INSTITUTE FOR DEFENSE ANALYSES

DATAWorks 2021:
Warhead Arena Analysis Advancements

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April 2021

Approved for Public Release.
Distribution Unlimited.

IDA Document NS-D-11038

Log: H 2021-000047

INSTITUTE FOR DEFENSE ANALYSES
4850 Mark Center Drive
Alexandria, Virginia 22311-1882

About This Publication
This work was conducted by the Institute for Defense Analyses (IDA) under contract HQ0034-19-D-0001, Task C9107, "Live Fire Methodology Advancements." The views, opinions, and findings should not be construed as representing the official position of either the Department of Defense or the sponsoring organization.

Acknowledgments
The IDA Technical Review Committee was chaired by Mr. Robert R. Soule and consisted of Dr. Rebecca Medlin, Mr. Kelso Horst, Ms. Pamela Rambow, Mr. Raymond Shetzline, and Dr. William Gardner from the Operational Evaluation Division.

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Executive Summary

Warhead fragmentation characterization is typically a critical piece of both lethality and vulnerability LFT&E assessments. Traditional methods for data collection in warhead arena tests using soft-catch bundles are expensive and laborious, but new optical tracking technology promises to increase the fidelity of fragmentation data, and decrease the time and costs associated with data collection.

However, with this increase in data fidelity, the new data will be complex, three-dimensional "fragmentation clouds," including information describing each of the individual fragments, and there will be a larger number of individual data points. This raises questions about how testers can effectively summarize spatial data and use it to draw conclusions about warhead performance for sponsors.

IDA funded a project through its Central Research Program to develop new methodologies to take this higher quality data and improve the lethality analyses. In this briefing, we will discuss Bayesian spatial models that are effective for characterizing the mass and velocity fragmentation distributions, along with several exploratory data analysis techniques that help us make sense of the data. Our goals are to:

- Produce simple statistics and visuals that help the live fire analyst compare and contrast warhead fragmentations.
- Characterize important performance attributes or confirm design/spec compliance.
- Provide data methods that ensure higher fidelity data collection translates to higher fidelity modeling and simulation down the line.

Due to the limited availability of optical tracking data at this time, we demonstrate the first part of our analysis methods on data that was generated using Extended Legacy Statistical Analysis (ELSA) Modeling and Simulation (M&S), which is a warhead fragmentation code developed by the Naval Air Warfare Center Weapons Division.

The ELSA data is a useful substitute because it has a similar format to the data we anticipate to see with optical tracking. In the second part of this project, we plan to work through the practical challenges of applying these analysis methods to optical tracking data. It will also explore techniques for determining the number of warheads to detonate, as well as methods for integrating M&S results with optical tracking results.

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04/12/2021

By Tom Johnson, John Haman, Kerry Walzl, Heather Wojton and Mark Couch

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Naval Air Warfare Center Weapons Division, China Lake, Ridgecrest, CA

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Advances in data collection accommodate new statistical analyses

Traditional Arena testing

- Slow, manually intensive

But importantly for our work…

- Zonal data (Z-data) is low resolution
    - provides mass and velocity within zones
    - One measure per zone
    - Kludges detonations together

Setting up an "arena"

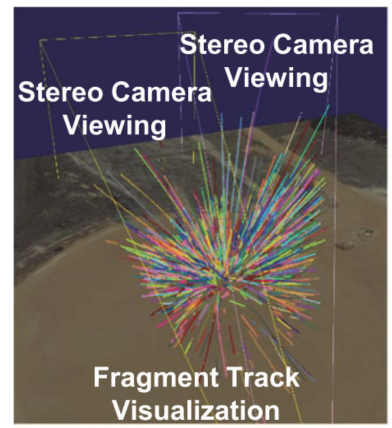
Optical tracking

- Full 3D view
- High resolution data
- Emerging technology

IDA Research:

- How should we analyze the new data?

