Influence of scattering surface inclination on the opposition effect

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New observations and analyses are presented of the opposition effect on mud cracks (mud polygons) on desert playas. The enhanced brightness of the surface near the antisolar point has been previously and correctly ascribed to two sources: shadow-hiding and coherent backscatter. The observations reported here suggest that a third optical mechanism influences the OE: some parts of the mud polygon are more strongly illuminated than others, depending on the angle of incidence of sunlight. This causes the areas facing the observer and the sun to be brighter than the rest of the polygon field. This mechanism, called "dilution," also should occur in all OEs.

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1. Introduction

The opposition effect (OE) is a bright spot a few degrees across seen on the ground around the antisolar point (ASP) at a scattering angle of ~180°. It is frequently visible from an aircraft whose shadow is penumbral and therefore essentially undetectable, as shown in Figure 1(a). The OE has been long known on the moon, when it brightens dramatically near opposition (i.e., at full moon). Indeed, the total amount of light reflected toward Earth at first quarter moon is only about 1/10th as much as full moon. Based on the brightening of Saturn's rings as it approaches opposition, Seeliger [1,2] explained the optical mechanism as shadow-hiding (SH). When the observer's line-of-sight (LOS) is parallel to the sun's rays, no shadows can be seen.

More recently, Kuga and Ishimaru [3] and Hapke [4,5] have shown that another optical mechanism known as coherent backscatter (CB) plays a major and sometimes dominant role in the brightness of surfaces when viewed in backscatter. In general, SH can be observed over the entire field of view whereas CB is limited to a few degrees around the ASP. Trowbridge [6] has presented a number of interesting backscatter mechanism related to SH and CB that have not yet been fully investigated.

The OE is present on every surface, natural and man-made. Its shape and brightness distribution depend primarily on the detailed geometry of the shadowers (SH), the microscopic optical properties of the sunlit surfaces of the shadowers (CB) and the scattering angle.

Studying the OE involves three challenges: First, the shadow of the observer's head prevents sunlight from reaching the ASP [Fig. 1(b)], and thus the observer cannot see the ASP. Second, from the air, the geometry of the surface is not known in any detail, so modeling is uncertain. Finally, even from the ground when the OE is within reach, most surfaces are inhomogeneous and therefore their backscatter characteristics are correspondingly irregular across the field of view. To minimize these complications, investigators would like to make ground-based observations of a wide, flat surface that is relatively homogeneous, and one that can be observed with the minimum possible observer shadow.

This paper presents spatially resolved, ground-based observations of the OE on natural mud

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(a) (b)

Fig. 1. (a) Terrestrial OE on grassy plain. Bright spot is elliptical and vertically elongated, typical of grassy plains. (b) Terrestrial OE on mud polygons seen as a bright glow around the shadow of the observer's head. No shadows can be seen above the shadow of the observer's head (ASP), but they are readily visible below it.

polygons ("mud cracks") using what I believe is a novel observation technique. The analysis shows that geometrical dilution of sunlight plays a significant role in the brightness distribution of the OE.

2. Observations

In October 2013, a prominent OE was observed on mud polygons on the New River delta in Imperial County in California [Fig. 1(b)], and subsequent observations were made in November 2013 (Fig. 2). To minimize the observer's shadow, a small point-and-shoot digital camera (Nikon AW100) was placed at the end of a 6 m long extendable painter's pole raised as high as possible. The camera's shadow was primarily penumbral with a small core of umbra. A field of mud polygons is relatively simple: It is a homogeneous, horizontal surface with many ~vertical cracks. They can be observed close up and *in situ* to obtain detailed shape information for modeling purposes.

The most striking aspect of Figs. 1(b) and 2 is the overall difference in brightness between the upper and lower portions of the photograph. Above the ASP, no shadows can be seen in the vertical plane defined by the sun and the observer, and relatively few on either side. Below the ASP, shadows are quite evident and subtend a progressively larger portion of the field-of-view (FOV) as the observer's LOS dips further below the ASP. The reason for these differences is illustrated in Fig. 3, which shows that above the ASP the observer has no visual access to the shadows but below the ASP the shadows are in the direct LOS.

