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Sensitivity Studies for CONFIDANTE (CONfirmation using a Fast-neutron Imaging Detector with Anti-image Null-positive Time Encoding)

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Introduction

CONFIDANTE is an approach to warhead verification using time-encoded imaging to produce a null result if two objects are identical, confirming without recording any sensitive information. The null result is present at all times, which presents the opportunity for both host and monitoring parties to see the data in real time without revealing sensitive information about the objects. Shown here are results taken from studies looking at the effect of misaligning objects or mismatching shapes. One study placed two Cf-252 sources on opposite sides of the system, then moved one source to be slightly misaligned. The second study used a 2D stage to trace out difference sizes of circles and squares with a Cf-252 source.

CONFIDANTE

CONFIDANTE uses time-encoded imaging (TEI) to produce a null result for warhead confirmation. TEI is a version of coded aperture imaging in which a cylindrical coded mask rotates around a central detector. The event rate in the detector is modulated by the mask as it rotates (Fig. 1a); that modulation pattern and the mask pattern can be used to reconstruct a 2D image of the source (Fig. 1b).

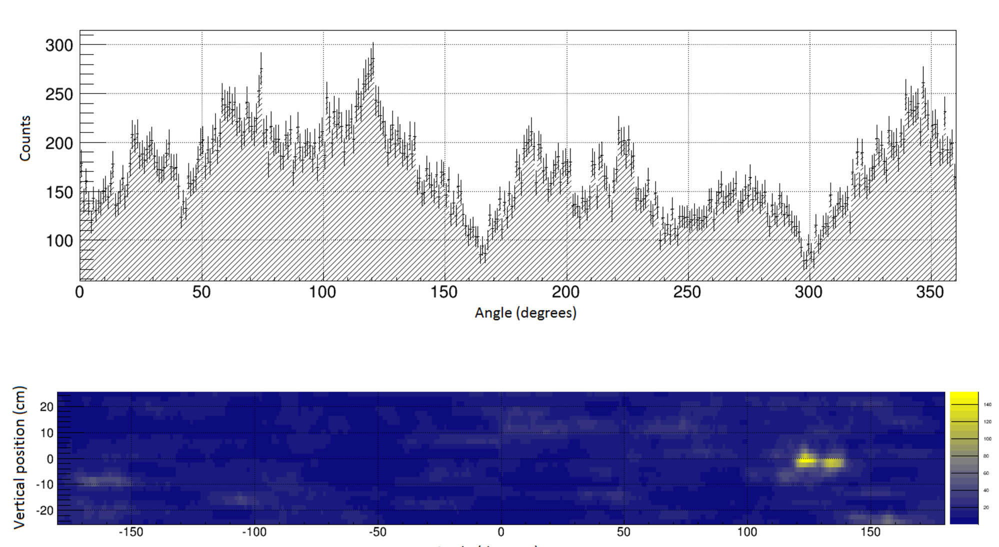

Fig. 1. (a) Detector count rate as a function of rotation angle of the TEI mask for two Cf-252 sources. (b) MLEM reconstruction of the sources.

To use TEI for warhead verification, the mask is designed with anti-symmetry. That is, if there is a mask element on one side of the mast, 180 degrees opposite from that position is an opening, and vice versa. If two objects are placed on opposite sides of the mask, the count rate in the detector is constant if and only if the two objects are identical. See Fig. 2 :

