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High-Resolution 3-D Radar Imaging through Nonuniform Fast Fourier Transform (NUFFT)

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Abstract. This paper applies a 3-D nonuniform fast Fourier transform (NUFFT) migration method to image both free-space and buried targets from data collected by a ultra-wideband ground penetrating radar (GPR) system. The method incorporates the NUFFT algorithm into 3-D phase shift migration to evaluate the inverse Fourier transform more accurately and more efficiently than the conventional migration methods. Previously, the nonuniform nature of the wavenumber space required linear interpolation before the regular fast Fourier transform (FFT) could be applied. However, linear interpolation usually degrades the quality of reconstructed images. The NUFFT method mitigates such errors by using high-order spatial-varying kernels. The NUFFT migration method is utilized to reconstruct GPR images collected in laboratory. A plywood sheet in free space and a buried plexiglas chamber are successfully reconstructed. The results in 3-D visualization demonstrate the outstanding performance of the method to retrieve the geometry of the objects. Several buried landmines are also scanned and reconstructed using this method. Since the images resolve the features of the objects well, they can be utilized to assist the landmine discrimination.

Key words: Ground-penetrating radar (GPR); migration; interpolation; phase shift; nonuniform fast Fourier transform (NUFFT).

1 Introduction

Ground-penetrating radar (GPR) is an ultra-wideband detecting technique used for subsurface exploration and monitoring. Many works have been done in the area of statistical signal processing to develop powerful statistical models to discriminate the targets [6, 8, 10]. On the other

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hand, the abundant information carried by GPR data also provides a possibility to reconstruct high resolution images of the objects beyond just a confidence of detection. Three-dimensional image reconstruction from GPR data is therefore of great interest lately. Migration is one of the most useful time domain inversion methods as it focuses the reflections and diffractions to their actual positions. Various migration techniques have been studied to refocus the scattered signals from the time domain back to their true spatial locations in the object space. Kirchhoff depth migration [2–4], finite difference migration [16, 17] and phase-shift migration [9, 11] are the ones most widely used for seismic imaging. Recently, based on the seismic migration, Song and Liu [20] proposed a two-dimensional phase-shift migration method using nonuniform DFT for GPR landmine imaging and achieved promising results.

The migration methods usually migrate data in the frequency-wavenumber domain, therefore inverse Fourier transform is needed as a key step to transform the migrated data back to spatial domain. However, due to the nonuniform nature of the frequency-wavenumber space data, most of the migration methods share a common problem, i.e., the FFT is not directly applicable. This is because when data are not located on a uniform Cartesian grid, the multi-dimensional discrete Fourier transform can no longer be evaluated by the tensor product of multiple 1-D FFTs. Previous works used linear interpolation method [27] or direct summation method [20] to solve this problem. However, the interpolation-FFT method degrades the accuracy of discrete Fourier transform (DFT) and direct summation is computationally too expensive to evaluate.

The problem with the nonuniformly sampled data has been recently addressed by the nonuniform fast Fourier transform (NUFFT) algorithms [1, 7, 12–15, 26]. The direct evaluation of a nonuniform discrete Fourier transform (NUDFT) costs $\mathcal{O}(N^2)$ arithmetic operations, whereas the NUFFT algorithms reduce this to $\mathcal{O}(N \log N)$. The NUFFT algorithms have been applied to biomedical image reconstruction [18, 19, 23, 25], as well as to subsurface sensing for landmine detection and other buried objects [21, 22, 24].

Recently, several new data sets for complicated objects and landmines have been obtained by an ultra-wideband radar system developed at Georgia Institute of Technology. In this paper, an NUFFT-based image processing method based on the phase-shift migration [9, 20] is applied to process these data sets to achieve high resolution images. The nonuniform fast Fourier transform (NUFFT) algorithm proposed by Liu and Nguyen [13, 15] has been utilized to process the nonuniform discrete Fourier transform data. The NUFFT-based reconstruction method improves both accuracy and speed compared to the conventional phase-migration method. In section 2, the formulation and application are applied to 3-D objects. In section 4, the new 3-D NUFFT GPR migration method is applied to experimental data sets collected at Georgia Institute of Technology (section 3). The reconstructed results for a plywood sheet, a buried plexiglas chamber, and several landmines are excellent.

2 Theory

In subsurface sensing application of a GPR system, the transmitter sends out an electromagnetic wave to the ground. The transmitted signal traverses the ground surface and is scattered by