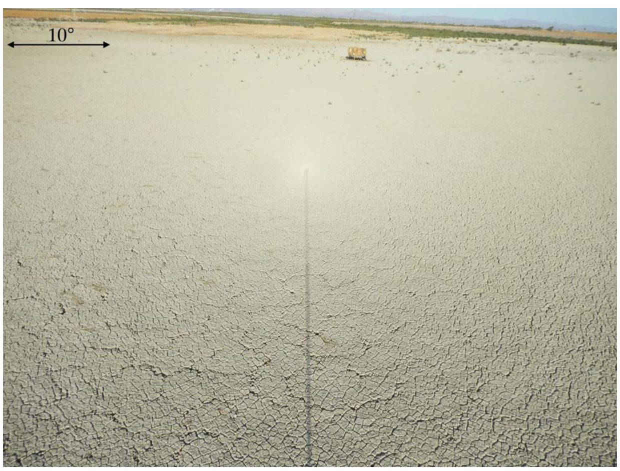

Fig. 2. Terrestrial OE on mud polygons with the camera placed on a pole 6 m in length. Compared to the same surface as Fig. 1(b), the observer's shadow (camera shadow) is greatly reduced, allowing more complete OE exposure.

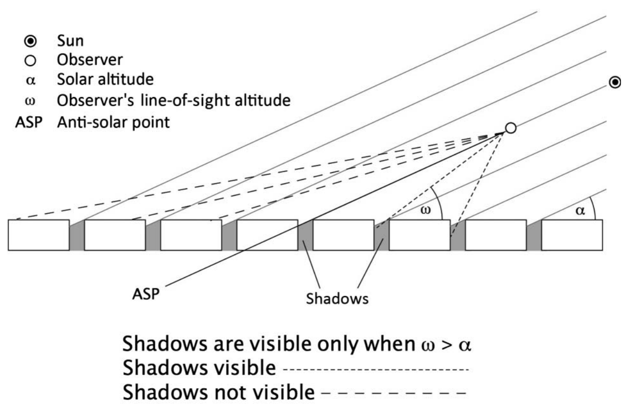

Fig. 3. Viewing geometry of mud polygons in the sun-observer vertical plane. Shadow can only be seen below the ASP.

3. Image Analysis

Horizontal and vertical scans were made through Fig. 2 that passed as close as possible to the unobscured (by the camera shadow) ASP. After removing the camera's vignetting by dividing the scan by an identical scan through a flat image, the resulting scans were roughly proportional to brightness (Figs. 4 and 5). Although the scans are not in true radiometric brightness, the response of the camera's sensor was monotonic and nearly linear. Therefore, the RGB colors represented in Figs. 4 and 5 are a good proxy for brightness. Pixel-to-pixel noise in the image was measured from dark images and found to be only between 1 and 3 units out of 255. Although the downward vertical excursions might at first be interpreted as noise, they are not. They are shadows.

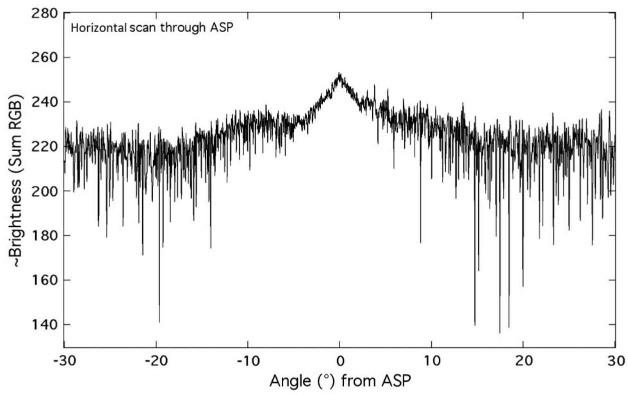

Fig. 4. Horizontal scan through the ASP in Fig. 2, after removing vignetting. The scan was done ~0.1° away from the ASP, as close as possible while still avoiding the camera's shadow. Horizontal profile quantitatively confirms the visual impression: a bright area surrounding the ASP that grows gradually fainter with angular distance from the ASP. Enhanced brightness has two components: The narrow, central triangular peak is due to CB and is about 2.7° wide (FWHM). The broader enhanced region is due to SH (FWHM ~30°). Shadow signatures appear as narrow spikes in the scan, always downward because they are dark.

