Abstract—A technique has been implemented for improving the 3-D position resolution in a germanium strip detector. By using the signals induced on multiple electrodes, the position of the drifting charges can be interpolated to a resolution smaller than the width of the strips. Interpolation allows for a desired position resolution to be achieved with the fewest number of electronic channels. Applications include portable and space-based instruments where power, cooling, and mass are at a premium. Measurements were made on a fully instrumented 19x19 planar germanium strip detector. This system is used as a Compton imager and detects gamma-ray sources anywhere in a 4-pi field of view. It is shown that, using interpolation, the point spread function for a 662 keV point source improves from 25° to 10° FWHM under specified conditions. However, it is shown that many interactions occur too close together to be effectively interpolated. This and other practical limitations are discussed. In addition, an electrostatic model has been developed and shown to be in good agreement with measurements. This model was used to optimize detector design, predicting signal to noise ratios, and check the calibration of the signals.

I. INTRODUCTION

Germanium detectors are preferred for gamma ray spectroscopy because of their excellent energy resolution. In addition, they can be used to give the 3-D position information of gamma ray interactions in the active volume. This 3-D information benefits several types of gamma ray imaging systems including coded aperture, pinhole collimators, and Compton imaging.

For a planar detector, the electrode on each side is segmented into strips to give the x and y coordinates of an interaction. The z coordinate (depth of interaction in the crystal) is determined by the difference in the arrival time of the electrons and holes [1,2]. To improve the resolution in the x and y directions, a finer segmentation is required which means more electronic channels. For some applications, such as a space-based Compton telescope, the practical limitations of mass, power and heat dissipation limit the feasible number of channels. To help solve this problem, the technique of interpolation between strips is demonstrated. Interpolation improves the achievable resolution without increasing the number of electronic channels.

The measurements for this work were made using a single germanium planar strip detector that is 10.5 mm thick and 38 mm in diameter. There are 19 strips on either side (in orthogonal directions to give the x and y dimension respectively). The strips are 2-mm pitch with 1.5-mm electrode width and 0.5-mm gap between strips.

Each strip has a dedicated preamplifier followed by a 100-MHz, 13-bit digitizer. For each gamma-ray interaction, all waveforms (with deposited energy above a minimum threshold) as well as the waveforms of the nearest neighbor channels are read out to a PC for analysis. This analysis included determining the energy, position and timing of each interaction.

The detector is used either by itself or in conjunction with other strip detectors for different imaging modalities including coded-aperture imaging and pinhole imaging. Because the system can resolve multiple simultaneous interactions, a single detector can be used for Compton imaging as well.

II. METHOD OF INTERPOLATION

A gamma ray interaction (Compton scatter or photoelectric absorption) generates free electron/hole pairs. Under an electric field, these charges drift to the electrodes on opposite sides of the detector and induce a signal on the collecting strips. In addition, the drifting charges induce transient signals on all the electrodes adjacent to the collecting strip. In particular, the strips immediately to the left and right of the collection strip receive a relatively large signal (fig. 1). In the past, these transient signals have been ignored or considered a nuisance. The amplitudes can be relatively high and, if not treated properly, can exceed threshold levels and create false triggers. However, they also contain information about the position of the drifting charges and can used to improve the resolution.

![Fig. 1. Schematic demonstrating interpolation. Signals are induced on the collecting strips (x and y) from the charges. Signals are also induced on the neighbor electrodes (x1 and x2). The interpolation signals give additional position information.](image-url)
III. SIMULATION OF INTERPOLATION SIGNALS

A simple electrostatic model has been shown to reproduce the interpolation signals to good agreement with measurements (fig. 2). Because these signals vary significantly in shape and amplitude, the model is useful for calibration and predicting S/N ratios of various interpolation techniques. These signals are calculated through a four step process.

1. Model the electric field of the detector using an electrostatic simulation package. A 2-D simulation was sufficient for this purpose. The model should include the detector geometry, bias voltage and the bulk charge of the detector.

2. Determine the trajectory of the drifting charges in the detector. This can be done by following an imaginary point charge, step by step, through the electric field (using a sufficiently small step size for resolution). To correctly determine the time dependence of the signals, it is necessary to take into account the velocity of the charge at each point in the detector. The velocity is a function of electric field and is given empirically by equation 1 [7],[8].

\[
\nu(E) = \frac{\mu_0 E}{\left[1 + \left(\frac{E}{E_0}\right)^\beta\right]^\beta}
\]

(1)

where \(\mu_0\) is the low field mobility and \(E_0\) and \(\beta\) are empirical constants. These values are different for electrons and holes and are given in Table 1. Note that these values assume a temperature of 80 K.

