NEW EXTENDED RANGE WAC TiO_2 MAP OF THE MOON. H. Sato[1], B. Hapke[2], M. S. Robinson[3], [1]Japan Aerospace Exploration Agency, 3-1-1 Yoshinodai, Chuo-ku, Sagamihara, Kanagawa, Japan (sato.hiroyuki@jaxa.jp), [2]University of Pittsburgh, Pittsburgh, PA, [3]Arizona State University, Tempe, AZ.

Introduction: Accurate knowledge of the distribution and the abundance of TiO_2 of the lunar surface is key to understanding the magmatic history and thermal evolution of the Moon. TiO_2 abundance maps were derived by various studies using multiple remote-sensing datasets. The UV sensitivity of the Lunar Reconnaissance Orbiter Wide Angle Camera (WAC) enables quantification of the unique spectral shape of ilmenite that increases toward shorter wavelengths from visible to UV, whereas reflectance for other major lunar silicate minerals decreases into the UV. The WAC 321/415 nm ratio derived TiO_2 map [1] was sensitive down to TiO_2 abundances of 2 wt% (corresponds to the dominance of ilmenite in the total TiO_2 content). Below 2 wt% range for the WAC TiO_2 map, a new algorithm was proposed by [2,3]. It utilizes the 566/689 nm ratio that correlates with the content of pyroxene, the other TiO_2 bearing mineral. The algorithm is valid only for mature soils; for immature soils it gives a lower limit. Based on this new algorithm, here we created a new merged WAC TiO_2 map with no limit of the valid range, and we compared it with other pre-existing TiO_2 maps.

Methodology: We used the WAC seven color semi-global mosaic created by [4] (400 m/pixel at the equator, 70°S to 70°N in latitude). The new TiO_2 algorithm [2,3] first calculate two TiO_2 values:

$$\mathrm{TiO_2}(566/689) = 34.48 - 41.49 * r(566/689)$$

$$\mathrm{TiO_2}(321/415) = 169.8 * r(321/415) - 121.9$$

where r(566/689) and r(321/415) correspond to the I/F ratio of 566 nm over 689 nm and 321 nm over 415 nm, respectively. Then the final TiO_2 values (hereafter called WACTiO$_2$) are derived by the following condition:

$$\mathrm{TiO_2} = \begin{cases} \mathrm{TiO_2}(321/415), & \text{if } \mathrm{TiO_2}(321/415) > 3 \\ \mathrm{TiO_2}(566/689), & \text{otherwise} \end{cases}$$

$$\mathrm{TiO_2} = 0, \text{if } \mathrm{TiO_2} < 0$$

We compared the new WAC based map with the TiO_2 map derived from the Clementine UVVIS 415 and 750 nm bands (200 m/pixel) [5] (hereafter called CLMTiO$_2$) and the Lunar Prospector Gamma-Ray Spectrometer (GRS) based map (1 pixel/degree) [6,7] (hereafter called LPTiO$_2$). We down-sampled both maps of WACTiO$_2$ and CLMTiO$_2$ to 32 degrees/pixel to minimize the residuals of photometric normalization along steep slopes. We also down-sampled WACTiO$_2$ to the resolution of LPTiO$_2$ (1 pixel/degree) and applied the same smoothing filter as [1] to simulate the GRS's large footprint with the WAC data.

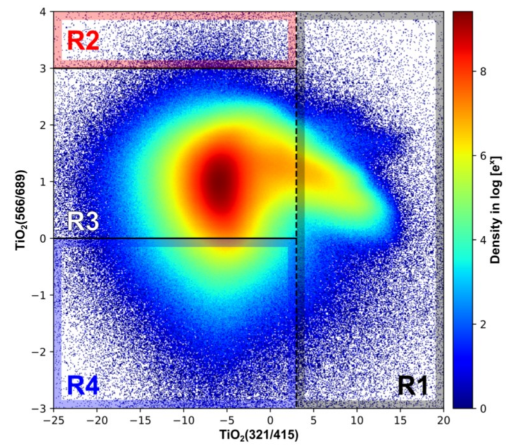

Figure 1. Density plot of TiO_2(321/415) vs TiO_2(566/689) for the whole area of WAC semi-global mosaic (70°S to 70°N). R# indicates the region number.

