DETERMINING THE INFLUENTIAL DEPTH FOR SURFACE REFLECTANCE OF SEDIMENT BY BRDF MEASUREMENTS

Hao Zhang[1], Kenneth J. Voss[1] and Eric M. Louchard[2]
[1]Physics Department, University of Miami, Miami, FL 33124,
hzhang@physics.miami.edu
[2]Marine Geology and Geophysics, RSMAS, University of Miami, 4600 Richkenbacker Causeway, Miami, FL 33149

INTRODUCTION

One of the unsolved problems in shallow-water remote sensing is the prediction of the Bi-directional reflectance distribution function (BRDF) from the optical properties of the individual particles. The BRDF, defined as the ratio of the radiance scattered by a surface into a given direction to the collimated power incident on a unit area of the surface [1], is an important parameter needed to accurately predict how light would be reflected from a surface. In past years we have made BRDF measurements on various benthic sediments and found they are very anisotropic [2]. It is important to know the sensible sediment depth which influences the BRDF to properly consider parameters such as surface morphology, packing structure, organic matter and so on. We have carried out laboratory BRDF measurements on ooid sands with different particle sizes by embedding both a reflective mirror and an absorbing black tile at different depths in the sediments. Measurements have been done on both dry and wet samples at 3 visible wavelengths. Albedos are then evaluated from BRDF in order to determine the small variations of the reflectance factors.

INSTRUMENT AND SAMPLE DESCRIPTIONS

Our in-situ BRDF-meter [3] uses fiber optics to collect light from 107 fixed viewing angles located from 5 to 65 degrees in zenith and from 5 to 345 degrees in azimuth and bring light to a cooled CCD array camera (Apogee AP 260). 3 colors of LED (red at 658, green at 570 and blue at 475 nm in wavelength) located from 0 to 65 degrees in zenith sequentially illuminate the sample area. The spot of illumination light ranges from a 1.5 cm-diameter circle at 0 degree incidence to a 3.8 cm *1.5 cm ellipse at 65 degrees. Calibration is done by taking ratio of the measured reflectance in a given direction to that which a 99% nominal lambertian reflector (Labsphere) would have, thus the data presented in this form are bidirectional reflectance factors (REFF) [1].

On a stable surface, such as a Labsphere calibration plaque, the relative BRDF difference between measurements are less than 0.1% which includes surface level variations caused by loading the plaque. The integrated quantity albedo has typical relative variations of 0.03%, up to 0.1% in rare cases.

Ooid sands were collected in the vicinity of Cat Cay, Bahamas in 1999. The lammelar carbonate coatings of these ooid grains were formed in high-energy tidal channels and providing a highly reflective, lusterous surface for BRDF measurements [4]. The sediment was bleached with sodium hypochlorite (5.25%) for 24 hours and then sieved into three sizes, 0.5-1 mm (sample A), 0.25-0.5 mm (sample B) and 0.125-0.25

mm (sample C). The fine (C) and medium (B) ooids are mainly spherical particles while the coarse one (A) is a mixture of spherical grains and broken shells.

Grain layers of thickness 6.8 mm (depth I), 4.5 mm (II), 2.9 mm (III), 2 mm (IV) and 1.2 mm (V) were formed for these three samples by first laying aluminum plates with various thickness combinations on the bottom of the sample holder, then either a mirror or a black tile was placed on top. Grains were slowly poured into the holder to form a thin layer with desired thickness above the mirror or black tile. The plate containing the sample holder was tapped and shaken to settle down the grains. To level the surface, the edge of a plastic ruler was moved along different directions to make it macroscopically smooth and orientation independent. Four measurements were made for each surface to minimize the sampling inhomogeneity, between each measurement set the sample holder plate was rotated 90 degrees to eliminate any remaining orientation biases of the sample surface. At each thickness, after a dry surface was measured, BRDF of wetted surface was also measured. Water was carefully dripped in from the edge of the sample holder until the grains were thoroughly saturated and a small amount of water ponded on the surface. Then the surface edge was touched by a small piece of towel paper to absorb the excessive water. In this way all grains were wetted thoroughly yet the wet surface was made to bear the closest morphology as the corresponding dry one; different layers could also have very similar water concentrations.

TYPICAL DATA

In this abstract only results of layers on mirror are presented. The typical REFF of a 10mm-thick dry layer of sample A without an underlying mirror, illuminated by red light is plotted in Fig 1. At 0° illumination, the surface can be regarded as lambertian, with about 10% variations from nadir to 65° viewing zenith. As the incident zenith moves off from nadir, REFF becomes more and more anisotropic with an enhanced backscattering peak showing up around 0° phase angle. Within our available phase angle range, the measured REFF is strongly backscattering. Fig 2 is the REFF of dry sample A of depth V (1.2mm-thick on mirror) illuminated by red light. The most prominent effect of an embedded mirror below this thin layer is the enhanced reflectance in near-normal incidences 0° and 5°, as seen by comparing Fig 1 and 2. The specular peak that a mirror would exhibit [3] is not obvious at higher incident angles thus it may not be straightforward to see the mirror effects even for such a thin layer from REFF. To manifest any possible thickness-dependent REFF variations we have evaluated albedo, defined by:

$$\alpha = \pi^{-1} \int_{2\pi} \int_{\pi/2} \rho(\theta,\phi) \cos\theta \sin\theta d\theta d\phi \qquad (1)$$

where $\rho(\theta, \phi)$ is BRDF, θ is incident zenith angle and ϕ the relative azimuth angle. The albedos versus incident zenith angles for 3 ooids at 3 illumination colors are shown in Fig 3; error bars are standard deviations between the sample rotations. We have noticed that when measuring a powdered surface, factors such as the packing density and surface flatness have a large effect on its final albedo values, in contrast to a stable surface repeatable with maximum 0.1% error. While every measure was taken to ensure grain layers with different thickness have the same porosity and flatness, it's impossible to achieve the same precision as for plaque, as determined by the microscopically random

