. Moscovienne (or about 40% of all mare surfaces). For these locations the difference in TiO$_2$ between the two techniques is 4-5 wt.%. Moreover, the magnitude of the $\pm \Delta \Sigma^{*}_{\text{eff}}$ points, calculated using the algorithm of [4], corresponds to an over estimation of TiO$_2$ by ~5 wt.% [6], indicating that the LP-NS data and TiO$_2$ values calculated using the hybrid equation are in closer agreement.

![Figure 3](image.png)

**Conclusions:** This analysis suggests that there is a significant factor related to soil “darkness” and UV/VIS slope that is not accounted for by previous methods [1-5]. Although a firm theoretical explanation is lacking, the hybrid method for calculating TiO$_2$ improves considerably the correspondence between Clementine UVVIS data and LP-NS data.

We find that approximately 40% of the maria are composed of surfaces that exhibit reflectance values of 0.66 or darker when measured at 415 nm and continuum slopes $>$0.6. This indicates that the three “anomalous” landing sites may more accurately represent the spectral character of a majority of the lunar maria.

We do not yet know what factor(s) controls the spectra of these “anomalous” soils. It could be related to a subtle petrographic feature, for example, differential comminution in mixed mare-nonmare soils in which fine-grained bright particles preferentially coat dark particles. Studies of the petrography, chemistry, and spectral reflectance of fine soil grain sizes may prove useful in addressing the problem.

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