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Imaging via Inverse Scattering Approach and its Resolution

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The inverse scattering problem consists of determining characteristics of an object (viz.,its shape and internal constitution) based on its scattering data when it isilluminated by incident waves. In many real world applications, imaging via inverse scattering is desired. For example, when sensor is far from object, or when barriers are present between sensor and object. Different from direct imaging (or physical imaging), such as images appearing in film and charge coupled device (CCD), which displays the intensity of electromagnetic wave in a two-dimensional plane, inverse scattering approach provides reconstructed images, which is able to display three-dimensional information (viz., geometrical and optical properties) of an object. Inverse scattering technique has wide applications in the field of biomedical diagnosis (ultrasonic imaging of internal organs), semiconductor industry (integrated circuit failure analysis), defense (through-wall imaging), material sciences (X-ray diffraction imaging to obtain interior images of crystals), and nanotechnology (in-process measurement of micro-machined surface profile). Regarding the resolution of imaging via inverse scattering approach, there are two widely spread opinions: (1) the resolution of imaging is limited to half wavelength if sensors are placed in the far field; (2) multiple scattering effect improves resolution. Given that time harmonic wave is considered, in this article, we comment that the aforementioned two opinions are only conditionally correct.

For the first opinion, when sensors are placed in the far field, only low spatial frequency components are measured, whereas the subwavelength information, which is encoded in the evanescent wave, is lost due to its fast decay. If we simply apply the inverse Fourier Transform (IFT) to these measured low spatial frequency components, as done in Born approximation inversion method [1] or in traditional optical microscopy where the lens plays the role of inverse Fourier Transform, the resultant image is definitely limited to half wavelength. However, there are inverse methods other than IFT that are able to achieve imaging results with much better resolution. In fact, although only travelling wave is measured at far field, the far field scattering data are uniquely related to near field data by complex mathematical functions, which can be rigorously proved in the mathematical sense that the scattered field, which is a smooth function of space, can be analytically continued to the near field [2]. The above idea is in the same spirit as the following well-understood problem. For a given circle, we can easily find the radius of the circle. If only part of information about the circle is known, say, only three points on the circle are given, we can apply trigonometric identities to calculate the radius, where three points are sufficient and the loss of other points do not refrain us from obtaining the radius. Thus, in principle the sub wavelength information is retrievable from only far field data by inverting complex mathematical functions, even if evanescent wave is lost. But in practice, the reconstruction results noticeably depend on the level of noise, which is the characteristic of inverse problems. Indeed, there exist inversion algorithms that are able to achieve super resolution imaging. The multiple signal classification (MUSIC) method is a good example for reconstructing point-like objects. The distorted Born iterative method (DBIM), the contrast source inversion (CSI), and subspace-based optimization method (SOM) are good examples for reconstructing large objects.

For the second opinion, several publications claim that multiple scattering (MS) leads to a better resolution imaging result in the framework of inverse scattering. However, such a claim is not generally true and it depends on how we interpret the "multiple scattering (MS)". We consider three cases:

Case one

The role of MS is discussed for a given physical experimental setup, in which an exact model where MS is present (referred to as the MS model) and a fictitious model where MS is absent (referred to as the single scattering model or SS model) is compared. We highlight that the SS model is employed as if it were "exact," i.e., we model a fictitious reference scenario where there is ideally no MS among objects being probed. We employ the concept of the Cramér-Rao bound (CRB) to quantitatively analyze the reconstruction result. The CRB quantifies the lower bound on the variance of any unbiased estimator of a parameter, given the physical model behind the image formation process and knowledge about the statistics of the observation. It is important to note that different estimators usually have different precision, whereas the CRB is independent of estimators (inversion algorithms). Numerical simulations conducted on the CRB analysis show that for the case of two small spheres, MS does not always improve the accuracy of estimation, and the results depend on the positions and scattering strengths of spheres, as well as the angles of the illuminations and sensors [3]. The reason for such an observation is understood as follows. To retrieve the information of spheres from scattering data is a complex and nonlinear process. Although MS is able to transfer more information of scatterers in to the far-field scattered field, the inversion process is also more complex. In addition, the MS effect may be either constructive or destructive. For these reasons, MS does not always improve the resolution of reconstructed image.

Case two

We consider a specific imaging method: the time reversal imaging. It is well known that the time reversal imaging method in a multiple scattering experimental setup (an object is surrounded by inhomogeneities, such as a bunch of wires or random media) has a better imaging result than that in a single scattering experimental setup (an objectis embedded in an otherwise homogenous background). It is worth highlighting that in the time reversal imagining the comparison of the MS and SS effect is conducted by investigating the performance of a specific estimator (time reversal imaging method) under two different experimental setups, and this is different from Case one, where a real MS model and a fictitious SS model are compared under the same experimental setup.

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Case three

We understand that for a given scattering experimental setup, MS does exist in nature and cannot be neglected, i.e., measured scattering data automatically include the MS effect. In many publications, comparison is made between two inversion approaches: a full-wave nonlinear inversion method that includes the MS effect and the Born approximation (BA) inversion that excludes the MS effect. Since measured scattering data include the MS effect, the full-wave nonlinear inversion model is an exact inversion model. However, the BA inversion model neglects MS, and this approximation inevitably introduces errors, yielding a degraded quality of the image. Thus, publications where such comparisons are conducted perfectly illustrate that an exact inversion model outperforms an approximate inverse model. Consequently, it is inappropriate to cite these publications as a proof that MS is better than SS in enhancing the resolution of reconstructed image.

To conclude, this article discusses two widely spread opinions regarding the resolution of imaging in inverse scattering approach.The half-wavelength resolution limit for far field measurement applies only to inverse Fourier Transform related imaging methods, but does not apply to many other inverse algorithms. There exist inversion algorithms that are able to achieve superresolution imaging. Whether multiple scattering effect improves resolution of imaging depends on how we interpret the meaning of "multiple scattering" in our model of comparison.

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