

Why Optical Images are Easier to Understand Than Radar Images? — From the Electromagnetic Scattering and Signal Point of View

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Abstract— As the bandwidth of SAR/ISAR system continuously increases as well as the synthetic aperture techniques develop, the spatial resolution of radar image is higher and higher. However, the high resolution of radar image does not mean the resolving ability for targets is high. We may have the same experience that the optical image is much easy to understand than radar image even if it has less resolution. A simple and frank explanation is due to the wavelengths of optical waves are much shorter than that of microwaves at which radars usually work, e.g., in the order of 10^{-5} – 10^{-4} . Are there any the deep reasons for this? We will illustrate the inherent reasons in this paper from the aspects of imaging geometry and principle, electromagnetic scattering, signal characteristics, and so on.

1. INTRODUCTION

High spatial resolution radars and optical cameras are two major kinds of sensors for civilian earth observation, and military applications. Their images are quite different from each other and radar images are usually much more difficult to understand [1–3]. This paper will discuss about this issue and show the reasons.

We know that the human eye's vision system is similar to a camera, or in another words, the human eye is indeed a camera. The basic imaging principle of optical camera is “small-hole” imaging, it gets the two dimensional resolutions about the target through angular discrimination, but for SAR/ISARs, they get the range resolution by discriminating the arrived time from target, which is proportional to the signal bandwidth, and thus is inversely proportional to the time duration of compressed pulse signal, while get the azimuthal resolution through aperture synthesis, which is inversely proportional to the coherent integration time. So radar images have unavoidable and severe geometric distortion compared with optical images, e.g., layover and foreshorten, which makes the radar images more difficult to read.

For ordinary optical camera, the signal (light) comes from the sun or other artificial sources, it is wideband, continuous, random and incoherent. When imaging, the signal interacts with the target, where reflections and scattering occur. Due to the short wavelength, which is in the order of several hundreds of nanometers, the scattering exhibits diffusion characteristics and is localized for almost all natural or man-made targets, i.e., the scattered signals from every part (structure) of the target go through the lens and is sensed by different part of CCD matrix to form a pixel. The pixel is formed by incoherently summing the single scattering and multi-scattering signals from the same part of the target, so there is only additive noise, at the same time the scattering center (referred to as the pixel) is very stable and independent on the direction of incident light if the looking direction is fixed. But for SAR/ISAR, the transmitted signals and the scattered signals are both coherent, and the image is reconstructed by coherent processing the echoes, where the pixel position is not stable but dependent on the direction of incident wave, i.e., one may get different radar images for the same target even the looking direction is fixed but the incidences are different. The role of multiple scattering effect is very useful for camera in some degree for increasing the randomness of incident light, so make the image looks more uniform and smooth, but for radar, it is very harmful because it leads to the scattering centers deviated from their geometric position or induces ghost scattering centers. The noise in SAR/ISAR images is composition of additive and multiplicative noises, so it is very hard to remove. For camera, the signals come from the surface scattering of the target, but for radars, the signals come from both the surface scattering and the volume scattering for general nonmetal target, and the volume scattering makes the scattering centers more complicated.

As for the signal point of view, for camera, the light waves are continuous, non-coherent and are of one octave. But for SAR/ISAR, the signals are usually pulsed and coherent. So integration

time for optical image can be much longer than that of radar image, i.e., the signal to noise ratio (SNR) of optical image could be much higher than that of radar image.

Optical images and SAR images are presented and compared to illustrate the similarity and the difference between them.

2. COMPARISON OF IMAGING PRINCIPLES

Generally, SAR works on side-looking mode (the boresight is normal to the moving direction of SAR platform). It gets the range resolution by compressing the echo pulse (usually LFM pulse, i.e., chirp signal is used) and the wider the bandwidth of the pulse the finer the range resolution, i.e., the closer the distance between two targets at which they can be resolved. Fig. 1 shows the imaging geometries for SAR (range direction) and optical camera. As can be seen, the target A , B and C on the ground plane are transferred to A' , B' and C' in the slant plane for SAR, while they are transferred to A'' , B'' and C'' in the focal plane for camera. Obviously, the transformation from A , B and C to A' , B' and C' are nonlinear and even becomes much complicated if A , B and C are of different height, but it is linear from A , B and C to A'' , B'' and C'' , and becomes less distorted if the targets are not of the same height.

