Multidimensional GPR array processing using Kirchhoff migration

Mark L. Moran a,*, Roy J. Greenfield b, Steven A. Arcone a, Allan J. Delaney a

a US Army Cold Regions Research and Engineering Lab, Hanover, NH 03755-1290, USA
b Department of Geosciences, Penn State University, University Park, PA 16802, USA

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Abstract

We compare the ability of several practical ground-penetrating radar (GPR) array processing methods to improve signal-to-noise ratio (SNR), increase depth of signal penetration, and suppress out-of-plane arrivals for data with SNR of roughly 1. The methods include two-dimensional (2-D) monostatic, three-dimensional (3-D) monostatic, and 3-D bistatic Kirchhoff migration. The migration algorithm is modified to include the radiation pattern for interfacial dipoles. Results are discussed for synthetic and field data. The synthetic data model includes spatially coherent noise sources that yield nonstationary signal statistics like those observed in high noise GPR settings. Array results from the model data clearly indicate that resolution and noise suppression performance increases as array dimensionality increases. Using 50-MHz array data collected on a temperate glacier (Gulkana Glacier, AK), we compare 2-D and 3-D monostatic migration results. The data have low SNR and contain reflections from a complex, steeply dipping bed. We demonstrate that the glacier bed can only be accurately localized with the 3-D array. In addition, we show that the 3-D array increases SNR (relative to a 2-D array) by a factor of three. © 2000 Elsevier Science B.V. All rights reserved.

Keywords: Ground-penetrating radar; Signal-to-noise ratio; Kirchhoff migration

1. Introduction

Two-dimensional (2-D) seismic data sets are routinely migrated using a variety of methods (Yilmaz, 1987). The need for higher spatial resolution, greater target localization accuracy, and increased signal-to-noise ratio (SNR) has driven the petroleum exploration community to develop elaborate three-dimensional (3-D) survey and migration processing methods. Some ground-penetrating radar (GPR) applications have similar requirements. Application of petroleum exploration data acquisition and processing methods have been demonstrated to improve GPR results (Fisher et al., 1992, 1994). However, differences in the scale of costs and data characteristics require modification of the seismic methods for practical implementation in GPR contexts.

We seek to develop methods to improve (GPR) performance in the areas of target detection, spatial localization, signal penetration, and noise suppression. For example, signal penetra-
tion is often limited by scattering losses. This is particularly true for GPR surveys of temperate glaciers (e.g., Watts and England, 1976). In this application, the depth of investigation is limited by signal levels which are low relative to noise scattered from inclusions in the ice.

There are different antenna configurations for taking GPR data. Normally, data are collected along a single traverse with essentially collocated transmitter (Tx) and receiver (Rx) antennas. This is denoted as a 2-D monostatic traverse. Grouping a series of parallel GPR traverses gives a 3-D monostatic survey array. Bistatic data are taken when each Tx position is recorded by a number of offset Rx positions. The survey configuration offering the maximum SNR gain would be a large number of Tx and Rx positions in a 3-D bistatic configuration. At practical spatial scales, bistatic configurations require a much greater data collection effort and processing capability than do monostatic surveys. For most GPR applications, bistatic data collection and processing are prohibitively expensive.

There are a variety of GPR processing methods that improve SNR. For monostatic data, combining reflections from a common point on the surface can improve SNR. Delayed summing of traces can be used to reject signal-generated noise from directions away from the regions of interest. For bistatic multicovery data, common midpoint stacking has been shown to improve SNR (Fisher et al., 1992). Only limited bistatic 3-D data have been obtained and processed on glaciers (Walford et al., 1986).

In this study, we discuss processing methods that we have developed and applied to synthetic and field data which contain GPR reflections from targets of interest (signal) as well as energy scattered from other objects not of interest (noise). We apply 2-D and 3-D methods to data collected or generated using both monostatic and bistatic arrays. Time domain Kirchhoff migration methods are applied to these array data sets to compare SNR improvement, target localization, and target resolution. The time domain Kirchhoff method (Schneider, 1978) is selected because its spatial sampling criteria is less stringent than frequency domain wave number (Stolt, 1978) and time domain finite difference (Claerbout, 1985) migration methods. The time domain Kirchhoff approach allows larger aperture arrays with lower sensor populations to be used (large apertures maintain array SNR improvements for deep targets). These less stringent spatial sampling criteria are critical for keeping data acquisition and processing costs within manageable bounds.