High Speed Cameras may soon replace soft-catch bundles and time of arrival screens



What we have done

Optical tracking requires new statistical analyses to use all the data

We proposed exploratory data analyses, because

- We need a simple summary statistic to compare and contrast detonations

We developed a novel model for complex data, because

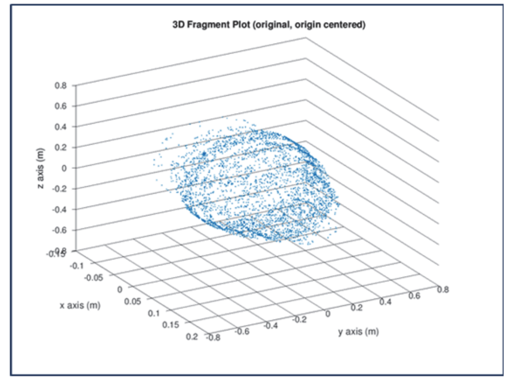
- A model based on observed detonations is a prerequisite for generating results for use in AJEM
- Models provide a basis for sample size determination

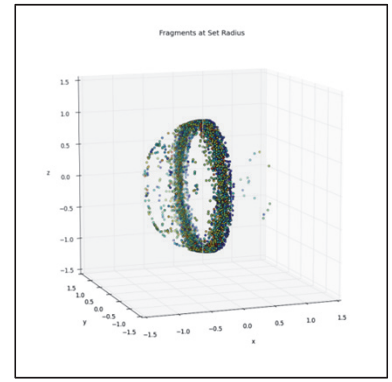
We demonstrate our analysis concept on ELSA M&S data

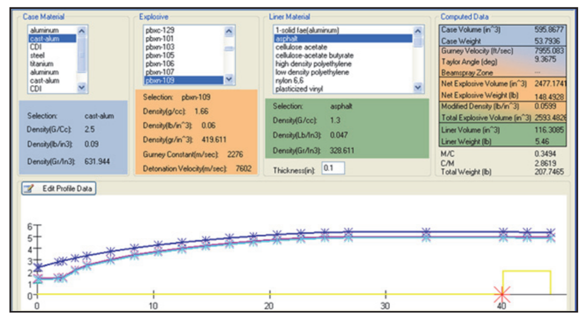
- Extended Legacy Statistical Analysis (ELSA) is a fast-running fragmentation M&S code developed and maintained by the NAVAIR Lethality Analysis Group at China Lake

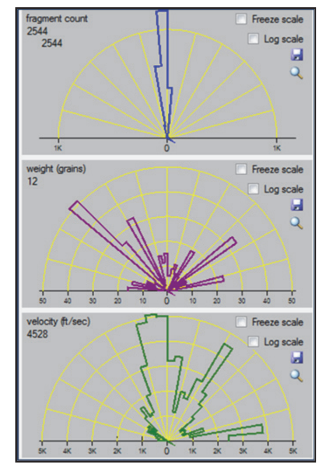
- ELSA M&S output has a similar format as the anticipated data from the new test instrumentation