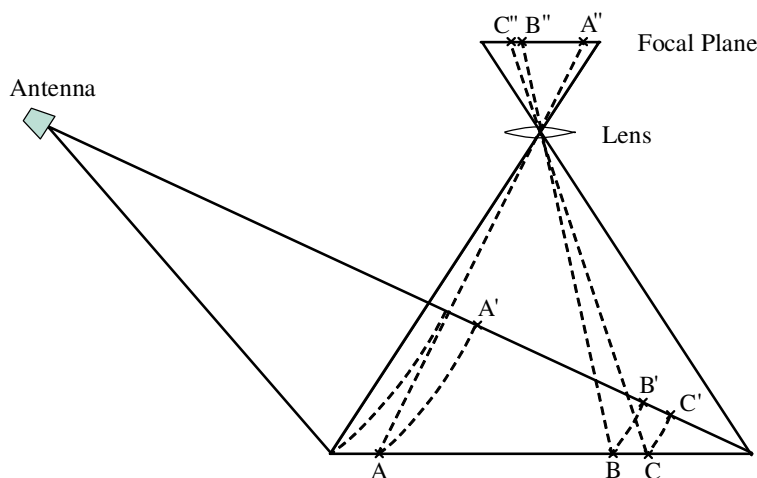


Figure 1: The geometries of SAR and optical camera.

For SAR, The resolvability of B and C depends on the signal bandwidth and the azimuth resolution and range resolution can be different; while for camera it depends on the aperture size of the lens and we do not need to distinguish the azimuth resolution and range resolution, we only need to concern about the angular resolution. When imaging, the SAR obtains the azimuth resolution and range resolution separately, while the camera obtains them simultaneously. It means the imaging process and the correction of geometrical distortion for optical camera is much simpler and easier than that of SAR. Fig. 2 shows the principle explanation for SAR obtaining the azimuthal resolution. Let us assume the SAR moves along a straight line and transmits pulses repeatedly with a period of T when moving, the Doppler frequency changes when the SAR moves at different position with the target still within the radar beam. The azimuth resolution of SAR depends on total change of the Doppler frequencies Δf_d as well as the speed of the SAR movement v .

Once again we should emphasize that the imaging principle of optical camera is exactly the same as human's eye system.

Figure 3 presents the SAR image and the optical image (from Google map) of the same ground area, as can be clearly seen, the building marked in the box has been severely distorted in the SAR image due to layover effect.

3. COMPARISON OF EM SCATTERINGS

3.1. Single Scattering and Multiple Scattering

When electromagnetic (EM) waves are incident on a target, currents will be induced on the surface or inside the target, and then scattering electromagnetic waves resulted from the induced current will be generated and some of them back to the radar. The EM scattering problem from a target can be solved by solving the corresponding magnetic field integral equation (MFIE) (or electric

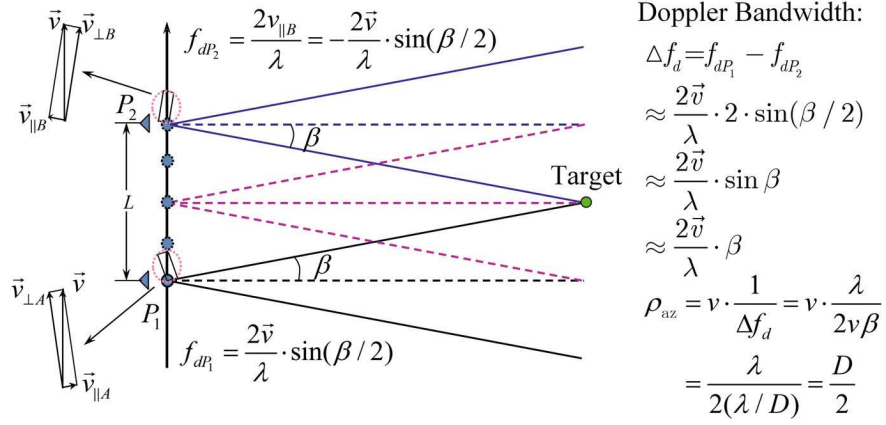


Figure 2: The principle explanation for SAR obtaining the azimuth resolution.