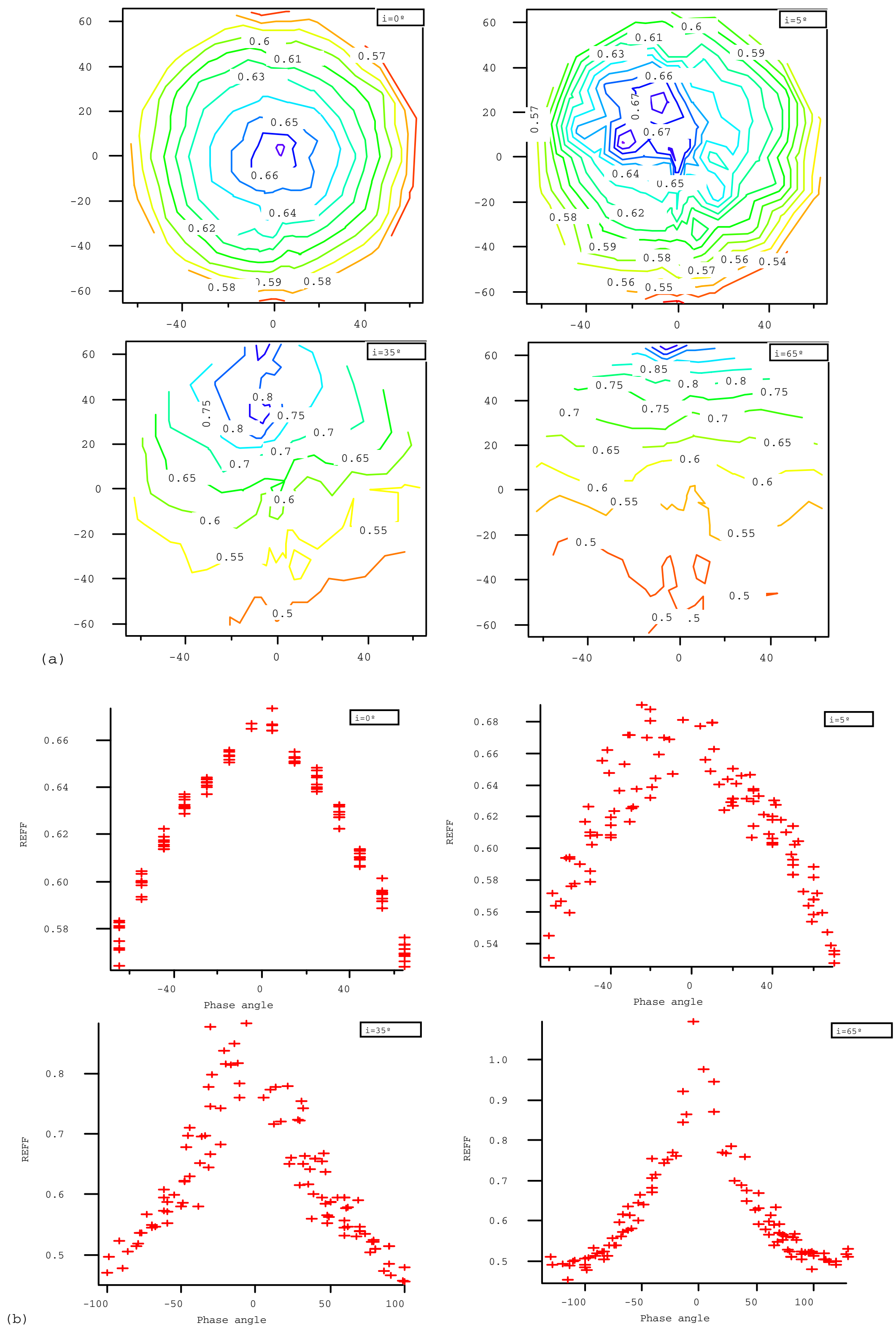


Figure 1 (a). REFF of a 10mm-thick dry layer of sample A by red light. (b). Same as (a) but REFF are plotted against phase angle. The incident zenith angles are indicated in boxes.