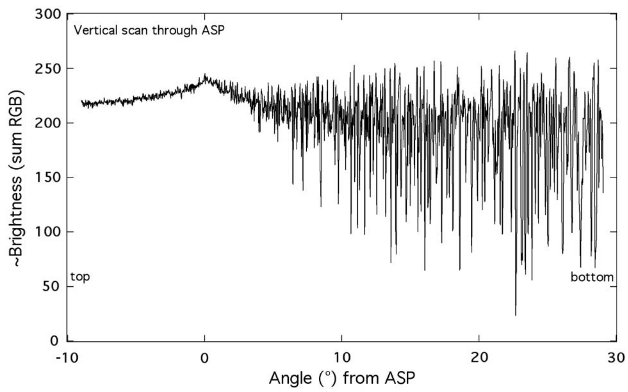

Fig. 5. Vertical scan through the ASP shown in Fig. 2, after removing vignetting. CB causes the central peak. Broader surrounding enhancement results from shadow hiding and bright, sunward facing surfaces of the mud polygons. (See Section 3 image analysis.) Shadows appear as dark, downward spikes in the scan. Note the ~absence of shadows near and above the ASP.

4. Dilution of Sunlight as a Function of Angle of Incidence

The horizontal scan in Fig. 4 is more or less symmetric and reveals the bright CB OE surrounded by a signature of the SH OE. It shows a progressively dimmer landscape away from the ASP as shadows become more exposed by the oblique LOS. As expected, the vertical scan in Fig. 5 was asymmetric and quantitatively demonstrates the brightness difference above and below the ASP that was discussed previously. The downward spikes due to shadows in Fig. 5 were expected but not the bright upward spikes, some which exceeded the brightness of the OE itself. Figure 6 offers a close examination of Fig. 2 and reveals the explanation.

The brightest upward spikes are those facing the camera (i.e., those that are perpendicular to the LOS), as shown in Fig. 7. These occur on the rounded edges of the mud polygons where the surface normals are parallel to the incoming sunlight. Sunlight falling on any other surface is spread out and therefore diluted based on the angle between the surface normal and the incoming sunlight, the angle of incidence $\mathbf{i}$. Dilution here is defined as $\cos(\mathbf{i})$. There is no dilution if the surface normal parallels the sunlight ($\mathbf{i} = 0°$); that is, dilution is 1.0 because $\cos(\mathbf{i})$ is unity. As the angle increases, dilution increases as $\cos(\mathbf{i})$, and becomes less than unity, eventually reaching 0 when sunlight is parallel to the surface.

Dilution as defined here is a simple, well-known geometrical effect. It is independent of the type of surface or its reflectivity properties. It is most easily understood and most relevant to the OE in the context of a Lambertian reflector. Surfaces with highly non-Lambertian reflectivities would not scatter light in such a way as to produce the sharp upward spikes seen in Fig. 5.

5. Discussion

It is well known that the brightness profiles for SH and CB both decrease monotonically away form the ASP. But dilution can produce bright areas that