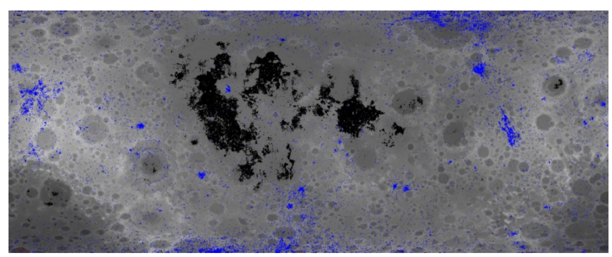

Figure 2. Spatial distribution of the R1 (black), R2 (red) and R4 (blue) in Fig.1.

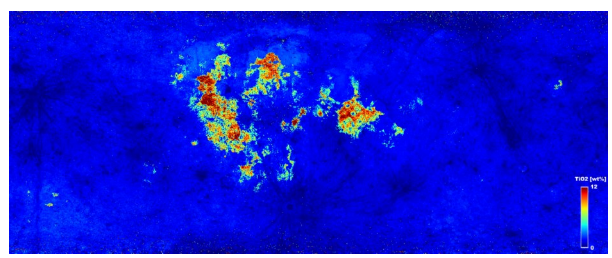

Figure 3. WAC TiO_2 map based on the algorithm proposed by [2,3]. The spatial extent is from 180°W to 180°E, 70°S to 70°N.

Results: First, we examined the incompatible regions with the new TiO_2 algorithm. From the scatter plot of TiO_2(321/415) vs. TiO_2(566/689) (Fig. 1), we defined the regions from 1 to 4 (Fig. 1, R1-R4). Regions 2 and 4 are the incompatible regions where TiO_2(566/689) is higher than TiO_2(321/415) and lower than 0 wt%, respectively. In a map view (Fig. 2), region 2 has less than 0.04% of areal fraction and dominantly corresponds to abnormal pixels (such as shadows). Thus we consider that region 2 is negligible.

The region 4 is mainly located on immature highland ejecta, dominated by anorthositic materials [8]

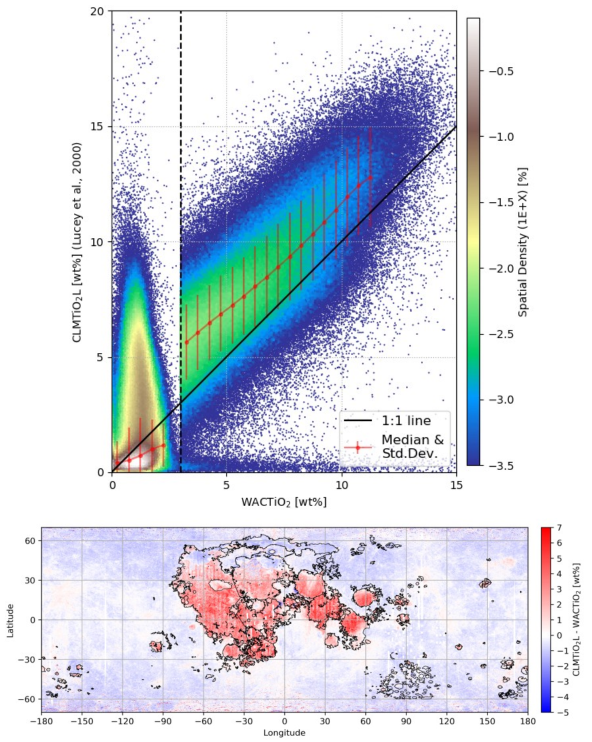

Figure 4. Density plot of $CLMTiO_2$ vs. $WACTiO_2$ (top) and difference map of $CLMTiO_2$ - $WACTiO_2$ (bottom). Bin size of the errorbar is 0.5 wt%. The mare boundaries are outlined by black line.

with TiO_2 values close to zero. Since an immature low-TiO_2 soil [2,3] is not covered by the new algorithm and is supposed to have too low TiO_2 values, the region 4 negative values are an expected result. The semi-global view of the new $WACTiO_2$ map (Fig. 3) has no noticeable offset at the 3 wt% transition.