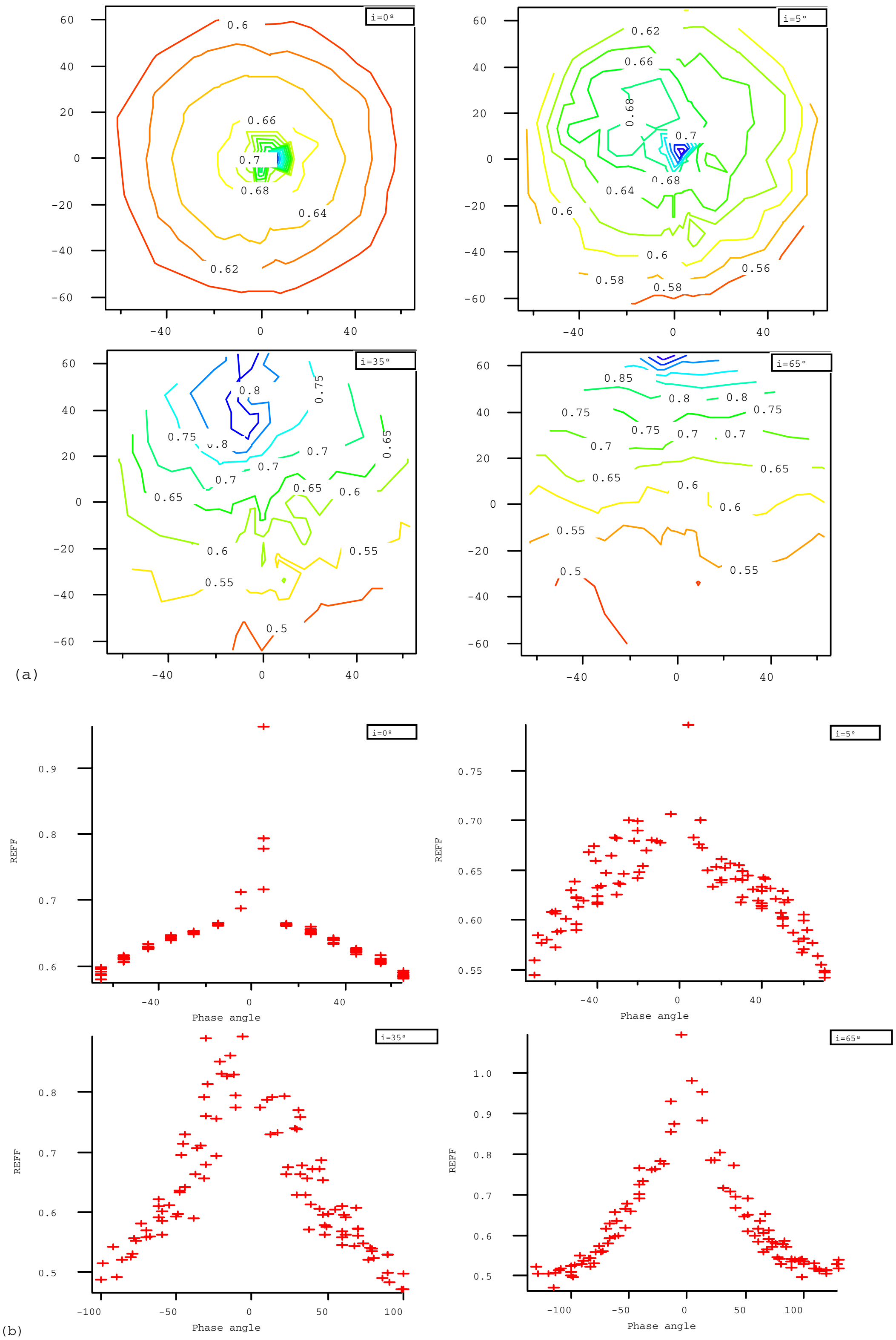


Figure 2(a). REFF of 1.2mm-thick dry layer of sample A on mirror. (b) Same as (a), but plotted against phase angle

nature of a powdered surface. In Fig. 4 one of the repeated measurements verifying the depth variations manifested by mirror is shown. In this verification measurement only the dry grains were measured at 5 depths, with 2 of them done twice: at depth II and 10mm-thick without mirror. From this experiment we can see the depth variations are basically the same as that shown in Fig 3(a), red light can "see" the mirror down to depth III, while the uncertainties caused by making the surface are typically around 1% (Fig. 4(c)). Thus any albedo variations within 1% are not attributed to depth variations, but measurement uncertainties.

For dry sample A, Fig. 3(a) shows red light can be affected by a mirror buried at 3 mm depth, while green and blue can not "see" the mirror when deeper than 2mm. Taking into account the uncertainties, a 4-5mm layer for red and 3mm for green and blue may be regarded as optically thick for sample A. For sample B (Fig. 3(b)) and C (Fig. 3(c)), all colors of light can be barely affected by mirror depths less than 1.2mm; as the mirror moves further down, other factors affecting albedos such as porosity and surface morphology overwhelm the mirror effect. Safely speaking, a 2mm-thick layer for sample B and sample C can be regarded as infinitely deep in BRDF measurement.

