STUDY OF 12.5CM RADAR AS A MEANS OF MAPPING TiO\textsubscript{2} IN LUNAR BASALTS

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ABSTRACT

Previous work using neutron spectrometer data and earth-based 70 cm radar has proven useful in mapping TiO\textsubscript{2} on the lunar surface but with coarse resolution. Spectral data from the Clementine mission attempted to map TiO\textsubscript{2} at higher resolution but accuracy was low. With new 12.5 cm Mini-RF radar data from the Lunar Reconnaissance Orbiter I attempted to build a higher resolution TiO\textsubscript{2} map by comparing the radar data to neutron spectrometer and spectral data. Initial investigation into 12.5 cm radar as a means of mapping TiO\textsubscript{2} revealed large standard deviations in the radar data such all the radar data points were statistically indistinguishable. Even after data averaging of overlapping radar swaths the wide range in radar values made it impossible to find any correlations with the neutron or spectral data. At 12.5 cm, surface roughness has too much of an affect over radar backscatter to be able to discern any affects related to rock composition.

BACKGROUND

Mapping TiO\textsubscript{2} in lunar basalts is of scientific interest, primarily because large differences in TiO\textsubscript{2} concentrations yields insight into the geologic complexity and cooling history of the moon (Heisinger et al., 2000). TiO\textsubscript{2} is also an exploration interest as an in-situ resource because ilmenite, the major carrier of TiO\textsubscript{2}, can be used to supply oxygen (Papike et al., 1991) which would enable long term stays on the moon. Previous studies have mapped TiO\textsubscript{2} in lunar basalts using either neutron spectrometer (Elphic et al., 2002) or spectral reflectance data (Gillis-Davis et al., 2006). NASA’s Lunar Prospector mapped TiO\textsubscript{2} in lunar basalts with good accuracy but low resolution (15 x 15 km per pixel) using neutron spectrometer data. UVVIS data from the Clementine mission was used to map TiO\textsubscript{2} composition at higher resolution (~ 200 m per pixel) however it was found that the accuracy was low. The accuracy at high and low concentrations was good but mid-range TiO\textsubscript{2} concentrations exhibited poor correlation (Gillis-Davis et al., 2006). Another method that has been used to determine lunar TiO\textsubscript{2} composition is Earth-based 70 cm radar data (Campbell et al., 1997). The benefit of using radar data is that it offers complimentary compositional information because it has different sensitivities to the lunar regolith than UVVIS and neutron spectrometer data (Campbell et al., 1997). Campbell et al (1997) found that there is consistent negative correlation between 70 cm echo power and Ilmenite content in lunar maria. On this basis I have attempted to use Mini-RF radar data from the Lunar Reconnaissance Orbiter (LRO) to map Ilmenite. In addition, besides being sensitive to different aspects of the lunar regolith than Clementine data, Mini-RF has much higher resolution (~ 15 x 15 m per pixel) than UVVIS, neutron spectrometer, and earth-based radar data that has been previously used to study TiO\textsubscript{2} content.
SCIENTIFIC BASIS FOR USING RADAR AS AN INDICATOR OF TiO$_2$

The Lunar Reconnaissance Orbiter (LRO) is the first in a series of NASA’s Lunar Precursor Robotics Program and is designed to pave the way for eventual permanent long term human presence on the moon (Chin et al., 2007). The LRO hosts a suite of instruments and is designed for a one year base mission with a goal of extending for four additional years. Mini-RF stands for miniature radio frequency and is synthetic aperture radar (SAR) with two frequencies (X band and S band). Mini-RF utilizes circular polarization (CP) with seven data products; the circular polarized ratio (CPR), same sense (SC), opposite sense (OC), and the four stokes parameters. Mini-RF is unique in that it is able to penetrate the lunar regolith at greater scales than any previous spaceborne imaging radar instrument (Nozette et al., 2010). The ability to probe deeper regolith is partially a function of the radar wavelength. The 12.5 cm wavelength S band data that we have been using is less susceptible to surface rocks and regolith structure (Campbell et al., 1997) as it is able to penetrate up to ~10cm. By comparison spectral reflectance is only able to penetrate a few microns. Where a thin layer of highland contaminant may drastically affect spectral reflectance, this thin layer comprises only a small portion of radar backscatter.