- We generated 25 ELSA data sets to demonstrate our concept







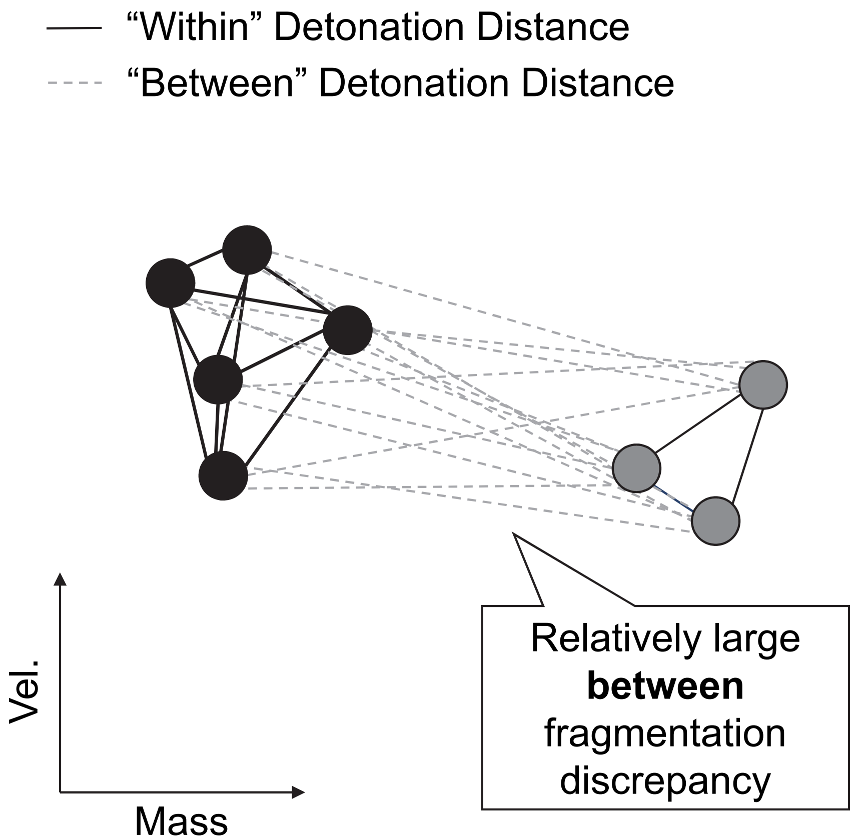


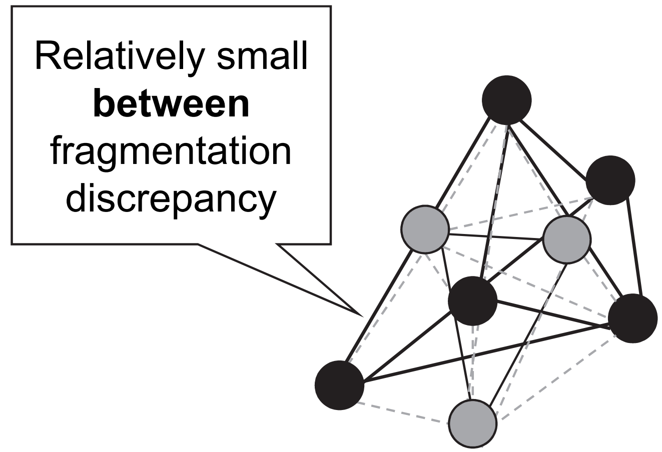
Why do we use EDA techniques?

We propose two techniques for different high level questions

1. **Goodness-of-fit statistics (Energy test)**
   - Are the detonations similar or different?
2. **Data transformations (Box-Cox)**
   - Is there any correlation between the warhead characteristics?

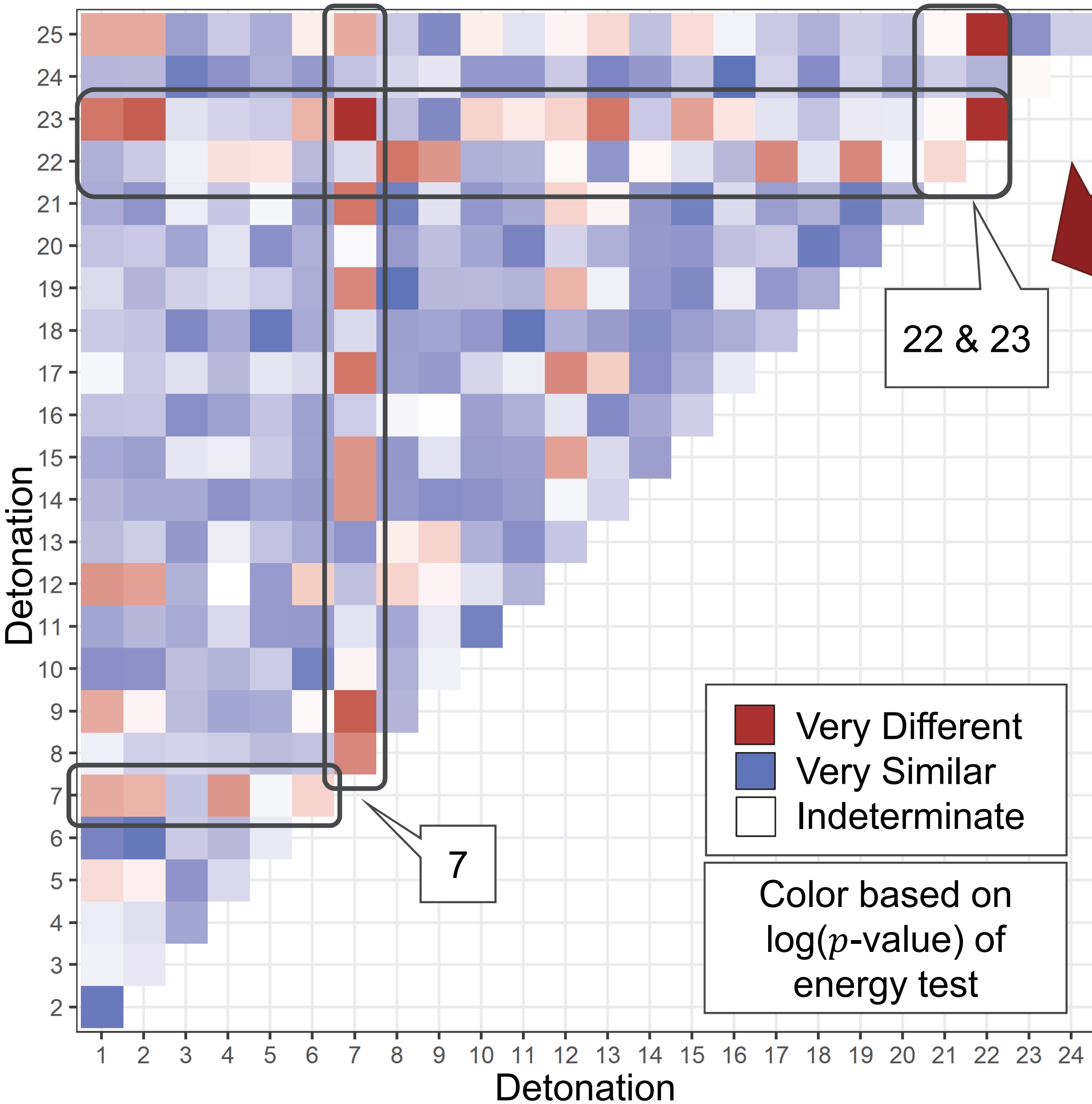
The energy test detects differences between detonations