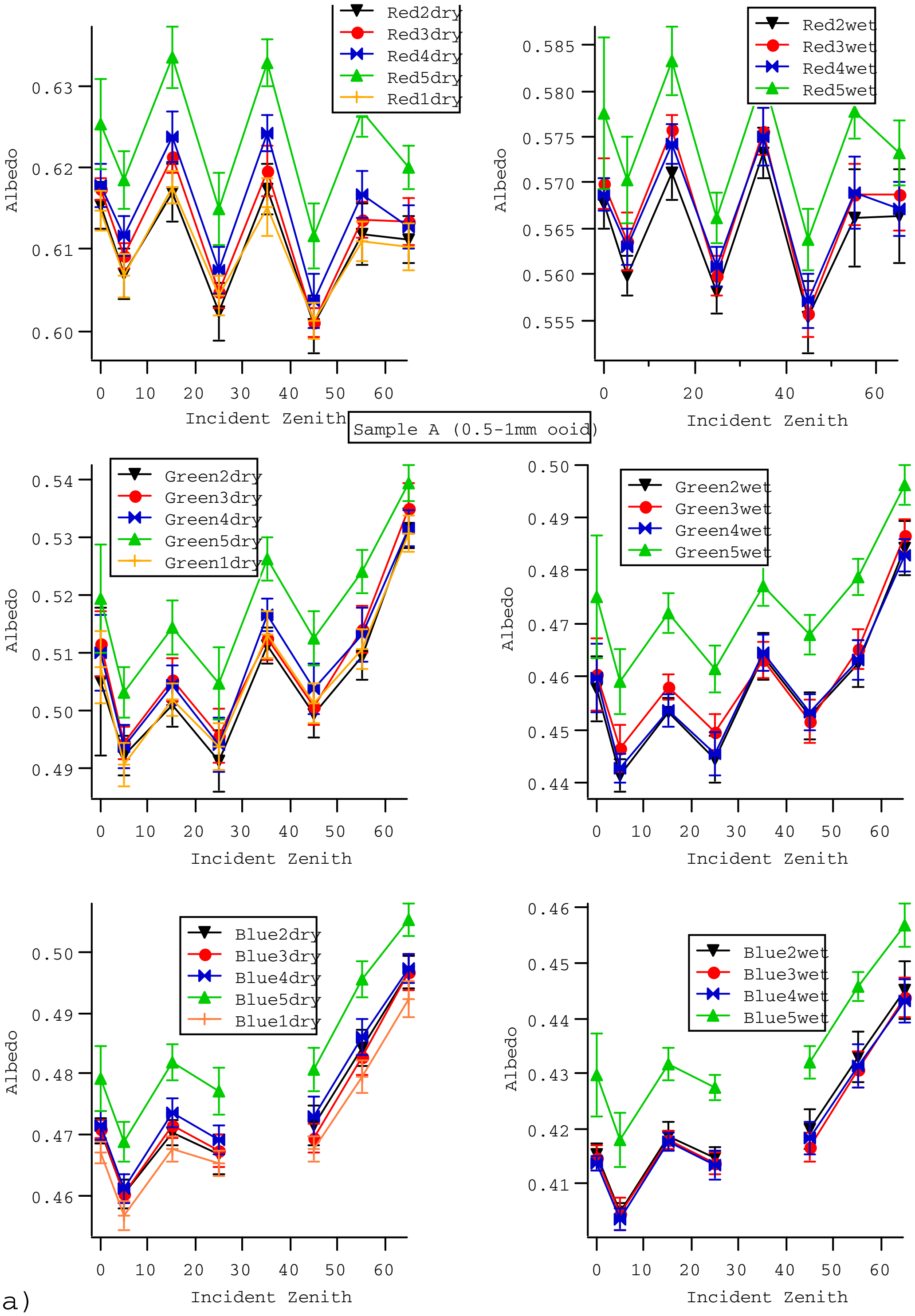
Effects of wetting

Overall the wet albedos versus incident zenith are seen to possess the same trends as the corresponding dry ones. All wetted surfaces are substantially darkened since upon wetting the refractive index contrast between grains and the surrounding medium decreases thus forward scattering increases and accordingly more absorption occurs [6]. The effects of enhanced forward scattering introduced by wetting are shown in Fig 5. We plot the relative difference of wet and dry REFF, i.e.

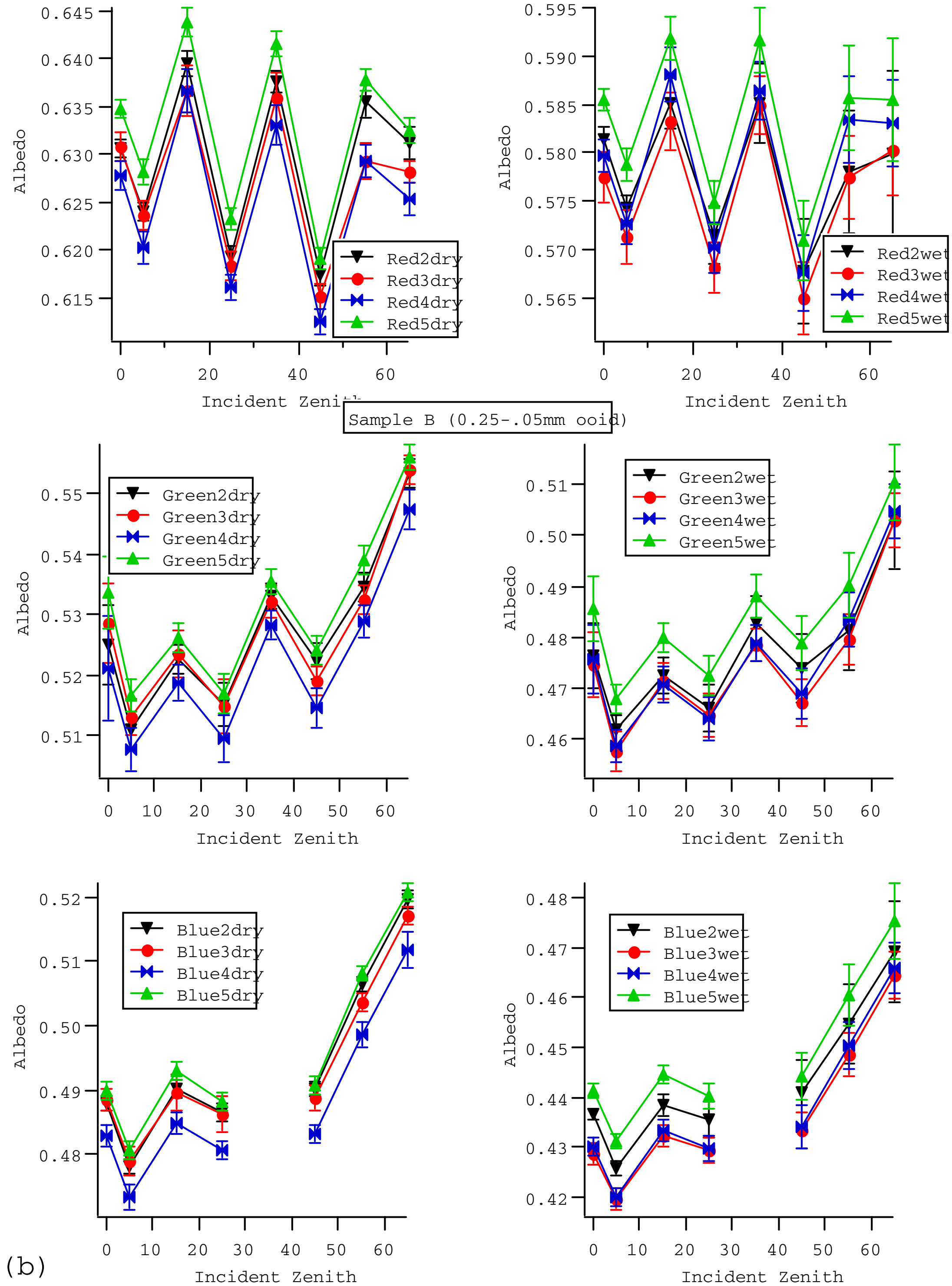
100*(Wet REFF- Dry REFF)/Dry REFF (2)