Radar backscatter is affected by two key factors, surface roughness and composition. Whether a surface appears rough or smooth to radar depends on roughness relative to radar wavelength. I used the 12.5 cm radar, meaning blocks of approximately 12.5 cm would appear rough to radar and radar backscatter would be high. Smooth surfaces cause a specular reflection, the majority of the radar signal reflects away from the radar detector, and backscatter is low. One of the obstacles was discerning between the affects of surface roughness and composition on radar backscatter. One of the reasons I chose the areas that I did is because they are all of similar age, have been exposed to similar amounts of space weathering, and presumably have similar roughness.

Because surface roughness is assumed to be comparable in all three maria, differences in backscatter can be attributed to mineralogical factors. Dielectric properties of surface materials are the main compositional factor affecting backscatter. The microwave loss tangent is defined by the ratio of the imaginary to real component of the complex dielectric constant. The real component is dependant primarily upon the density of the material while the imaginary component is a result of bulk chemistry. Interpretation of radar backscatter requires assumptions about the population of rocks within each maria. It seems plausible that rocks of a certain basalt flow will have similar densities within that unit (Campbell et al., 1997). Also, similarly aged basalts should have similar textures. Thus, with other main variables held relatively constant, changes in radar backscatter should be related to chemical composition of the basalt. Analysis of the 70 cm radar data suggests that the main cause of backscatter changes is due to variations in Ilmenite content (FeTiO3) (Campbell et al., 1997). By using radar to map Ilmenite variations it may be possible to build a better TiO2 map.

METHODS

There are two other reasons that I chose the three maria that I did for studying. First of all, data from each of the Lunar Prospector, Clementine, and Lunar Reconnaissance Orbiter missions
overlapped in those maria. Secondly, Mare Serenitatis, Crisium, and Tranquillitatis represent low, medium, and high TiO₂ compositions, respectively, as measured by Lunar Prospector. Also, TiO₂ composition in the samples returned from Mare Crisium (e.g. Luna 24) are in conflict with the abundances measured by Lunar Prospector. I compared radar backscatter values from the LRO mission to data collected from the Clementine and Lunar prospector mission to see if there were any correlations or anomalies between the data sets. The main tool I used in my work was the Image processing software ENVI. Initially I would create regions of interest in each of the maria and find the mean and standard deviation in each of these regions. I then compared those values to the UVVIS and neutron spectrometer data. The radar data had very large standard deviations such that each of the mare was statistically indistinguishable from the next.

Simply using the mean and standard deviation was not going to provide reliable information to draw any conclusions from the data. To increase confidence in the data I decided to use the standard error of the mean (SEM). SEM measures how much the sample mean varies from the population mean. I assumed the population mean to be the mean of all maria on the moon and the sample mean was the mean of each of the maria I was studying. SEM is calculated by:

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SEM = \frac{\sigma}{\sqrt{n}}
\]

where \(\sigma\) is the sample standard deviation and \(n\) is the number of observations. Using the SEM as my measure of confidence in the data helped significantly in reducing the range of error.