We generate synthetic data to allow different configurations to be examined without the cost of collecting the data. It also allows array results to be directly compared with the known target signal. And importantly, synthetic array results aid in the interpretation of processed field data. The improvements seen in the synthetic results are supported by applying our array processing methods to 50-MHz data collected on a small temperate valley glacier (Gulkana Glacier, AK). Like many temperate glacier GPR surveys, this data set has low SNR and complex bottom reflections.

2. Methods

2.1. 2-D and 3-D monostatic array processing

Relative to depths of interest, GPR data are typically collected by nearly coincident Tx and Rx antennas. Thus, each time series trace in a GPR survey can be considered as resulting from a single monostatic antenna. In a seismic context, common midpoint stacks may be considered as improved monostatic data. Application of 2-D and 3-D Kirchhoff migration to common midpoint seismic and monostatic GPR data has been widely reported (e.g., Berryhill, 1979; Robinson, 1983; Fisher et al., 1992). A modification made here is the inclusion of a half-space interfacial dipole radiation pattern (Smith, 1984; Arcone, 1995) in the Kirchhoff integral of
Our modified GPR formula is given by

\[ U(r) = \frac{1}{2\pi} \int_{\zeta=0}^{\zeta} \frac{E'_{\theta,\phi,\varepsilon}}{R^p v} \frac{\partial U(r_0',t_0)}{\partial t} d\theta d\phi d\varepsilon \tag{1} \]

where \( U \) is the migration depth image, and \( U(r_0',t_0) \) is the surface wavefield observation. Primed parameters (\( z', r', \) and \( a' \)) give spatial dimensions relative to an array’s coordinate origin, \( R \) is the subsurface diffraction point relative to a surface observation, \( r \) is the integral evaluation point relative to the array’s coordinate origin, \( v \) is the propagation speed in ice and \( E(\theta,\phi,\varepsilon) \) is the range normalized electric field dipole radiation pattern. The exponents \( \alpha \) and \( \beta \) are treated as processing parameters to be determined by systematic trial-and-error variation. This approach was taken because presently, there is no theory that includes effects of transmitter and receiver radiation patterns or considers radiation pattern distortions due to time range gain. In the synthetic data, \( \alpha = 2 \) and \( \beta = 1 \). In the glacier data, \( \alpha = 2 \) and \( \beta = 1.5 \). The interfacial radiation pattern is strongly influenced by the relative dielectric constant \( \varepsilon_r \). In 3-D problems, the dipole radiation pattern must be included under the integral since it is a function of both azimuth (\( \theta \)) and declination (\( \phi \)). These direction parameters vary significantly between antenna locations. The dipole radiation pattern is squared (\( \alpha = 2 \)) to account for antenna directivity upon transmission and reception. Use of the half-space dipole formulation is appropriate for GPR settings in which the upper region of the material being probed is relatively homogeneous.

The modified migration integral is applied to single (2-D) GPR survey lines or multiple parallel (3-D) survey lines. The antenna positions within the survey lines are grouped into subarrays. Using the recorded GPR time series in each subarray, Eq. (1) is evaluated at a series of evenly spaced nodes to yield a depth image in a subsurface focal plane. For large groups of long parallel survey lines, subarray divisions can be made in both \( x \) and \( y \) directions. Furthermore, subarrays may be overlapped in both \( x \) and \( y \) directions. This approach is similar to the synthetic aperture array processing done in high altitude radar imaging of the ground (Curlander and McDonough, 1991). The subarray overlap reduces edge effects in the migration results and provides increased continuity of migrated amplitudes.

Fig. 1 shows a series of survey lines running parallel to the \( x \)-axis. We refer to all antenna positions in this group of survey lines as the GPR array. The figure indicates that the array is broken into a series of overlapping subarrays. Directly below the center line of the array is a single vertically oriented image plane. When using 3-D surveys, our implementation allows the migration integral to be evaluated in a series of multiple parallel image planes with regular offsets. Each discrete antenna position in the array has an \( x \) and \( y \) coordinate on the earth’s surface. Within any given subarray, the inter-element sensor position should be specified to a precision of less than 0.25 of an in situ wavelength. These spatial accuracy requirements become easier to achieve in field surveys as GPR frequency decreases; for example, at 50 MHz in ice, a quarter wavelength is approximately 1 m. Fortunately, the accuracy requirements for inter-element sensor locations need only be enforced for distances slightly larger than the subarray dimensions.

