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Real-time microwave imaging of unknown anomalies via scattering matrix

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ABSTRACT

We consider an inverse scattering problem to identify the locations or shapes of unknown anomalies from scattering parameter data collected by a small number of dipole antennas. Most of researches does not considered the influence of dipole antennas but in the experimental simulation, they are significantly affect to the identification of anomalies. Moreover, opposite to the theoretical results, it is impossible to handle scattering parameter data when the locations of the transducer and receiver are the same in real-world application. Motivated by this, we design an imaging function with and without diagonal elements of the so-called scattering matrix. This concept is based on the Born approximation and the physical interpretation of the measurement data when the locations of the transducer and receiver are the same and different. We carefully explore the mathematical structures of traditional and proposed imaging functions by finding relationships with the infinite series of Bessel functions of integer order. The explored structures reveal certain properties of imaging functions and show why the proposed method is better than the traditional approach. We present the experimental results for small and extended anomalies using synthetic and real data at several angular frequencies to demonstrate the effectiveness of our technique.

1. Introduction

Generally, the purpose of the inverse scattering problem is to identify characteristics of unknown defects that cannot be observed directly, such as size, location, shape, and electric and magnetic properties, based on measured scattered-field or scattering parameter (or S-parameter) data. This is an old problem, known to be difficult due to the intrinsic ill-posedness and nonlinearity. Nevertheless, it remains an interesting problem in current science and mathematics because it has a wide range of applications, such as in breast-cancer detection [1–3], brain-stroke diagnosis [4–6], ground-penetrating radar for mine detection [7–9], and in damage detection [10–13], which are highly related to safety and reliability issues in human life.

To solve this interesting problem, various inversion techniques and related computational methods have been investigated; examples include the Newton or Gauss–Newton method [14–17], the Levenberg-Marquadt algorithm [18–20], the level-set technique [21–23], and the optimal control approach [24–26], most of which are based on an iteration scheme; these techniques help in obtaining the characteristics of the target (minimizer), which minimizes the discrete norm (usually, L^2-norm) between the measured data in the presence of true and artificial targets at each iteration procedure. Although these

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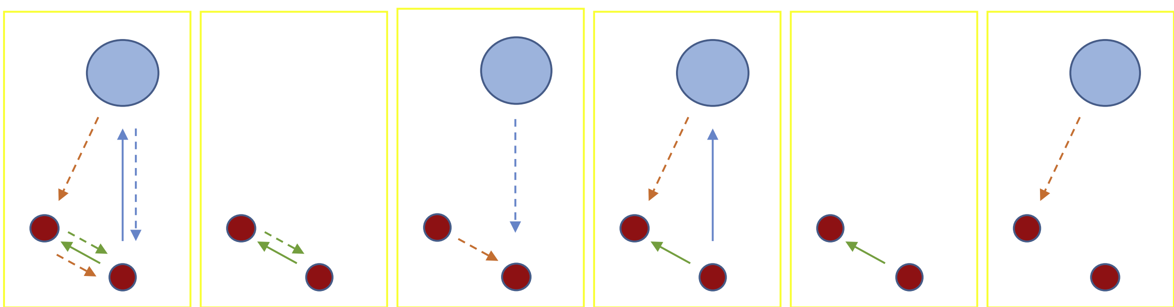
techniques have been proven to be feasible in determining the characteristics of unknown targets, some conditions such as *a priori* information, choice of an appropriate regularization term, and evaluation of the complex Fréchet (or domain) derivative at each iteration step must be fulfilled to guarantee a successful procedure. Nevertheless, if one begins the iteration procedure with a bad initial guess far from the unknown target, one faces non-convergence, the local minimizer problem, and the requirement of a large computational cost. Hence, it is natural to investigate a fast algorithm for obtaining at least a good initial guess without any *a priori* information about the targets.