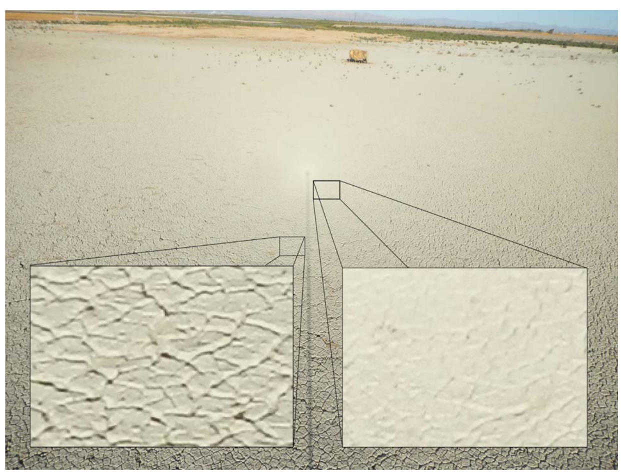

Fig. 6. Brightest parts of the scene are not at the ASP but rather on the sunward facing parts of the mud polygons.

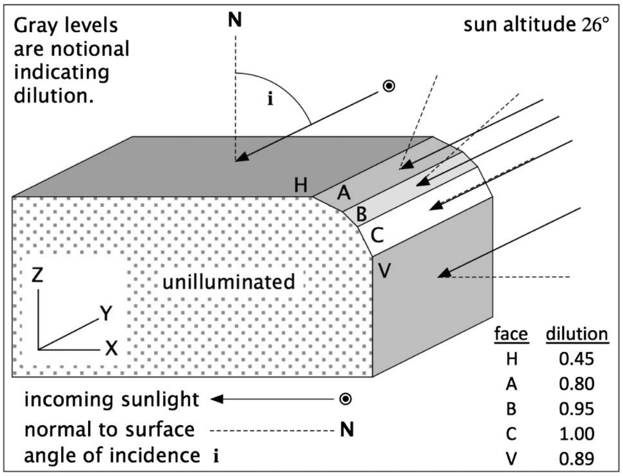

Fig. 7. Drawing of a slice through a mud polygon. The observer and sun define the vertical x–z plane. Solid lines indicate the direction of incoming sunlight, in this case with the sun at an altitude of 26°. Dashed lines are normals to each face, and **i** is the angle of incidence. Incoming sunlight reaching each face is geometrically diluted by an amount equal to cos(**i**). The brightest face is the one with its normal parallel to incoming sunlight [i.e., $\mathbf{i} = 0$, indicated in white (face C)]. All other faces are darker. This explanation assumes equal reflectivity of all surfaces.

Fig. 8. OE in a cabbage field. Despite the very different "surface" geometries between this field and the mud cracks in Figs. 1(b) and 2, the OEs are fairly similar.

increase away from the ASP. Therefore, modelers should include the effects of dilution when simulating the OE.

The findings reported here are for one particular set of mud polygons, but other factors are expected to introduce variations. There are two main factors: the ratio of the width of the polygon to the crack width and the geometry and amount of rounding at the edge of the polygon.

For more complicated geometries like vegetated fields, there is no true surface but rather an assemblage of myriad tiny, and often unresolved, reflectors (e.g., leaves, blades of grass, exposed soil and rocks), as shown in Fig. 8. These are much harder to model than mud cracks, but present similar dilution effects. The main difference between vegetation and mud cracks is the wide range of leaf surfaces and their orientation relative to incoming sunlight and the observer's LOS. In some cases, dilution will be more important than in others. In many cases the reflectivity is not Lambertian; in some instances, however, it is strikingly so, like in a shiny leaf.

6. Summary and Conclusions

Using a simple observation technique that minimizes the observer's shadow, I have obtained and analyzed a spatially resolved opposition effect (OE) for a particularly simple surface geometry: mud cracks. The surface was horizontal with vertical cracks and slightly rounded edges. I found that some parts of the rounded edges are always brighter than the OE itself because they are perpendicular to sunlight and the observer's line of sight at the antisolar point. Such a surface will always suffer the minimum amount of geometrical dilution and will therefore be the brightest part of the scene, providing that the surfaces are Lambertian-like reflectors.

These surfaces can be brighter than the OE. Thus, I have uncovered another optical mechanism that should be included in modeling the OE in addition to shadow hiding and coherent backscatter. The effect is expected to occur in all OEs regardless of the complexity of the surfaces (bushes, trees, etc.).

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