The number of elements in a subarray, the inter-element separations, and the spatial dimensions (aperture) of the subarray are chosen by considerations of the in situ GPR signal wavelength, the depths of interest, and the characteristics of the targets being investigated. In our work with GPR data, we find it is acceptable to have roughly 0.1 of a wavelength sampling along a survey line and roughly one to three wavelength separations between survey lines. In general, deeper targets and steeply dipping beds require larger subarray apertures (Yilmaz, 1987). Trial-and-error processing was used in this study to determine appropriate subarray dimensions.
To demonstrate proper implementation of the algorithm, we show the migration result for an impulse response (Fig. 2) in data space for the array in Fig. 1. The procedure follows Yilmaz (1987) (p. 258). To generate the impulse response, every array element’s time series is zeroed except the center element, which contains an impulse. The array data are then subdivided into subarrays (as shown in Fig. 1). The subarray data are used in the migration integral, which is evaluated in the focal plane to produce a depth image. For a properly functioning migration algorithm, a point in time should migrate (Eq. (1)) to a semicircle depth image, with the amplitude varying according to the obliquity characteristics (in our case, the interfacial dipole radiation pattern) of the Kirchhoff integral. Fig. 2 shows the E and H field impulse responses for a homogeneous earth with \( \varepsilon_r = 8 \). The impulse was placed at a depth of 2.5 m. To obtain the E plane result, each antenna is oriented with the E field parallel to the x-axis. To obtain the H plane response, each antenna’s E field is oriented parallel to the y-axis. Four subarrays are used. Each subarray overlaps the preceding subarray by 50\%. The plots show that the dipole arrays preferentially enhance backscatter from nonvertically positioned targets. The off-center H field maximum is 6 dB larger than the vertical. The off-center E-field maximum is reduced from the vertical by 3 dB. However, there are deep spectral nulls between the vertical and sidelobe maximum. In standard implementations of the Kirchhoff method, the array impulse response has a \( \cos(\theta) \) directivity with the maximum amplitude vertically downward.

2.2. Synthetic data generation

For the simulated data, we apply a pseudoscalar wave equation for point target diffractors in a homogeneous host material. The modification includes the directivity of the target diffractors resulting from each diffractor–antenna pair-
In this formulation, the target’s scattered field polarization is controlled by the incident electric field characteristics. For a given antenna–dipole pairing, the incident electric field is controlled by the interfacial dipole radiation pattern (Smith, 1984). This approximation for the polarization holds when scattering objects are small compared with a wavelength (van de Hulst, 1981). A more advanced treatment would consider the full Mie solutions (e.g., Stratton, 1941) for scattering from small spheres. Distributions in model space of many uncoupled smaller amplitude point inclusions allow background noise levels to be varied against a fixed target with a relatively larger scattering amplitude. Arrival times are determined using straight ray travel paths for each target or noise inclusion in the model space volume.

Target backscatter responses can be generated for point diffractors, line diffractors at arbitrary azimuths, and arbitrarily dipping planar reflectors. Material properties of the target scattering are emulated via specification of scattering amplitude and amplitude polarity. Noise in the synthetic data is produced by several categories of spatially organized point diffractors. These include randomly distributed volumetric scatterers, regionally localized scatterers, and angularly confined scatterers. This gives a statistically nonstationary noise field. We believe this accurately represents GPR signal-generated noise. Stationary random system noise can also be included. The level of noise in a data set is controlled by specifying the number, amplitudes, and polarizations of the scattering inclusions. For each object in the model space, small random perturbations in frequency content, and arrival time are added.

3. Results

Array results are given for monostatic 2-D, 3-D, and 3-D bistatic GPR arrays using synthetically generated data. The synthetic results are
followed by 2-D and 3-D array results from field data collected on a temperate glacier. The spatial scales of the synthetic results differ from those of the glacier data set. Using synthetic data for simple array geometries, we establish performance improvements for SNR, target localization, and target resolution from point diffractors. The results from glacier data use more complex GPR arrays to show similar array processing improvements for reflections from deep, steeply dipping bed topography under low SNR conditions. The combination of these results spans a wide range of typically encountered GPR survey scales and target types.