<table>
<thead>
<tr>
<th></th>
<th>Electrons</th>
<th>Holes</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\mu_0) (cm²/V*s)</td>
<td>3.6 * 10⁴</td>
<td>4.2 * 10⁴</td>
</tr>
<tr>
<td>(E_0) (V/cm)</td>
<td>275</td>
<td>210.5</td>
</tr>
<tr>
<td>(\beta) (unitless)</td>
<td>1.32</td>
<td>1.36</td>
</tr>
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3. Find the induced charge on the neighboring channels for a given trajectory. This is done using the standard technique of weighting fields [5,6].

4. The final signal is the superposition of the induced signals from the drifting electrons and holes. The results of this simulation for our detector are shown in fig. 3. This figure shows the family of induced signals (on the neighbor channels) that arise for a gamma-ray interaction occurring at different positions across a strip as well as at different depths (x and z coordinates).

IV. CALIBRATION

A calibration was made to extract the position information from the induced neighbor signals. The calibration was determined by using the simulation to compute the area of the right and left interpolation signals and taking the difference. Fig. 4 plots this difference between left and right areas as a function of depth and position across the strip. Note that the calibration is nearly linear. However, the slope changes considerably with depth. The slope is nearly flat around \(z = 2\) mm, in the region of the bipolar signals.
Other approaches for extracting the position information were considered such as using the amplitudes of the signals or taking the ratios of the areas or amplitudes. However, the chosen approach was found to give the most linear calibration and the best signal to noise ratio of the methods tested.

V. SCANNING

A scanning system was setup for the purpose of verifying the calibration as well as for quantifying the position resolution. The scan was made along the x and y directions using a 122 keV source and a collimator with a 200-µm hole. From these measurements, the position resolution was shown to be 0.5 mm fwhm (compared to the 2 mm strip pitch). The resolution improves with higher energy depositions as the signal to noise ratio improves.

VI. RESULTS

To demonstrate the effectiveness of interpolation, a shadow image was made of a pinhole using the 122 keV gamma ray line from a 57Co source. Fig. 6 shows the pinhole before interpolation was applied. The 2-D coordinates of each gamma ray interaction were determined from the x and y strip locations (no interpolation). Compton scattered events were eliminated by accepting only events that had a full 122 keV energy deposition in a single pixel. The hole was 12 mm in diameter.

Finally, the interpolation technique was applied to a Compton imaging experiment. In this case, exactly two interactions, adding up to the photopeak energy, were required for a valid event. The x, y and z coordinates were determined by the normal means and then the x and y coordinates were further resolved with the calibrated interpolation signals.

Fig. 7 shows the same data set with the addition of the interpolation information. Each pixel was subdivided into a 8 x 8 grid. The location of an interaction within the pixel was then determined using the neighbor signals. Note that the outline of the pinhole is much more clearly defined. Gaps between the pixels can be seen in the figure. These gaps correspond to the insulating region between the strips. Charges that are collected to this gap region do not deposit their full energy on a single strip and are thus discarded by the energy cut. The edges of the pixels show a higher intensity than the interior regions. This artifact suggests that improvements are still needed in the algorithm.

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Fig. 8 shows the 511 keV image from a 22Na point source. In this case, no interpolation has been applied; only the x and y strip location of each interaction is used.

Fig. 9 results from the same data set. However, each interaction coordinate has been updated using the interpolation technique.
signals. As a result, the FWHM of the point spread function went from 25° to 10°. This demonstrates, somewhat quantitatively, the improvement due to interpolation.

Fig. 8. Part of the Compton image resulting from a 511 keV point source. The FWHM of the point spread function is 25°.

Fig. 9. Image from the same data set as fig. 9. In this case, the position of each interaction was modified using the calibrated interpolation signals. The FWHM of the point spread function improved to 10°.

VII. LIMITATIONS TO INTERPOLATION

The image in fig. 9 shows a considerable improvement due to the use of interpolation. However, there are several qualifications that must be made about the technique. The first is that a severe cut was made to the data set used for figures 8 and 9. Because the images were made with a single detector, multiple interactions were required within the same device. It was necessary to make a cut requiring only interactions that were separated by 8 mm or more in both the x and y directions. This is due to the fact that drifting charges induce signals on all strips, not just the collection electrode and nearest neighbor. These signals diminish in amplitude with distance but, in the case of large energy depositions, can be large enough to interfere with the signals of another interaction.

