# Scattering of Directional Light

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**Abstract**
Backlight scattering in a single event provides an account of the nearly uniform full images of all the planets and their moons. The uniformity of the full moon image has been discussed in terms of multi-event scattering. Similar images of other bodies have not been discussed. Multi-event scattering must lead to Lambert's Cosine scattering law, however, there are no object images that comply with it. Single event scattering is automatically coherent since a single electromagnetic source wave stimulates all the scattering dipoles. The coherence provides an account for the "Opposition Effect", enhancement of 180 degrees backscattering, by constructive interference. Opposition enhancement has been considered so far as a separate effect from image uniformity.

The coherence of single event scattering may enable separation from non-coherent scattering noise by applying interferometric methods so that objects would be observed with better resolution or at a higher distance. Removal of incoherent noise may also enable deeper image observation within a scattering medium, such as biological tissues.

**Introduction**
Back scattering of directional light, started by Lambert with his cosine scattering law [1, 2]. The law states that the intensity of a back scattered light is proportional to the cosine of the angle θ between a light ray striking on a surface and a line perpendicular to that surface, fig-1. Thus the scattering intensity is maximal when the surface is perpendicular to the ray at $\theta = 0$ degrees, and it fades by the cosine function to zero when the ray is grazing the surface at $\theta = 90$ degrees.

In the case of scattering from a sphere the back scattering is maximal at the center of the sphere, and it dwindles to zero by the cosine law when moving toward the sphere periphery. This law seems nearly self-evident, since by looking on the surface through a unit area "$a$" in the direction of the coming ray. The area on the surface will be proportional to 1/Cos($\theta$), and the radiation density on the surface will therefore be proportional Cos($\theta$). The light scattered backwards will also be proportional to Cos($\theta$) since the scattering maximum is perpendicular to the surface, fig-1.

## Discussion

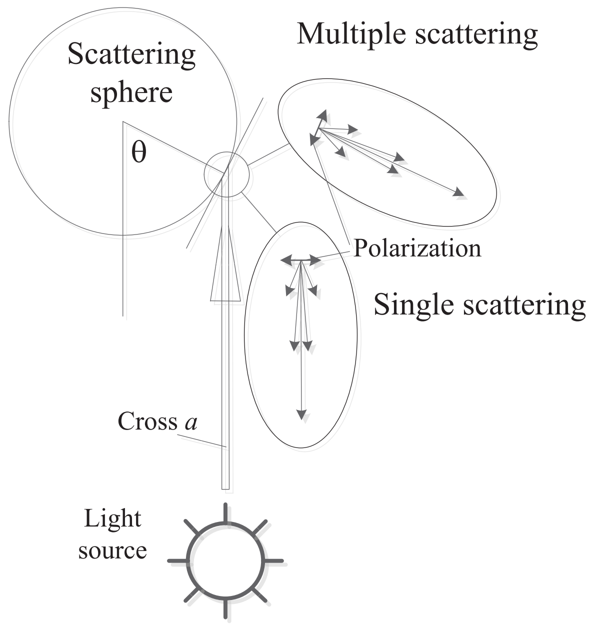


Fig-1: Back scattering in a multiple event and in a single event. The equivalent scattered light in a multiple event is perpendicular the surface. The maximal scattered light in a single event is aimed back to the source.

The full moon image [3] is best observed during moonrise. The image corresponds to back scattering of sun light, and it is somewhat surprising therefore, that the full moon image is uniform from the image center toward its periphery, except details of rocks and dry seas. The moon image does not obey Lambert cosine law. Similar uniformity or near uniformity is observed in the backward configuration of sun light scattering for images of all the planets and their moons [4].

In the last decades images of the full earth have been taken from space and the uniformity is observed in them [5]. There are no similar images that obey Lambert's cosine law, including also terrestrial images. The only images that do obey the law are rendered, images that are at least partly simulated.

The moon uniformity is discussed in the literature in terms of surface properties; roughness, shading, or retro-reflection [5, 6]. There are no discussions at all of the other planet images. However, the planets and moons surfaces differ significantly in types, structure and morphology, never the less, all their images are nearly uniform. So it is unlikely that the uniformity is an outcome of some specific surface properties, but rather, an outcome of a more general and fundamental principle. In particular, the earth full image, the "blue marble" [4], contains vast areas of gas phase – clouds, liquid phase – oceans, and solid phase – land, and each of them is nearly uniform separately.

The "opposition effect", the enhanced light scattering when the light approaches the backward direction, is observed in celestial and terrestrials bodies as well. It is discussed as an independent effect of the uniformity and is attributed to shading and to coherent light scattering [8 - 12]. However, it is not mentioned why the scattering is coherent.