3.1. Monostatic 2-D vs. monostatic 3-D: synthetic data

Using the analytical model, a 4-m-long, 21-position (monostatic) GPR survey line is simulated. The offset between antenna positions is 0.2 m. The model contains six point diffractors located 3 m below the ground surface. The half space has an $\varepsilon_r = 5.7$ and is nonconductive. We keep these electrical properties constant for all simulations discussed. Fig. 3B shows the target locations in the $x$-$y$ plane at a depth of 3 m. The targets are grouped in pairs along the $y$-axis. Within a pair, the target separation is 0.25 m. The polarities (sign) of the scattering coefficients are reversed within each pair. The magnitude of the reflection coefficients are equal for all six diffractors. The $x$ positions of each pair are $-0.75$, 0, and 0.5 m.

In the simulated data, a 3rd derivative of the Gaussian function is used as a source wavelet. For all simulations, the center frequency of the source wavelet is 700 MHz. This gives an in situ wavelength of roughly 0.18 m. Fig. 4A shows the source wavelet with a small amount of added noise. Fig. 4B gives the synthetic data time series for the array. Signal amplitudes indicate that the SNRs for the data are approximately 100. All SNR quantities discussed in this paper are determined by amplitude comparisons. Fig. 4C gives the 2-D monostatic Kirchhoff migration result in the vertical $y$-$z$ plane passing through $x = 0$ m. The depth image clearly resolves the targets around the $x$-$y$ origin. However, the out-of-plane diffractors (at $x = 0.5$ and $-0.75$) show large energy leakage into the migration plane.

We demonstrate the performance improvement for a 3-D monostatic GPR array relative to the 2-D result given above. In this example, we use the same center frequency, SNR, and target model parameters as those given for the 2-D case. The 3-D array is composed of five parallel survey lines with an aperture of $2 \times 4$ m$^2$. The offset between each line is 0.5 m (2.7 wavelengths). Within a survey line, the monostatic antenna positions are separated by 0.2 m. Fig.

![Fig. 3.](image)

Fig. 3. (A) Standard monostatic GPR survey with 21 sensor locations over 4 m line. Six point diffractors are located at a depth of 3 m. (B) $x$-$y$ locations of these six diffractors. Each pair is separated by 0.25 m.
Fig. 4. (A) 700-MHz center frequency source wavelet used for all synthetic data. (B) Synthetic data for standard GPR survey. (C) 2-D Kirchhoff migration result. Targets near \( x-y \) origin are resolved and target polarity is distinguishable. Large amplitudes in the vicinity of \( y = -0.5 \) and \( y = 0.5 \) are due to out-of-plane targets (at \( x = -0.75 \) m and \( x = 0.5 \) m).

5A gives the array geometry and shows ray paths from each sensor to a diffractor. Fig. 5B gives the 3-D Kirchhoff migration result in the vertical \( y-z \) plane at \( x = 0 \) m. Diffractors are clearly resolved in the vicinity of the \( x-y \) origin and the polarization reversals are distinct. Most notable is the suppression of out-of-plane energy leakage from the diffractors located along \( x = 0.5 \) and \( -0.75 \) m. Equally good results are obtained when a vertical \( y-z \) focal plane passes through the \( x = 0.5 \) and \( -0.75 \) m.

3.2. Monostatic 3-D vs. 3-D bistatic: synthetic data

For the 3-D bistatic data, we again utilize the modified integral of Schneider (1978) (Eq. (1)). For this demonstration, synthetic data are generated for two oppositely polarized diffractors at a depth of 2 m. Both targets are in the \( x = 0 \) plane and are offset by 0.125 m on either side of \( y = 0 \). This gives a separation of 0.25 m. The host half space has \( \varepsilon_r = 5.7 \). A large number of small amplitude point scatters are distributed throughout the model space to produce GPR data with an SNR of approximately 1. Monostatic signals are calculated for a \( 2 \times 2 \) m\(^2 \) array consisting of 25 equally spaced elements (0.5 m). This array geometry is marginal for resolving the two targets. Bistatic synthetic reflections are calculated for the same array element positions. However, in the bistatic case, when each element transmits a radar pulse, every element records the resulting backscattered radar signal. This results in 650 time traces from a 25-element array. Fig. 6A shows the model space (with target diffractors and noise inclusions) and array element locations. Fig. 6B shows the monostatic array time traces at each \( y \) position at \( x = 0 \) m. Target diffractor signals arrive in the vicinity of 35 ns.
Fig. 5. (A) 3-D monostatic GPR array using five parallel survey lines with 0.5 m separation between lines and 0.2 m separation between sensor locations along each line. 105 elements total. Target and source model parameters are the same as Fig. 3. (B) 3-D monostatic Kirchhoff migration result for the $y$-$z$ plane at $x = 0$. Targets near the $x$-$y$ origin are clearly separated and polarizations are maintained. Most notable is the suppression of energy from targets outside the focal plane.