at 8 incident angles, for depth V of sample A (red). It can be seen that the REFF increases in the forward direction while backscattering is greatly suppressed, as manifested by the negative values around the hotspot direction (Fig. 5(a)). Even for thinnest 1.2 mm-thick layer the enhancement of forward scattering induced by wetting is much greater than that by the introduction of a mirror, as the comparison of Fig. 1 and Fig. 2 shows.

One might expect light to penetrate deeper in wet layers as more photons are directed to hit the mirror and are then reflected back, yet this was not observed in our BRDF measurement. Although no quantitative control of water concentration was made for such thin layers when wetting, our method described earlier could make the layers have very close to the same water concentration. For wet sample A, thicknesses of II, III and IV are seen to be "squeezed" in contrast to their dry counterparts which indicates light is more attenuated thus mirror plays a smaller role. Albedo of depth V is 1.6% (red) and 3%(green and blue) higher than other thicknesses thus the mirror effect is obvious at this thickness. As the mirror moves down, the albedo difference between depth II and IV is within 1%. For wet sample B, thickness V is about 1% (red) and 2% (green and blue) higher. For wet sample C however, no increment can be detected at all. For wet sample C, no mirror effect even at thickness V can be perceived at all. As the mirror moves down the BRDF-meter can detect higher or comparable albedos with such fine grains. In this case, light is not seen to penetrate deeper than in the dry layer. This indicates that for wet sample C, a 1.2 mm-thick layer is indeed infinitely deep in BRDF measurement.


Red2dry
Red3dry
Red4dry
Red5dry
Red1dry
Albedo
0.63
0.62
0.61
0.60
0 10 20 30 40 50 60
Incident Zenith
Red2wet
Red3wet
Red4wet
Red5wet
0.585
0.580
0.575
0.570
0.565
0.560
0.555
0 20 40 60
Incident Zenith
Sample A (0.5-1mm ooid)
Green2dry
Green3dry
Green4dry
Green5dry
Green1dry
0.54
0.53
0.52
0.51
0.50
0.49
Incident Zenith
Green2wet
Green3wet
Green4wet
Green5wet
0.50
0.49
0.48
0.47
0.46
0.45
0.44
Incident Zenith
Blue2dry
Blue3dry
Blue4dry
Blue5dry
Blue1dry
0.50
0.49
0.48
0.47
0.46
Incident Zenith
Blue2wet
Blue3wet
Blue4wet
Blue5wet
0.46
0.45
0.44
0.43
0.42
0.41
Incident Zenith

(a)


Sample B (0.25-.05mm ooid)
Albedo
Incident Zenith
Red2dry
Red3dry
Red4dry
Red5dry
Red2wet
Red3wet
Red4wet
Red5wet
Green2dry
Green3dry
Green4dry
Green5dry
Green2wet
Green3wet
Green4wet
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Blue2dry
Blue3dry
Blue4dry
Blue5dry
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Blue3wet
Blue4wet
Blue5wet

(b)