In all these discussions of scattering, without exception, it is assumed that the scattering process is diffusive, that is, the light passes many scattering events before it returns to an observer. However, in a diffusive process the events are independent and there is no way that the scattering can be coherent. In such a case the Lambert cosine scattering law becomes very strong and the scattering process must obey it, which is never the case.

In order to have some insight into these light scattering processes it may be useful to consider an electromagnetic light wave travelling within a matter. The wave stimulates dipole oscillations, and each such a dipole becomes a source of a wave itself which adds to the overall light radiation. However, if the material is uniform, the radiation coming from all the dipoles interfere and cancel each other. There will be no light scattering except for the forward direction where the effect is refraction. Light scattering is the outcome of material non-uniformity, so that the interference of light from the dipole sources is not fully destructive.

A volume of non-uniform material may be divided into sub-volume uniform domains. The domain size determines the material's scattering properties. In a single micron size, or less, there is a wide angle Rayleigh Scattering that tends to be uniform in space. This scattering is typical of gases, liquids and solutions. In domain size of few tens of microns there is narrow angle Mie Scattering typical of solids. In both cases the scattering intensity is proportional to the intensity of the stimulating light. The icy rings of Saturn glow in the opposition configuration while the glow from the gaseous surface of the star is by far weaker [13].

There is a fundamental difference between single event and multiple event scattering. In single event scattering the light is scattered one time before it reaches the observer. Therefore, the dipoles which are stimulated by a single wave, will all oscillate coherently in one plane perpendicular to the original wave direction. The light scattered by each dipole is maximal in a direction perpendicular to this plane, that is, back to the light source. Therefore the back scattered light by all of them is also maximal at the direction back to the light source.

In multiple event scattering the light is scattered many times before it reaches the observer. Therefore any dipole oscillate in a random plane in space and there can't be any correlation or coherence between the radiations of different dipoles. The equivalent radiation will be perpendicular to the surface plane of the scattering material. In this case Lambert's cosine law of light scattering must be obeyed.

Consider a line between a light source and a point on the surface of a scattering sphere defined by the angle $\theta$. A unit cross section area "*a*" is perpendicular to this line (fig.-1).

The area on the sphere surface observed through the cross section area "*a*" will be $a$ / Cos($\theta$), thus, it is equal to *a* at the sphere center, and it increases toward the periphery. Similarly the light density on the sphere is proportional to $a$ * Cos($\theta$) and it will dwindle to zero at the periphery .

In a single event scattering the scattering intensity back to the light source, $I_{max}^{s}$, is equal to the maximal scattering intensity *a*:

$$I_{max}^{s} = a * \text{Cos}(\theta) * 1 / \text{Cos}(\theta) \qquad (1)$$

Thus in the back scattering of a single event the intensity is independent of the surface angle to the source, and a sphere will appear uniform.

In a multiple event scattering the maximal scattering intensity, $I_{max}^{m}$, is perpendicular to the scattering surface, and its component back to the light source is proportional to Cos($\theta$):

$$I_{max}^{m} = a * \text{Cos}(\theta) * \text{Cos}(\theta) * 1 / \text{Cos}(\theta) \qquad (2)$$

Thus in multiple event scattering the intensity will follow Lambert's Cosine scattering law, and the maximum intensity at the sphere center will dwindle by the Cosine function to zero at its periphery.

Why does single event scattering seem to be dominant? In opaque substances the mean free path within the material is too short for many scattering events before the light is absorbed. But also in transparent materials, the probability, that light will return back to the source, will fall with the number of scattering events. A single scattering event seems to have the highest probability.

**Summary and conclusions**

Back light scattering by a single event provides an account for the nearly uniform full images of all the planets and their moons. There are no objects that comply with Lambert's Cosine scattering law. Single event scattering is automatically coherent since a single electromagnetic source wave stimulates all the scattering dipoles. Thus the coherence provides an account for the "Opposition Effect", enhancement of 180 degrees back scattering, by constructive light interference. Opposition enhancement has been considered so far a separate effect from image uniformity.

The coherence of single event scattering may enable separation from non-coherent scattering noise by applying interferometric methods, so that objects would be observed with better resolution or at a higher distance. Removal of incoherent noise may also enable deeper image observation within a scattering medium, such as biological tissues.

Most of the imagery that surround us consists of mainly single event scattering. Including it in illumination models may improve them for illumination engineering.

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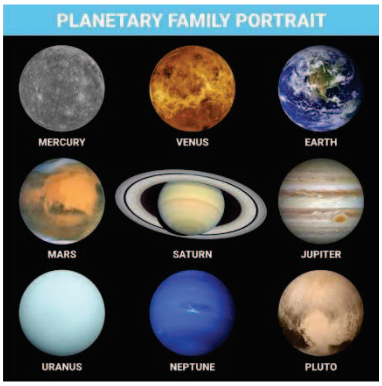


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