Fig. 7A gives the 3-D monostatic migration. The two targets are marginally resolved. However, the target polarities are ambiguous, if not misleading. This is caused by spatially coherent noise in the vicinity of the target signal arrivals. Fig. 7B gives the bistatic migration result for data with the same signal and noise statistics. In this case, the target diffractors are clearly separated in space and the target polarizations are correct. Also of importance is the substantially suppressed noise field. However, these improvements are very costly in terms of data acquisition and computation times. Both the computational burden and size of the data sets scale as the square of the number of element positions ($N^2$).

Fig. 8 shows the amplitude variation vs. depth from the 3-D monostatic and bistatic results. This depth profile was taken at surface point $x = 0, y = -0.125$ m. In the vicinity of the target depth ($z = -2$ m), the bistatic migration shows a roughly 12 dB noise suppression improvement relative to the monostatic migration result. In problems with incoherent random noise, the noise suppression should be enhanced by $1/\sqrt{N}$ (with $N$ being the number of independent samples of the process). If the noise in our synthetic data was totally incoherent, the noise suppression for the bistatic array should have been roughly 14 dB greater than the monostatic array.

3.3. Results from temperate glacier data

The electrical characteristics of temperate glaciers present challenging processing problems for time domain GPR operating above 10 MHz (Watts and England, 1976; Arcone et al.,...
Fig. 6. (A) $2 \times 2$ m$^2$ (25 position) GPR array and model space. Coherent spatial noise is simulated by adding random point diffraction scatters. Targets (heavy circles) are at depth of 2 m and are separated by 0.25 m around $y = 0$, at $x = 0$. Target reflection coefficients have opposite signs. The array geometry provides minimal resolution capability for targets at this depth and separation. These model/array parameters are used for both the monostatic and bistatic data synthesis. (B) Monostatic synthetic waveforms are from the center line. SNR is roughly 1. Target reflections arrive between 35 and 40 ns.

Fig. 7. (A) 3-D monostatic Kirchhoff image from $2 \times 2$ m$^2$, 25 element array. Raw data SNR is 1.25. Targets at 2 m depth are barely resolved and the polarity is confused by the noise field. (B) 3-D bistatic Kirchhoff image from $2 \times 2$ m$^2$, 25 position array (generates 650 time traces). Raw data SNR is roughly 1. Both targets are clearly resolved and the polarity distinction is clear. The added performance is due to the $N^2$ increase in data coverage.
Temperate glaciers have thermal states at or slightly below 0°C. Thus, there is typically a significant fraction of liquid water present in the ice. The large dielectric contrast between liquid and frozen water ($\varepsilon_r_{\text{water}} = 81$, $\varepsilon_r_{\text{ice}} = 3.17$) causes GPR signals to scatter strongly, producing high clutter data (low SNR). Crevasses and rock inclusions also produce scattering losses. Multidimensional GPR arrays can mitigate these problems by rejecting energy scattered from undesirable directions.

We have collected and processed GPR array data from the Gulkana Glacier, AK (145° 30’ longitude, 63° 15’ latitude). The Gulkana is a small (8-km-long) temperate valley glacier in the Alaska Range of central Alaska. The array was situated just below the firm line (roughly 1800 m elevation) in the upper northeast end of the glacier. On temperate glaciers, the firm line is defined as the boundary between snow and ice at the end of the melt season (Patterson, 1994). The array’s rectangular dimensions are 100-m-wide by 340-m-long. The western end ($y = 0$ m) of the array was situated on the toe of a rock outcrop below a hut maintained by the University of Alaska, Fairbanks. The grid is shown in Fig. 9. The 100-m-wide base of the grid had a roughly north-south orientation that paralleled the ice flow direction. The width direction is defined as the $x$-axis. The 340-m length of the survey grid trended roughly west to east and is designated as the $y$-axis of the survey grid.