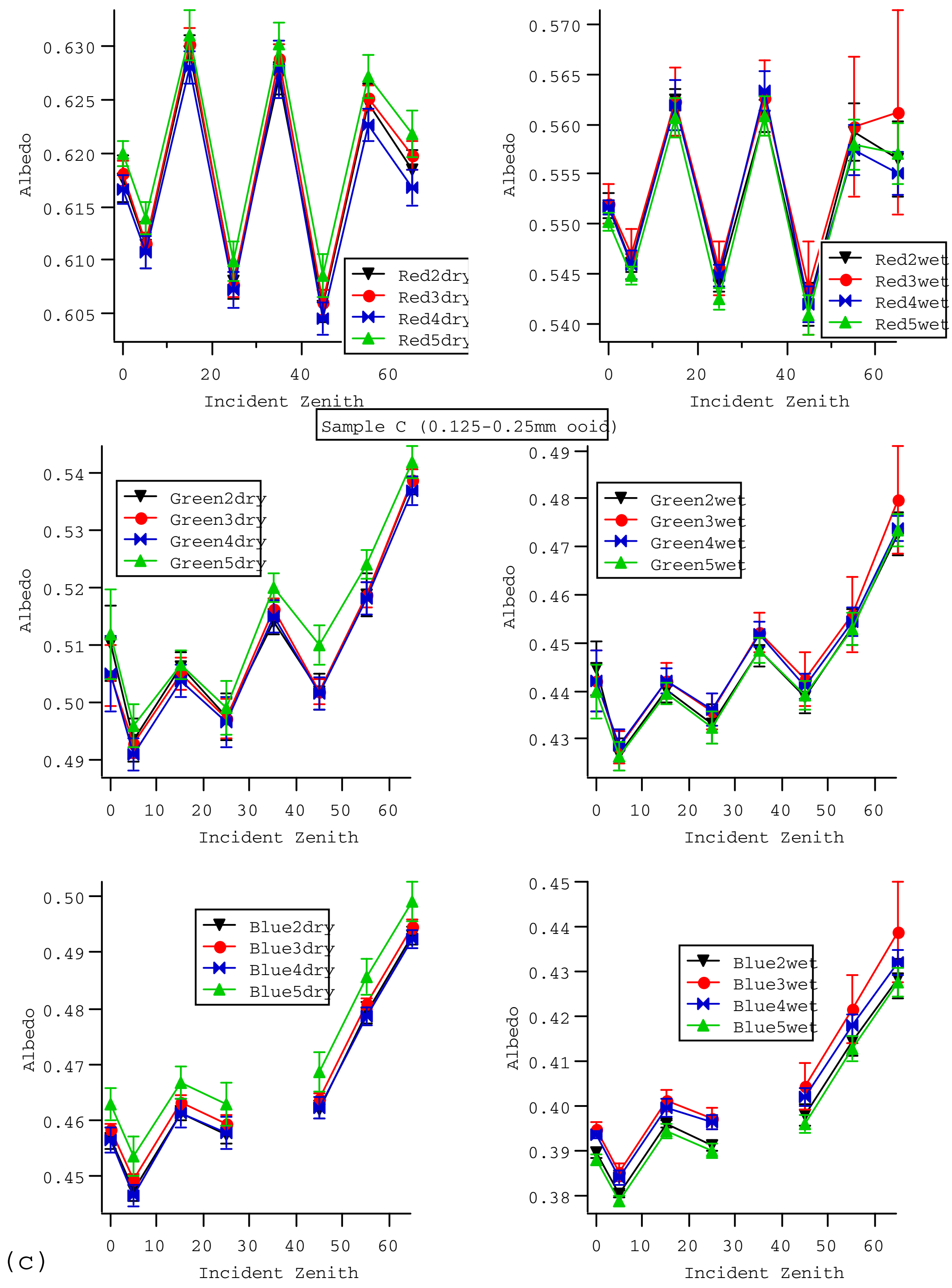


Figure 3. Dry and wet albedos of sample A (a), B (b) and C (c) at 3 colors. The Arabic number "2", for example, represents depth II in text. A broken blue LED caused a void data point at 35-degree incident. Depth I is very close to depth II thus for clarity it is only shown for dry sample A.