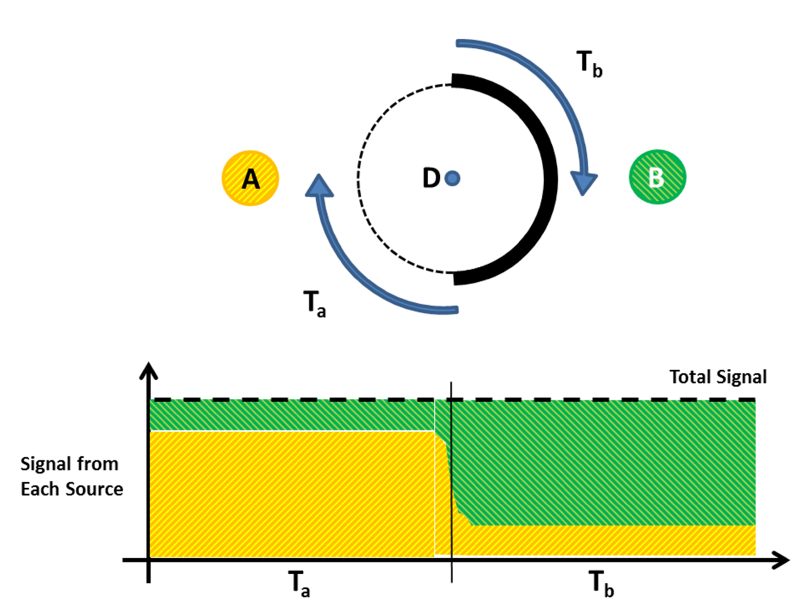

Fig. 2. An example of the simplest anti-symmetric mask, a half-cylinder. The top shows two objects, A and B, on opposite sides of detector D, with the mask rotating around the detector. The bottom graph shows the count rate in the detector as a function of time as the mask rotates and the contribution to the total count rate from each object changes

A prototype system was built out of high density polyethylene with 17 vertical layers and 150 angular divisions, as shown in Fig. 3. Two 1" Stilbene detectors were places along the axis of the cylindrical mask, coupled to 2" Hamamatsu PMTs. Fast neutron and gamma-ray counts as a function of rotation angle were separated using pulse shape discrimination in offline analysis.

Fig. 3. Overhead view of CONFIDANTE with sources to the left and right.

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Misalignment Experiments

This set of experiments placed two Cf-252 sources on opposite sides of the mask. One source was moved from exactly opposite the first source (i.e. a zero degree misalignment) to a small misalignment of 0.5 to 2.5 degrees in increments. The distance from the outside surface of the mask to the source was kept constant. Fig 4 shows the Feynman-Y as a function of time for each set of measurements, as well as a measurement of a single Cf-252 source.

The Feynman-Y is a direct test of whether the number of counts as a function of angle has a Poisson distribution around a constant mean. It is defined as

$$FY = \frac{variance}{mean} - 1$$

A perfect Poisson distribution would have a FY value of 0. A smaller FY value indicates the distribution is close to Poisson and therefore the two sources are aligned well. A larger FY value means the distribution is not Poisson and the two sources are not aligned.

The 0.5 and 1 degree misalignments are unable to be distinguished from the aligned sources for the length of dwell times explored here, but the 2.5 degree misalignment is distinguished as misaligned due to the higher FY values. This is expected as the intrinsic resolution of the mask is 2.4 degrees.