We used a laser theodolite to place survey flags at 10-m intervals along the $x$-axis and at 20-m intervals along the $y$-axis. Relative elevation changes between flags were also obtained from the theodolite. A snowmobile was used to tow the antennas along the $y$ direction at every 2-m interval along the $x$-axis to yield 51 parallel survey lines. The center frequency of the 16-bit array data was 50 MHz. Total trace duration was 3400 ns with 1024 samples. All signals
of interest were contained in the first 2000 ns of the GPR records. The raw data were justified to give 10 traces per meter. Elevation corrections, spatial justification, and Wiener spike deconvolution (Robinson and Treitel, 1980) were applied prior to array processing. The deconvolution operation substantially broadened the frequency content of raw GPR reflections and improved the resolution of bottom reflections and ice inclusions.

Fig. 10 shows a data record from the survey line located at \( x = 71 \) m. The data have been elevation-corrected and justified. The tails of hyperbola resulting from diffraction scattering from ice inclusions, can be used to estimate GPR signal phase velocity (or \( \varepsilon_r \)). The steepest hyperbolae in our data at a variety of depths consistently indicated a value of \( \varepsilon_r = 3.17 \). In Fig. 10, the ice bottom reflection is the steeply dipping reflector, sloping from the upper left down to the lower right. At \( y \) locations beyond 125 m, the data are dominated by spatially coherent noise from scattering. The data are relatively noise-free at \( y \) locations less than 100 m. The apparent bed discontinuity in the vicinity of \( y = 130 \) m is due to a local increase in bed dip. In addition to the bed’s \( y-z \) plane dip component, there is also a strong \( x-z \) dip in and out of the plane of the figure. With such steep, complexly dipping bed characteristics, the depth to the ice bottom cannot be determined from the raw data. Migration must be applied to accomplish this.

Fig. 11 gives the 2-D monostatic migration result using the survey line located at \( x = 71 \) m. The \( y \) subarray aperture was 60 m and contained 60 elements separated by 1 m. Each subarray overlapped the preceding subarray by 50%. The figure contains a portion of the vertically oriented migration focal plane oriented perpendicular to the \( x \)-axis. It shows the migrated image between \( y \) values of 100 and 320 m and depths between 80 and 160 m. In this region, the bed reflection is weak and the SNR is low. The bottom reflection is the vague dipping reflector starting at \( z = -100 \), \( y = 100 \) m and trending downward to \( z = -138 \) m at \( y = 230 \) m. The migration image plane was specified to be vertically down, and perpendicular to the \( x \)-axis. However, the result is misleading since a 2-D migration can incorrectly place out-of-plane reflections in the image. This would be the case for reflections from a bed with a significant \( x-z \) dip. The lobate dipole directiv-
Fig. 11. 2-D migration from Gulkana Glacier. The survey line was located at $x = 71$ m. The bottom reflection is the dipping reflector starting at a depth $z = -100$, $y = 100$ m and trending downward to $z = -138$ m at $y = 230$ m. However, this 2-D array has no out-of-plane control. Therefore, the normal reflection from a plane with a strong $x$-$z$ dip will be resolved, but may be mislocated.

ity aggravates this mislocation problem in standard 2-D surveys by having the maximum in the radiation pattern occur at nonvertical azimuths.

For our 3-D monostatic migration result, we used a rectangular subarray with an $x$ aperture width of 40 m, and a $y$ aperture length of 60 m. The elements in each subarray are separated by 1 m in the $y$ direction and 2 m in the $x$ direction. Each subarray contained 1200 antenna positions. The survey line located at $x = 71$ m defined the centerline of the 40-m $x$-aperture. As in the 2-D case, each subarray overlapped the preceding subarray by 50%. When using a 3-D array, we have both $x$ and $y$ resolution control, which allows the image focal plane to be substantially offset from the array. In this example, the focal plane was vertical and oriented perpendicular to the $x$-axis at $x = 35$ m. Fig. 12 shows this geometry in an $x$-$z$ plane cross-section. The $x = 35$ m image plane location puts the array focal point in the vicinity of a normal reflection for the $x$ component of the bed dip. Fig. 13 shows the 3-D migration result using these processing parameters. The bed now has a high degree of continuity and the SNR along the bed reflection shows a significant increase relative to the 2-D result (Fig. 11).