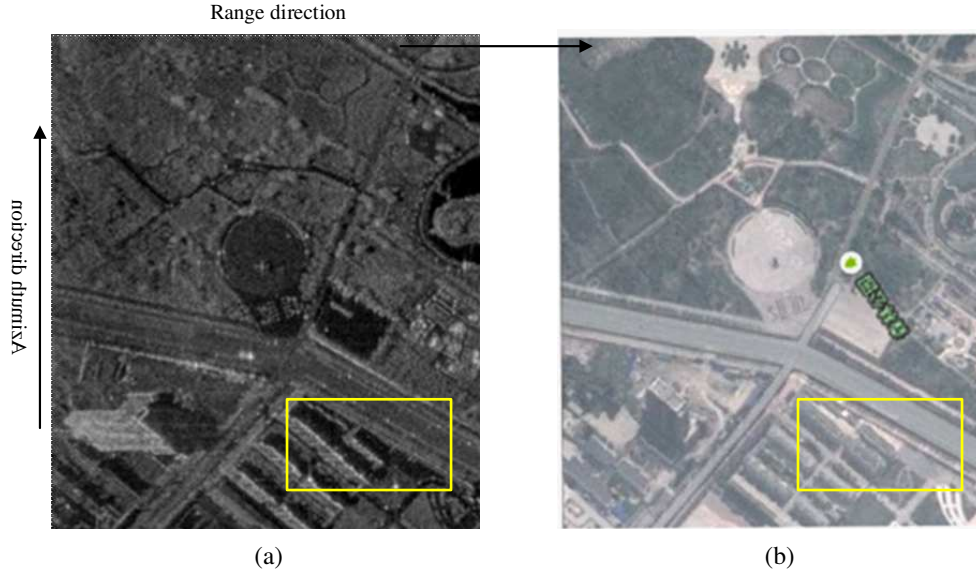


Figure 3: (a) The SAR image and (b) the optical image.

field integral equation, EFIE) as shown by (1). The total induced current by the incident field can be decomposed into two parts, one part is directly resulted from the incident field (1st scattering) as represented by the first part of (2), the other part is resulted from the interactions between different parts of the target (2nd or higher multiple scattering) as represented by the second part of (2).

$$2\hat{n} \times \mathbf{H}^i(\mathbf{r}) = \mathbf{J}_s(\mathbf{r}') - 2\hat{n} \times \int_S [\mathbf{J}_s(\mathbf{r}') \times \mathbf{g} + \nabla' g] ds' \quad (1)$$

$$\mathbf{J}_s(\mathbf{r}') = 2\hat{n} \times \mathbf{H}^i(\mathbf{r}) + 2\hat{n} \times \int_S [\mathbf{J}_s(\mathbf{r}') \times \mathbf{g} + \nabla' g] ds' \quad (2)$$

$$\mathbf{H}^s = -\frac{jke^{-jkr}}{4\pi r} \int_S \hat{s} \times \mathbf{J}_s(\mathbf{r}') e^{j\mathbf{k}\mathbf{r}' \cdot (\hat{s} - \hat{i})} d\mathbf{r}' \quad (3)$$

The g in (1) and (2) is the Green's function. As we know the higher the frequency of the EM wave the weaker the multiple scattering of a target, i.e., the more the g as well as the interaction is localized and thus the stable the equivalent scattering centers may formed.

As for SAR imaging, the pixels are of range information relative to radar, and thus multiple scattering may easily lead to ghost target as shown in Fig. 4 (the dashed target). But for optical

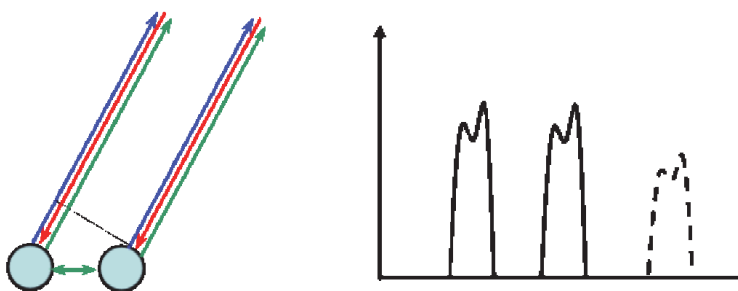


Figure 4: The effect of multiple scattering for radar: Ghost target.

camera the ghost target is relatively hard to produce by multiple scattering.

3.2. Coherent Scattering and Non-Coherent Scattering

As shown in Fig. 2, SAR utilizes the coherent echoes from the same target to form a synthesized large antenna aperture to realize high azimuth resolution, so, the echoes from infinitesimally sub-scattering centers within a resolution cell will superposed in complex domain (with both amplitude and phase taken into account), and thus multiplicative speckle noise (MSN [4, 5] will be generated. The existence of MSN preclude us from understanding SAR images especially for high-resolution SAR images, because they may destroy the inherent texture information [6] of the true target. We have a Chinese proverb to describe coherent scattering's role for SAR imaging: "succeeded because of Xiao He, defeated also because of Xiao He". One of the most difficult things for SAR image processing is just the MSN because we have to sacrifice the spatial resolution in order to get rid of it.