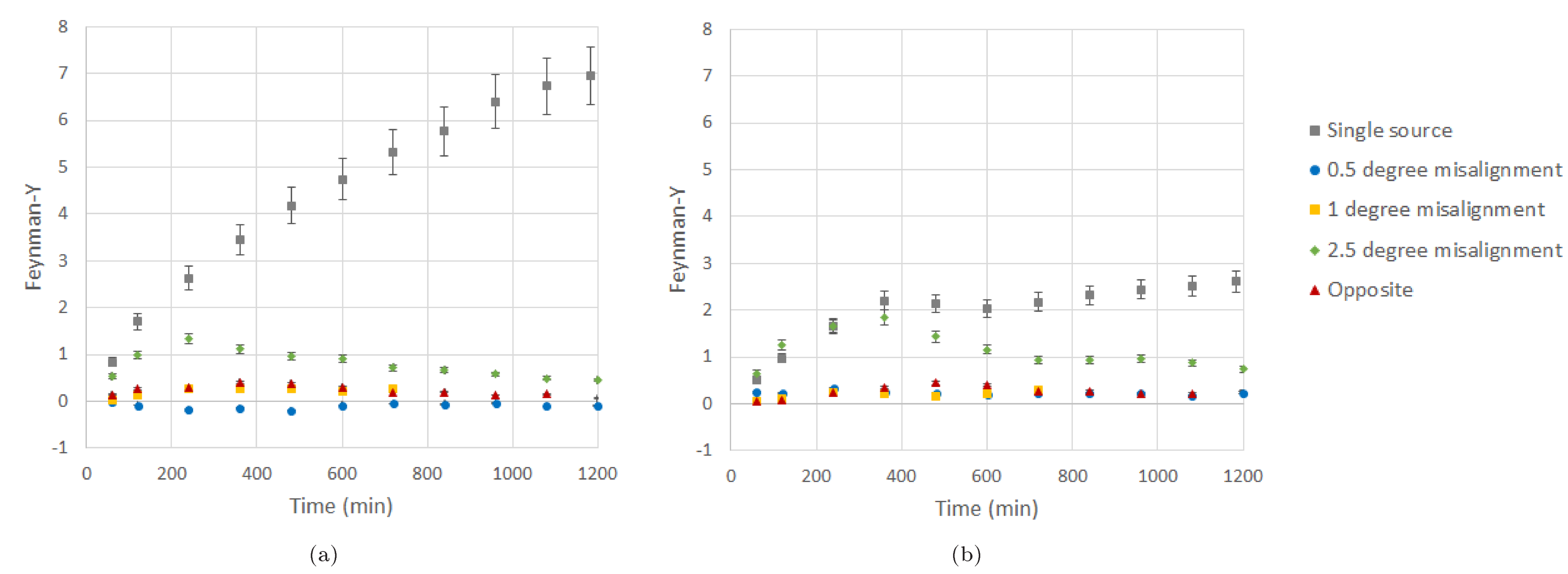

Fig. 4. Feynman-Y vs. dwell time for (a) top detector and (b) bottom detector for a single source and two sources misaligned by 0.0, 0.5, 1.0, and 2.5 degrees.

Matching Shapes

The second set of experiments used a stage to move a Cf-252 source and trace out 2D images of squares and circles. Table 1 shows the results of different combinations of shapes with different dimensions (digitally added together in post-processing). Fig. 5 shows the MLEM reconstruction of three of the shapes. Note that the metrics presented in the table are based upon the counts from the raw data and do not require image reconstruction. All images and results are based on a 1000-min dwell time.

An additional metric is included here which measures the χ^2 and p-value, where the null hypothesis is the count rate of a function of angle being constant. A p-value of less than 0.1 is considered significant and rejects the null hypothesis. Therefore, for the first set of shapes, which are matching, a low Feynman-Y and high p-value are expected; the inverse is true for the second two sets of shape, where either the shape or the dimensions are mismatched.