One of the factors I thought that may be contributing to the wide range in the radar data was a low signal to noise ratio (SNR). The SNR can be estimated as the number of signal photons divided by the number of noise photons. The number of noise photons can be estimated by taking the square root of the number of signal photons. Increasing the number of signal photons causes the SNR also to increase because noise photons are only increasing by a fractional exponent. To increase the SNR I co-registered overlapping radar swaths, averaged the data in the areas that overlapped, and used the SEM from the averaged data. Figure 1 is a mosaiced image that shows conceptually what I was doing when averaging the data. To co-register the images I used USGS's image processing software ISIS. Each radar image is geo-registered to a location on the moon and ISIS automatically co-registered the images based on the latitude and longitude I input from the header file. I would then link the co-registered images in ENVI and draw regions of interest in areas that overlapped then combine and average that data in excel. Finding areas of overlap proved to be somewhat difficult. Radar backscatter is affected by the angle of incidence; the edge of the swath nearest the sensor has higher backscatter values than the far edge (Fig. 2). For this reason I avoided data averaging swaths that overlapped only at the farthest edges because those areas had backscatter extremes that are a function of incidence angle and not of surface composition. The Mini-RF had varying Incidence angles, and larger angles would yield a greater range in backscatter values as a result. In addition to avoiding areas at the edges, I also avoided radar swaths that had extreme radar swaths (>50°). The increase in my SNR combined with the use of the SEM allowed for me to make comparisons to other data sets.
To compare the radar data to the other data sets I used ENVI to create regions of interest in both the spectral and neutron spectrometer images and took the mean values from each region. Because the resolution is so different for each of the data sets, the regions of interest and the size of the area sampled were all different as well. The regions of interest for the neutron spectrometer and spectral (UVVIS) data were approximately the same size as the maria themselves. It was impossible to make the regions the same size for the radar data because firstly there wasn't enough radar coverage, secondly I was having to choose only the radar swaths that overlapped, and thirdly the pixels size was so small for the radar data that choosing very large regions of Interest put too much of a burden on the computers I had access to. There is a disparity in the area sampled between the radar data and the other two data sets.

**DATA**

To compare the radar to the other data sets I plotted the radar data versus the neutron spectrometer and spectral data, respectively (Fig. 4). The neutron spectrometer and spectral data is a single point because those data sets cover the entire maria. There are multiple points for the radar data because I sampled small areas within each maria for the radar data. If the 12.5 cm radar data were being affected primarily by Ilmenite, there would be an inverse relationship between radar and the other two data sets. Because there is such a wide range in the radar data I cannot draw any conclusions about possible correlations between the data sets. Surface roughness may be responsible for the wide range observed in the radar data.
Figure 1 (left): CPR band radar vs. neutron spectrometer epithermal/thermal ratio (left) and radar vs. Clementine 415/750 nm spectral reflectance (right). The wide range in the radar data makes it difficult to draw any kind of correlations between the radar data. Error bars are hidden behind the legend symbols. Note the TiO$_2$ content of Mare Crisium is in conflict between the spectral and neutron spectrometer data sets. This was one of the problems I was hoping to address with this study.

**DISCUSSION AND IDEAS FOR FUTURE WORK**

It appears that 12.5 cm radar may be too short of a wavelength for making a map of TiO$_2$. After averaging the data together to increase the SNR there is still a wide range in the radar data within the same mare. The neutron spectrometer data indicates that Mare Tranquilitatis and Mare Serenitatis are fairly uniform in TiO$_2$ content, so it seems unlikely that the range seen in the radar data is indicative of Ilmenite content and is probably related to surface roughness.

In my research I mainly used the CPR band radar but future studies involving longer wavelength radar may want to use the SC and OC bands as well. Changes in rock population or mineralogy contribute a diffuse component to both the SC and OC radar. Changes in roughness contribute only to the OC return. The CPR is the ratio of the SC/OC. In areas dominated by rough terrain the CPR approaches unity. But if those areas have low Ilmenite abundances the SC component decrease much faster than the OC while the CPR still remains near unity. Thus, areas that have similar CPR values but different SC values may have different Ilmenite abundances (Ghent et al., 2005).

Future studies using longer wavelength radar in combination with the 12.5 cm radar may be able to create a higher resolution TiO$_2$ map. The 12.5 cm radar could be used to map surface roughness on the moon. Longer wavelength radar would not be affected by roughness in areas that are rough to 12.5 cm radar. Thus, changes in backscatter of the longer wavelength radar can be assumed to be related to Ilmenite content.

**CONCLUSION**

Mapping TiO$_2$ at higher resolution continues to be of scientific interest both for understanding the geologic evolution of the moon and for the possible resources that TiO$_2$ may provide. The Clementine and Lunar Prospector missions as well as the earth based radar have proven to be very useful in creating maps of TiO$_2$. Based on that work future studies may be
able to employ space borne radar to improve the resolution. The 12.5 cm radar aboard the LRO seems to be much too affected by surface roughness to make any interpretations of mineralogy, but that wavelength may prove useful as a roughness map. Future work using longer wavelength radar or utilizing differences between the CPR and SC radar backscatter may be able to improve upon current TiO$_2$ maps.

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