Fig. 10 shows a schematic representation of a measured 662 keV photon event. The total energy was deposited in two interactions, one large and one small, which occurred close together.

Fig. 10. Schematic showing an event in which the interactions were too close for interpolation.

Fig. 11 shows the waveforms (electron collection side only) for the two interactions and their respective neighbor signals. The large interaction has two proper-looking induced neighbor signals and should give an improved position resolution. The smaller interaction, however, has one neighbor signal that can not be explained by that interaction alone. In fact, it has two humps. The first one is the induced signal from the large interaction which was only 6 mm away.

If interpolation had been applied to the smaller interaction shown in fig. 11, then obviously an erroneous result would result. Thus, for the purposes of quantifying interpolation, these events were discarded from the data set. A better implementation would keep this event and only apply interpolation to the larger interaction. It was found that at least 8 mm separation was needed between interactions (in a given x or y dimension) to reduce the interference of signals. For multiple interactions in a single detector, this results in a significant loss of events useful for interpolation. Fig. 12 shows that only ~5% of 662 keV photons (which deposit their full energy in two interactions) occur 8 mm or more apart.

Fig. 11. Two interactions from a single 662 keV event in which the interactions occurred close together. The large energy interaction induces a charge onto the neighbor channel of the smaller interaction. Note that the two plots have different vertical scales.

Fig. 12. Distance between interactions from a 662 keV source. Events were accepted only if the full energy was deposited in two interactions.
Another limitation to the interpolation technique is the useful energy range per interaction. Below 100 keV per interaction, the signal to noise ratio becomes poor, as can be seen from the smaller interaction in fig. 11.

Conversely, for very large energies, it is difficult to know whether a deposition occurred from a single interaction or multiple interactions close together. The larger interaction shown in fig. 11 occurred as a point interaction, which can be determined by visual inspection of the waveform (assuming familiarity with how these waveforms look). However, discriminating between single and multiple interactions in an algorithmic way would require sophisticated processing and has not yet been demonstrated.

As stated above, a resolution of 0.5 mm FWHM was measured at 122 keV. This resolution scales with increasing energy as the signal to noise ratio. At 200 keV, for example, the resolution is approximately 0.25 mm. However, this resolution is not achieved across the full depth of the detector. Fig. 13 shows the resolution as a function of depth (at 200 keV) and it can be seen that there is a region, around z = 2 mm, in which the resolution is almost as wide as the strip itself. This occurs in the region where bipolar signals are induced on the neighbors. These bipolar signals are very insensitive to position, at least using the algorithms that we have explored. Thus, an interaction occurring at this depth will not resolve to better than the strip dimension. One subtlety is that an event occurring 2 mm from one side of the detector is 8.5 mm from the other side. Thus it will resolve well in one dimension (the x coordinate, for example) but not in the other dimension (the y coordinate).

Large energy depositions also suffer from effects arising from the finite size of the charge cloud. The electron ejected from a photoelectric or Compton interaction will have a range on the order of several hundred microns, depending on the energy. The simulations have so far assumed point-like interactions. In addition, this charge cloud, instead of residing over a single strip, may straddle the boundary between two strips. The charge cloud effects are further complicated by the aforementioned inability to discriminate between single and multiple interactions in the same strip. Further modeling might help unravel these various effects but we have not yet carried this out.

VIII. CONCLUSIONS

Interpolation has been incorporated into our imaging systems to improve the ability to resolve the position of gamma-ray interactions. Using a simple calibration of neighbor signals, it was shown that a resolution of 0.5 mm FWHM (at 122 keV) could be achieved over much of the depth range of the detector. However, interactions occurring around 2 to 3 mm from a strip are very insensitive to interpolation. In addition, for Compton imaging in a single detector, interpolation was applied to only a small subset of events (~ 5%).

A more sophisticated approach might increase the number of events for which this technique applies. Such an approach would involve simulating the complex family of signals arising from interactions occurring close together and storing those signals in a library. This library could be consulted to return better position information. However, we have not yet explored this approach.

IX. REFERENCES


Fig. 13. Resolution as a function of depth, simulated for 200 keV interactions.