Compared to the $CLMTiO_2$, the $WACTiO_2$ of region 1 is consistently lower (~2.5 wt% on average; Fig. 4 top). For TiO_2 values less than 3 wt%, the $WACTiO_2$ values are greater than (up to twice on average) those of the $CLMTiO_2$. In the map view of $CLMTiO_2$ – $WACTiO_2$ (Fig. 4 bottom), the maria are dominantly red (= $CLMTiO_2$ > $WACTiO_2$) except Mare Frigoris and northern portions of Imbrium and Procellarum. In the highlands, mature regions are typically blue (= $CLMTiO_2$ < $WACTiO_2$), and the immature ejecta (set $WACTiO_2$ = 0 wt%) are displayed in red.

The difference between the $LPTiO_2$ and $WACTiO_2$ is relatively small (-0.1 wt% on average with σ = 0.5 wt%, Fig. 5 top). The difference map (Fig. 5 bottom) shows locally red (= $LPTiO_2$ > $WACTiO_2$) region (up to +6 wt%) near Kepler and Aristarchus craters. A similar trend was also found in [1], possibly related to the sensible depth of GRS (~30 cm [9]) and the WAC (a few millimeters [10]). Immature highland ejecta are relatively red but boundaries are not as sharp in Fig. 4

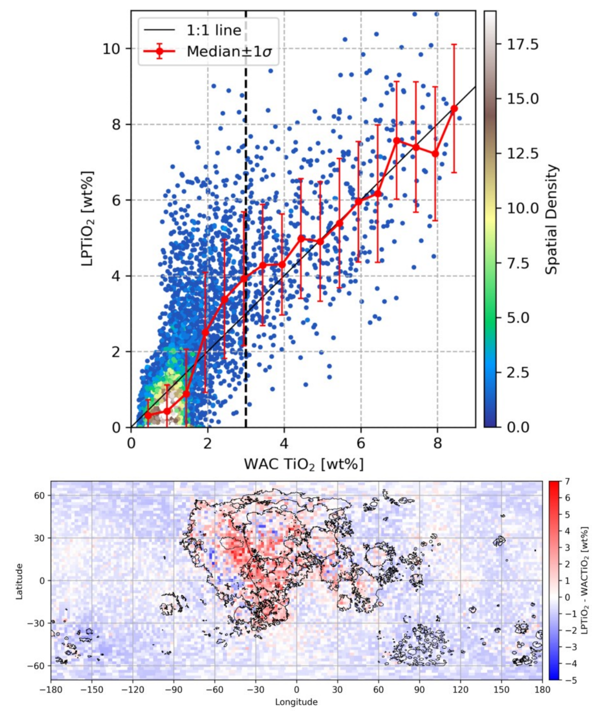

Figure 5. Density plot of $LPTiO_2$ vs. $WACTiO_2$ (top) and difference map of $LPTiO_2$ - $WACTiO_2$ (bottom). Bin size of the errorbar is 0.5 wt%.

(bottom), likely due resolution effects. The difference in the highlands is -0.4 wt% on average, with σ = 0.7 wt%. Averaged difference only for the mature highland surfaces, however, will have a larger difference in negative value (= $WACTiO_2$ > $LPTiO_2$).

Discussion: The sharp discontinuity of $WACTiO_2$ in Fig. 4 (top) corresponds to the boundary of TiO_2(321/415) and TiO_2(566/689). In Fig. 5 (top), however, such discontinuity was not observed. An improved algorithm with a gradual transition (based on the laboratory experiments) might reduce the uncertainty of this discontinuity observed in Fig. 4 (top). More low-TiO_2 samples from the highlands (and the maria) are required for more accurate estimates of spectral reflectance for low-TiO_2 abundance, particularly in 0-1.5 wt% range. Once the polar color WAC mosaics are released, the extended range of TiO_2 estimates can be applied to the poles, which could open a new frontier of lunar polar science.

References: [1] Sato et al. (2017) *Icarus* 296, 216-238. [2] Hapke et al. (2019) *Icarus* 321, 141-147. [3] Hapke et al. (2019) *Icarus*, in press. [4] Sato et al. (2014) *JGR-Planets*, 119, 1775-1805. [5] Lucey et al. (2000) *JGR,* 105 (E8), 20297-20305. [6] Elphic et al. (2000) *JGR-Planets,* 107 (E4), 5024. [7] Prettyman et al. (2006) *JGR*, 111 (E12), E12007. [8] Ohtake et al. (2009) *Nature*, 461 (7261), 236-40. [9] Lawrence, et al. (2002) *JGR* 107 (E12), 5130. [10] Hapke Hapke (2012) Cambridge University Press, New York.