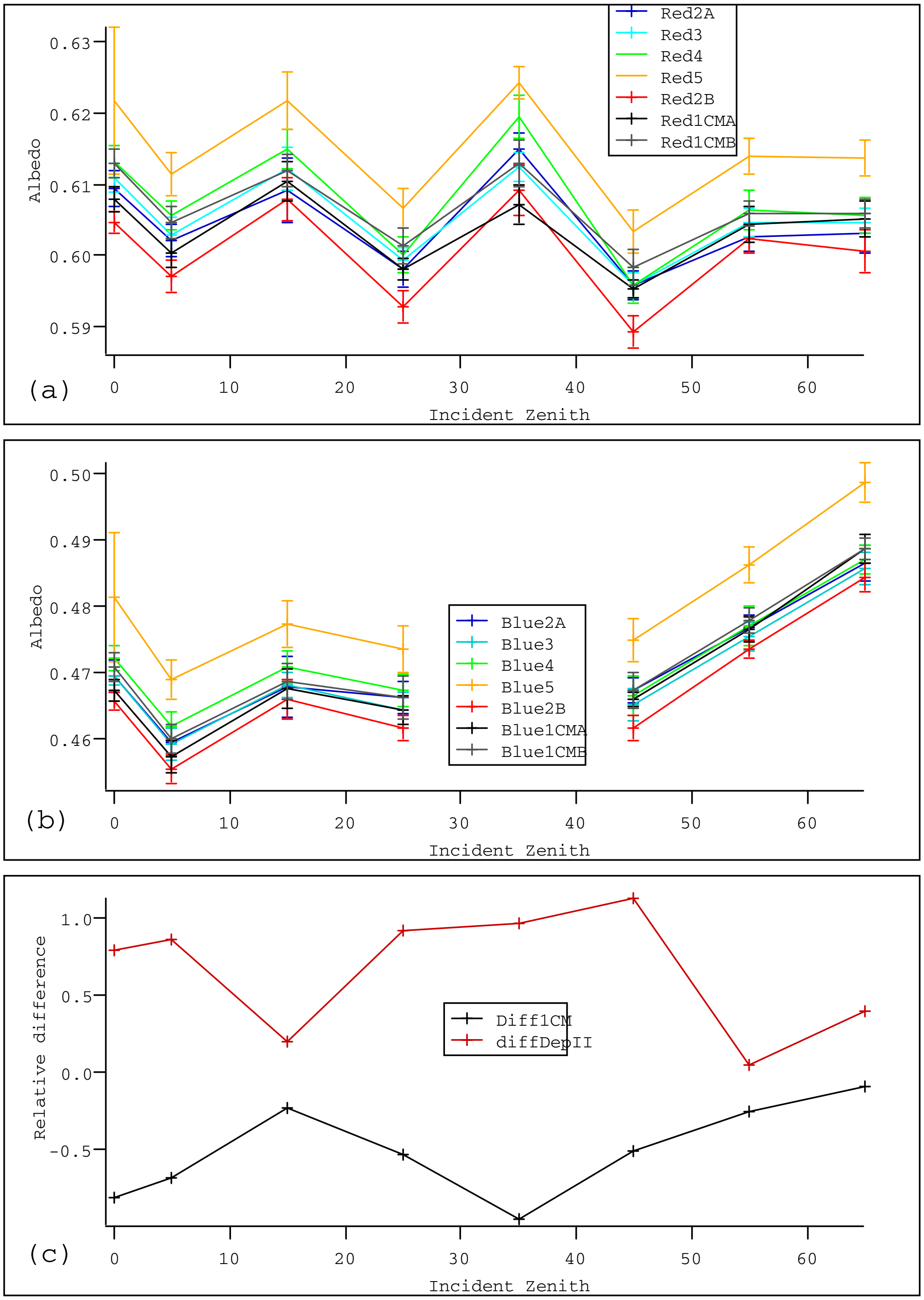
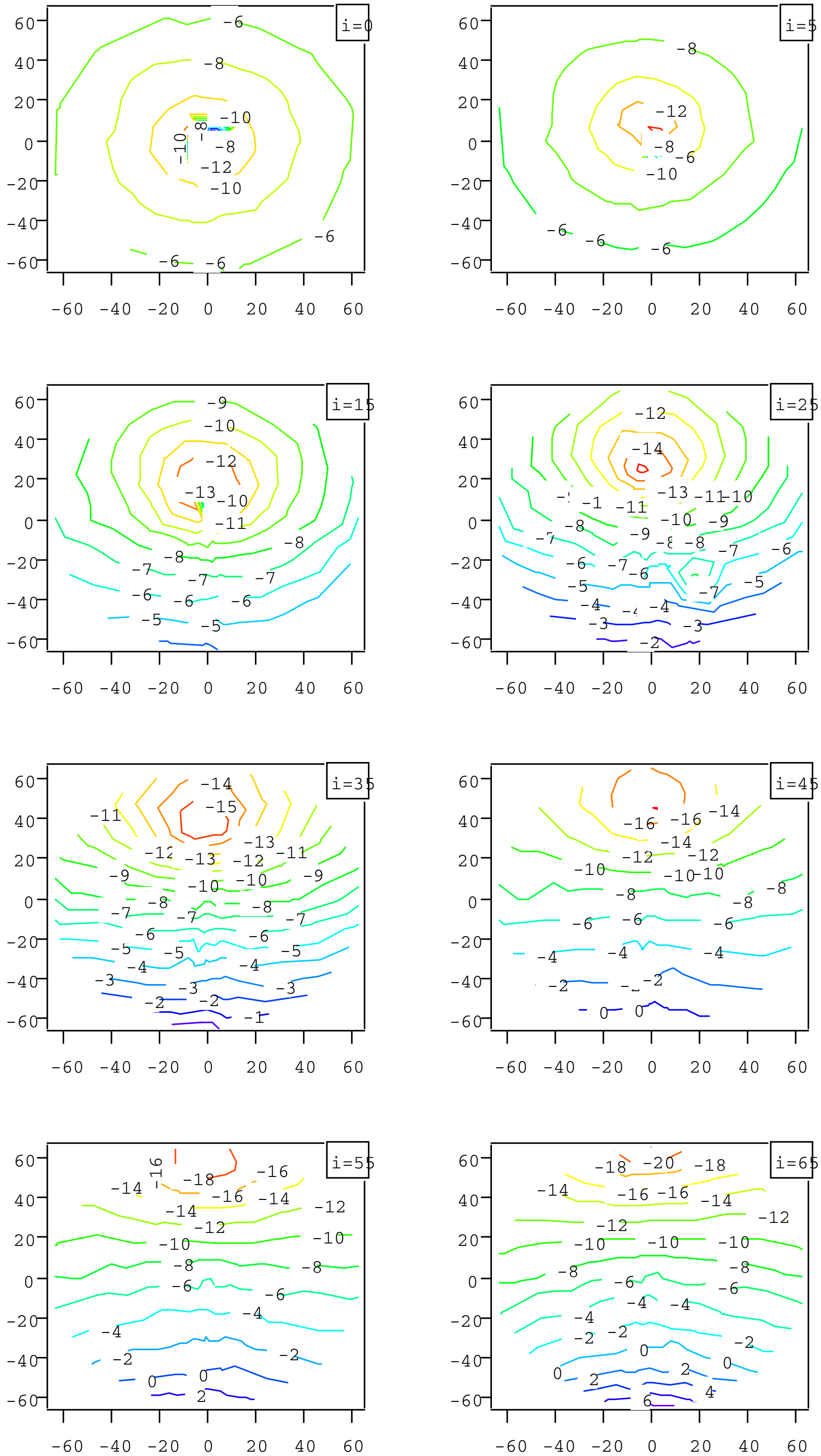


Figure 4. Repeated measurements on sample A to determine the albedo variations caused by different surface makings probed by (a) red light and (b) blue light. (c) Relative differences in percentage between two surfaces of depth II and 10mm-thick at red.