The optimal $x = 35$ m, $y$-$z$ focal plane location was determined by calculating results for multiple parallel focal planes spaced between $x = 25$ and 71 m. The $x = 35$ m focal plane location (shown in Fig. 13) produced the largest

Fig. 12. 3-D Gulkana migration geometry in an $x$-$z$ plane cross-section. The $40 \times 60$ m$^2$ subarrays are centered on the $x = 71$ m survey line. Individual antenna elements in the array record the normal reflection from the dipping bed. To observe the maximum signal return from the bed’s normal reflection, the migration focal plane must be positioned at $x = 35$ m.
amplitudes, and highest SNR in the vicinity of the bed reflection. To demonstrate this 3-D localization capability, we give results for a vertically oriented $y$-$z$ focal plane at $x = 71$ m (Fig. 14). This is directly below the centerline of the array (Fig. 12). The image shows poor bed continuity. And in most places, it has lower SNR in the vicinity of the bed reflection. Also of significance is the mislocated bed reflection (indicated with an arrow). In Fig. 14, the depth to the bed reflection is given as $125$ m at $y = 140$ m. In the properly focused result (Fig. 13), the bed reflection has a depth of $115$ m at $y = 140$ m.

In Fig. 15, we compare the amplitude variation at $y = 180$ m as a function of depth for the three Gulkana migrations discussed. The upper trace shows the result at $x = 71$ m for the 3-D migration result. The rectangular array had an $x$ dimension of $40$ m, and a $y$ dimension of $60$ m. The vertically oriented image plane was located at $x = 35$ m. The image plane offset puts the array focal point in the vicinity of normal reflection for the $x$ component of the bed dip. In addition to accurately positioning the bed, the 3-D migration has substantially increased the SNR of the bed reflection, when compared with the 2-D result.

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array focused in the $y-z$ plane; the middle trace is from the 3-D array with the $y-z$ focal plane at $x = 35$ m. The bottom trace is from the 2-D array (which resolves the normal reflection). The properly focused $x = 35$ m trace has a SNR of roughly 3. It indicates a bed depth of 121 m (at $x = 35$ m, $y = 180$ m). The 2-D result has an SNR of roughly 1. The bed reflection has a depth of 126 m (at $x = 71$ m, $y = 180$ m). The vertically focused ($x = 71$ m) 3-D array has no identifiable bed reflection at this location.

4. Conclusions

There are many circumstances in which GPR survey objectives require high precision target localization, increased signal penetration depth, and noise suppression. We have presented cost effective array processing methods to address these requirements.

The Kirchhoff migration integral of Schneider (1978) was modified to include the radiation pattern for an interfacial dipole and implemented for monostatic 2-D, 3-D, and bistatic 3-D data. Utilization of time domain Kirchhoff migration allows array elements to have separations as large as two wavelengths. In 3-D surveys, this less stringent sampling requirement greatly reduces the data collection and computational expenses. The presence of strong dipole radiation patterns in GPR data tends to enhance signal scattering from out-of-plane objects. Consideration of this effect in the migration integral coupled with greater spatial control from a multidimensional array allows increased accuracy in target localization and noise suppression.

Application of these array processing methods to synthetic GPR data demonstrated that significant improvements in target localization and noise suppression can be achieved by 3-D monostatic GPR arrays (compared to standard 2-D methods). Simulation results using 3-D bistatic arrays shows a further increase in performance. However, dramatic increases in data coverage and processing costs make it impractical to conduct 3-D bistatic GPR surveys using commercially available GPR hardware.

2-D and 3-D monostatic array results for the field data support the results observed in the synthetic data processing. Our glacier results demonstrate that 3-D monostatic arrays can improve SNR from bed reflections by a factor of three, that signal penetration is improved, bed reflection continuity is improved, and that the complexly dipping bed can be accurately localized. Lastly, the resolution improvements using a 3-D array bring out bed reflection details not observed in the raw data, or in the 2-D array processing.

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