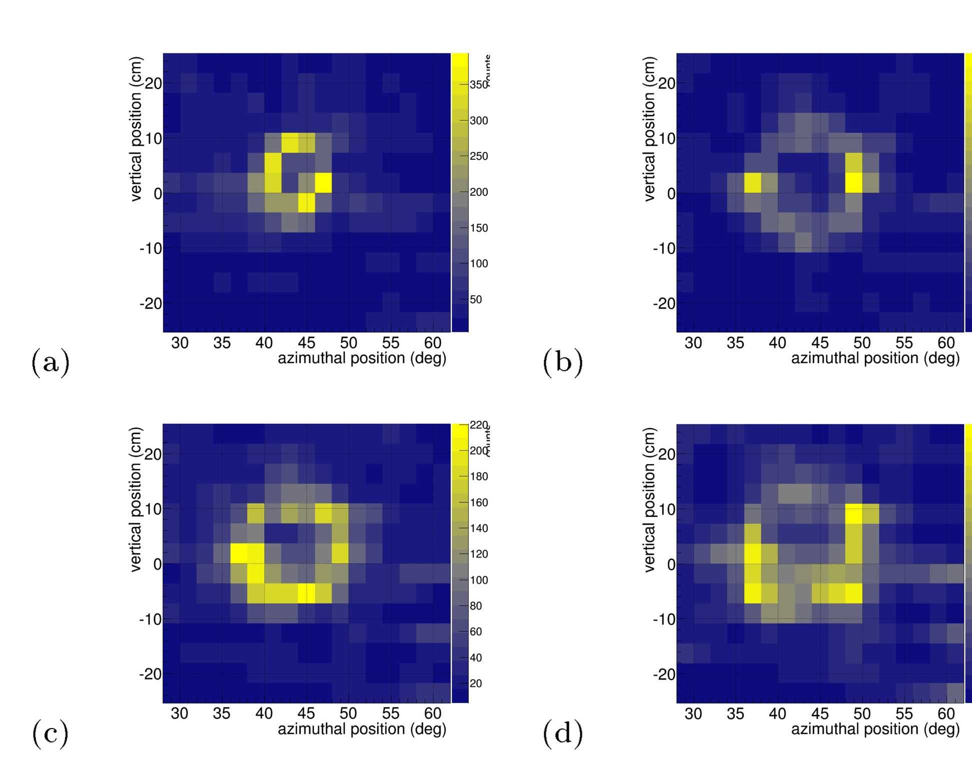

Fig. 5. MLEM reconstructions of the 12.92 cm circle (a), 20.32 cm circle (b), 16.26 cm square (c) and 20.32 cm square (d) after 1000 min.

Object 1	Object 2	Feynman-Y	P(χ^2,NDF)
Circle, 12.19 cm	Circle, 12.19 cm	-0.1472	0.7993
Circle, 16.26 cm	Circle, 16.26 cm	0.1060	0.0843
Circle, 20.32 cm	Circle, 20.32 cm	0.0808	0.1223
Circle, 24.38 cm	Circle, 24.38 cm	0.1642	0.0126
Circle, 28.45 cm	Circle, 28.45 cm	-0.0160	0.0161
Square, 16.26 cm	Square, 16.26 cm	0.1111	0.1263
Square, 20.32 cm	Square, 20.32 cm	-0.1531	0.3411
Circle, 16.26 cm	Square, 16.26 cm	0.2244	0.0006
Circle, 20.32 cm	Square, 20.32 cm	0.1987	0.0000
Circle, 12.19 cm	Circle, 16.26 cm	0.3237	0.0000
Circle, 12.19 cm	Circle, 20.32 cm	0.6086	0.0000
Circle, 12.19 cm	Circle, 24.38 cm	0.9249	0.0000
Circle, 12.19 cm	Circle, 28.45 cm	0.9227	0.0000
Circle, 12.19 cm	Square, 16.26 cm	0.4786	0.0000
Circle, 12.19 cm	Square, 20.32 cm	0.7044	0.0000

Table 1. Results from combining different sizes of circles (diameter) and squares (side length) traced out by a Cf-252 source.

Conclusions and Future Work

These experiments explored the sensitivity of CONFIDANTE to misalignment and to different shapes and sizes of objects. While very small angle misalignments could not be seen, larger misalignments could be distinguished. The appropriate or sufficient length of time to distinguish between misalignments requires further investigation, as some of the metrics were inconsistent for very long dwell times.

The second set of experiments showed that CONFIDANTE functions very well at distinguishing between circles of different sizes and consistently getting the null hypothesis for shapes of matching sizes. Distinguishing between circles and squares close in size was possible but not as significant. Further analysis is needed to determine if length of dwell time or other factors are affecting the ability to distinguish between two similarly sized but differently shaped objects.

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