(a)

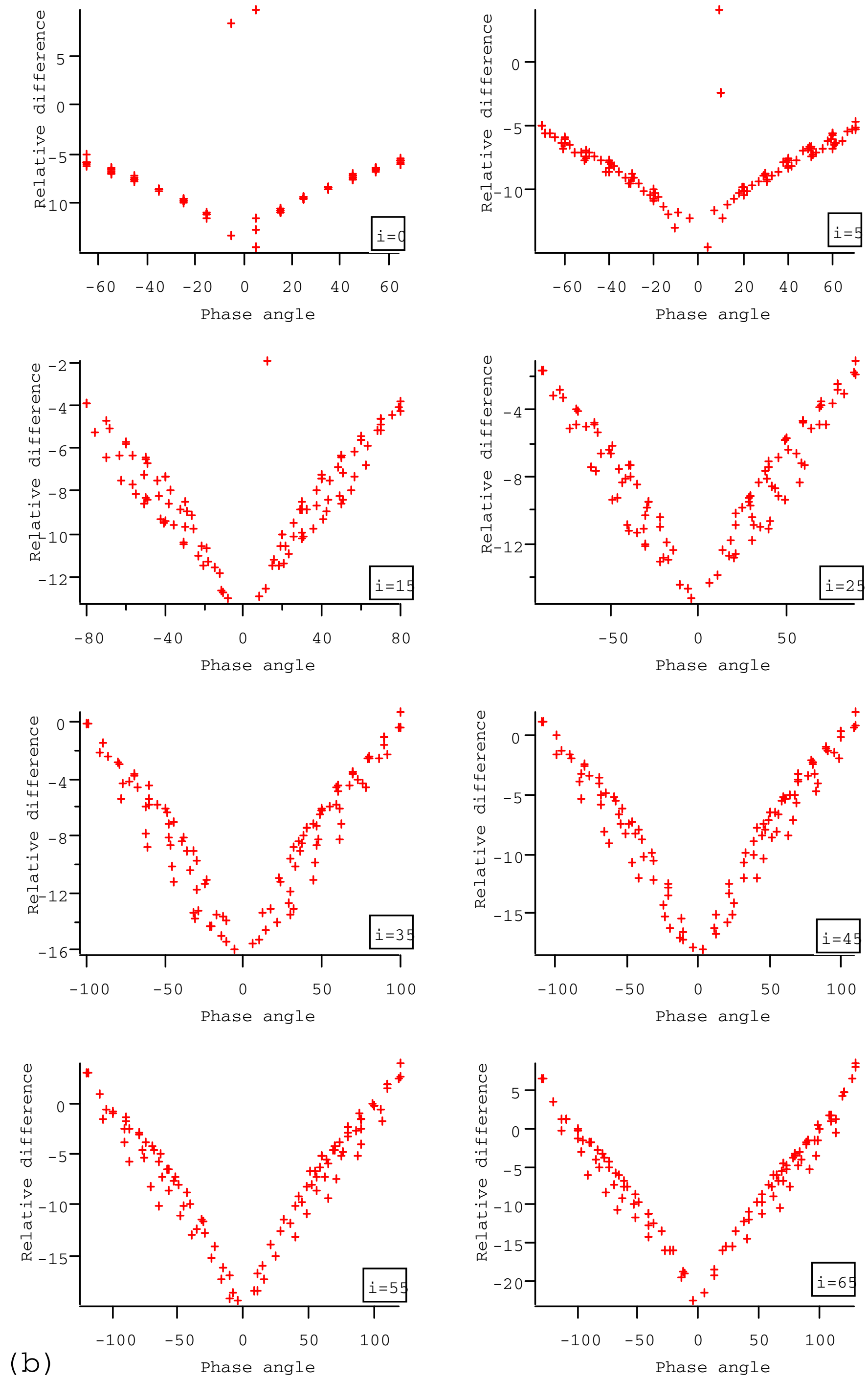


Figure 5. Relative difference (Eq. (2)) of wetted sample A at depth V. (a) Contour plot of REFF. (b) Same as (a) but plotted against phase angle.

Although scattering becomes more forward when wetted, within a thick enough layer, insufficient photons can be directed to the mirror before they are absorbed thus the mirror plays smaller role as in the dry grains.

Taking into account the measurement uncertainties, BRDF measurements show that for both dry and wet 0.5-1 mm diameter ooids, the discernable penetration depth is at most 5 mm for red and 4 mm for green and blue light. For 0.25-0.5 mm and 0.125-0.25 mm diameter dry and wet ooids, penetration depth is at most 2 mm for 3 colors. These results are in qualitative agreement with radiative transfer calculations of soil that the sensible depth is about 4 times the effective particle radius when particles are much larger than the probing wavelength [6].

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