Recently, various non-iterative techniques have been investigated, including MUltiple SIgnal classification (MUSIC) [27–29], direct-sampling method [30–32], linear-sampling method [33–35], and topological derivatives [36–38]. Subspace and Kirchhoff migrations are also known as non-iterative techniques in inverse scattering problem. When total number of directions of the incident field and corresponding scattered fields is sufficiently large, it has been confirmed that the Kirchhoff and subspace migrations operated at single and multiple time-harmonic frequencies are effective, stable, and robust non-iterative techniques. Refer to [39–43] and the references therein. Following the traditional results, subspace migration based imaging algorithms were established for cases where every far-field element of the so-called scattering matrix is collectable; the total number of transducers and receivers (here, dipole antennas) are sufficiently large, and measurement data is not affected by the dipole antennas. However, in real-world application, when the locations of the transducer and receiver are the same, measurement data (diagonal elements of the scattering matrix) are influenced by not only anomalies but also by antennas (see Fig. 1). Furthermore, sometimes manufacturing microwave systems that can measure scattered field data with the transducer and receiver at the same location is inconvenient. Hence, considering the mentioned situation, designing an alternative imaging algorithm is an interesting direction for research.

Recently, the MUSIC algorithm and direct sampling method for identifying the location of the dielectric anomaly from scattering parameters collected by a small number of dipole antennas has been developed when the diagonal elements of the scattering matrix or scattering parameter with the same transducer and receiver location are measurable [44,45]. In [46], subspace migration for imaging of thin inhomogeneity without diagonal elements of so-called multi-static response (MSR) matrix whose elements are far-field pattern has been concerned. However, to the best of our knowledge, there are no theoretical results of subspace migration for real-world imaging an unknown anomaly when scattering parameter data is collected and affected by a small number of dipole antennas. Thus, in this study, we design an imaging algorithm based on the subspace migration technique with and without diagonal elements of the scattering matrix. Since, only the diagonal elements of the scattering matrix are affected by antennas, the result will be better than that with diagonal elements, and the designed approach will be useful in real-world microwave imaging. In order to verify this phenomenon, we carefully analyze imaging functions by establishing a relationship with an infinite series of Bessel function of integer order, the total number and location of dipole antennas, and the applied value of wavenumber. This is based on the Born approximation or asymptotic expansion formula in the presence of a small anomaly [47] and also based on the physical factorization of the scattering matrix in the presence of an extended anomaly [48]. From the identified structures of the imaging functions, we can compare the performance of traditional and designed imaging functions, discover various properties (such as the dependence of the number and location of antennas, the reason for the appearance of arbitrary and ring-type artifacts, etc.), and the fundamental limitations. In order to support our theoretical results, simulation results for small and extended anomalies using the synthetic data generated by the commercial CST STUDIO SUITE and real-data generated by a manufactured microwave machine at several angular frequencies are presented. It is worth mentioning that although the result obtained with low computational cost is good, it cannot completely determine the shapes of the anomalies. Fortunately, it can be accepted as an initial guess, and it will be possible to retrieve a better shape through an iteration process.

The remainder of this research is organized as follows: In Section 2, we briefly introduce the forward problem and scattering parameter. Then, in Section 3, we design imaging functions with and without the diagonal elements of the scattering matrix, analyze their structure by establishing infinite series of Bessel functions of integer order, and discover some proper-



(a) $S_{\text{tot}}(n,n)$ (b) $S_{\text{inc}}(n,n)$ (c) $S_{\text{scat}}(n,n)$ (d) $S_{\text{tot}}(m,n)$ (e) $S_{\text{inc}}(m,n)$ (f) $S_{\text{scat}}(m,n)$

Fig. 1. Illustration of the influence of antenna when the locations of the transducer and receiver are the same (a)–(c) and different (d)–(f). Red-colored circles are dipole antennas $\mathbf{d}_n$ and $\mathbf{d}_m$, navy-blue colored circle is anomaly Σ. Solid and dashed arrows describe the incident and corresponding reflected fields, respectively. Definition of $S_{\text{tot}}(m,n), S_{\text{inc}}(m,n), S_{\text{scat}}(m,n), \mathbf{d}_n$, and Σ are given in Section 2. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)