As for optical cameras, only thermal (additive) noise exists in the images because the scattering echoes from the target are non-coherent with each other and they are superposed in real domain. Up to now, there are plenty of effective methods proposed to denoise optical images. Besides, super-resolution algorithms work much better for optical imaging than for radar imaging. The reason is just due to the noise model for optical images is different from that for radar images.

3.3. Mirror Scattering and Diffuse Scattering

The wavelengths of optical waves (hereinafter visible optical waves are assumed) are usually $10^{-5} \sim 10^{-4}$ order of that of radar waves and the facet surfaces of natural targets as well as man-made target are rough for optical waves but they are smooth for radar waves. So diffuse scattering occurs for optical waves but mirror scattering occurs for radar waves. The diffuse scatterings are very helpful for forming localized equivalent scattering centers because no matter what direction of the incident waves, there always have comparable backscatterings with other directions, i.e., the impacting points of incident waves are always visible to the optical camera and thus can be imaged. In this way, the geometrical shape of a target can be very well recorded by an optical camera. As for radars, the mirror scatterings can result in the impacting points not visible to radar (no backscattering back to radar) and also make the scattering centers unstable (slight change of incident angles may lead to position change of scattering centers). Fig. 5 schematically shows how the scattering center changes as the incident wave changes.

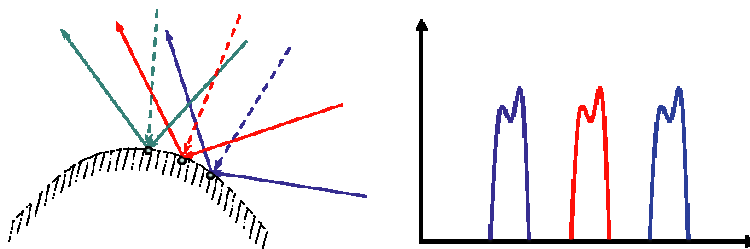


Figure 5: The position of scattering center changes as the incident direction changes.

3.4. Surface Scattering and Volume Scattering

We know that the penetration capability of EM waves into a target relates to the wavelengths, the longer the wavelength the stronger the penetration. Therefore, for general non-metal target, the optical waves mainly scatters on the surface, but for radar waves, not only surface scattering but also volume scattering exist. The volume scattering may further complicate the echoes and deteriorate the imaging process.

4. COMPARISON OF SIGNALS

As introduced above, for SAR imaging, each transmitted pulse has fixed phase relation with other transmitted pulses. The role of the signal bandwidth for SAR imaging is for obtaining high resolution, but it is for enriching the reflection of detailed structures for optical camera imaging. We all have the same experience that the pictures taken inside a room using the artificial light or the flasher, are always not as good as that taken outside under a good weather condition. The reason is that the natural light signal is of high quality compared with artificial lights: they are wideband (with wavelength ranges from 380 nm to 800 nm), continuous and non-coherent.

For SAR, the pulse duration, i.e., the integration time for radar receiver is usually in the order of several to tenths of microseconds, but for optical cameras the integration time is usually in the order of hundreds to thousands of microseconds. It is to say the integration time of an optical camera can be hundreds of times larger than that for a radar receiver. The longer the integration time for a receiver, the better the random noise can be reduced.

In this regard, radar signals always cannot be comparable to natural lights.

5. CONCLUSION

We have shown in this paper that the imaging geometry, the EM scattering and the signal characteristics are the three major reasons which make the SAR images more difficult to understand than optical images. We also mention that the similarity between human's eye system and optical camera is also a reason in this regard. It is also interesting to point out that optical camera is indeed a radar because it is also composed of antenna (lens), transmitter (non-cooperative, the sun or other artificial light source) and receiver (CCD), which are the typical parts of a radar. For SAR, the spatial resolution is usually decoupled into azimuthal resolution and range resolution, and they are decided respectively by the synthesized aperture size and the signal bandwidth, having nothing to do with the distance between the scene and the radar. As for optical camera, the spatial resolution is decided by the angular resolution which is inversely proportional to the lens size, the shortest wavelength of the light, and the distance between the observed scene and the camera, having nothing to do with the bandwidth of light.

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