The energy test is a powerful, non-parametric test that alerts us to significant differences in the multivariate mass/velocity distributions between detonations

Compare all detonations against each other with two-sample energy tests



We can find detonations that statistically differ from other detonations in our collection

<u>In ELSA data:</u>

- Detonations 7, 22, and 23 may differ the most when compared to all other detonations
- Perhaps #12 is also peculiar…

We use a power transform to convert highly skewed fragmentations to symmetric distributions

Variable transforms are a simple way to make the data more symmetric.

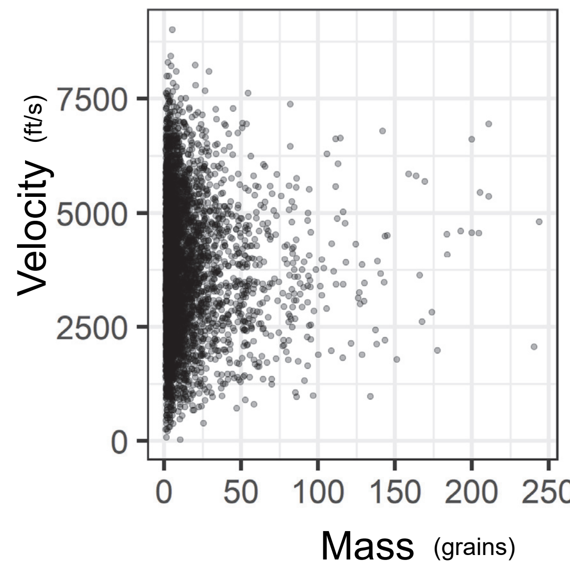
Otherwise, means and variances do not summarize the data well.

Box-Cox transform is a traditional transform that brings skewed data towards a Normal distribution:

$$\left\{ \begin{aligned} \text{B. C. Mass} &= \frac{Mass^{\lambda} - 1}{\lambda} \\ \text{B. C. Velocity} &= \frac{Velocity^{\theta} - 1}{\theta} \end{aligned} \right\}$$

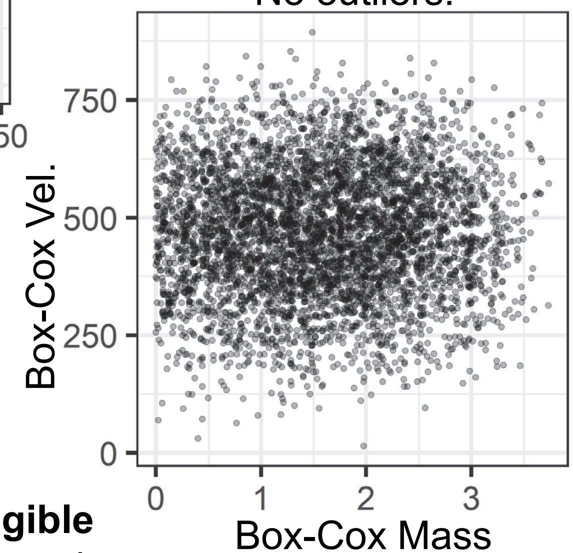
λ and θ chosen optimally for a set of fragmentations

Ugly raw fragmentation data



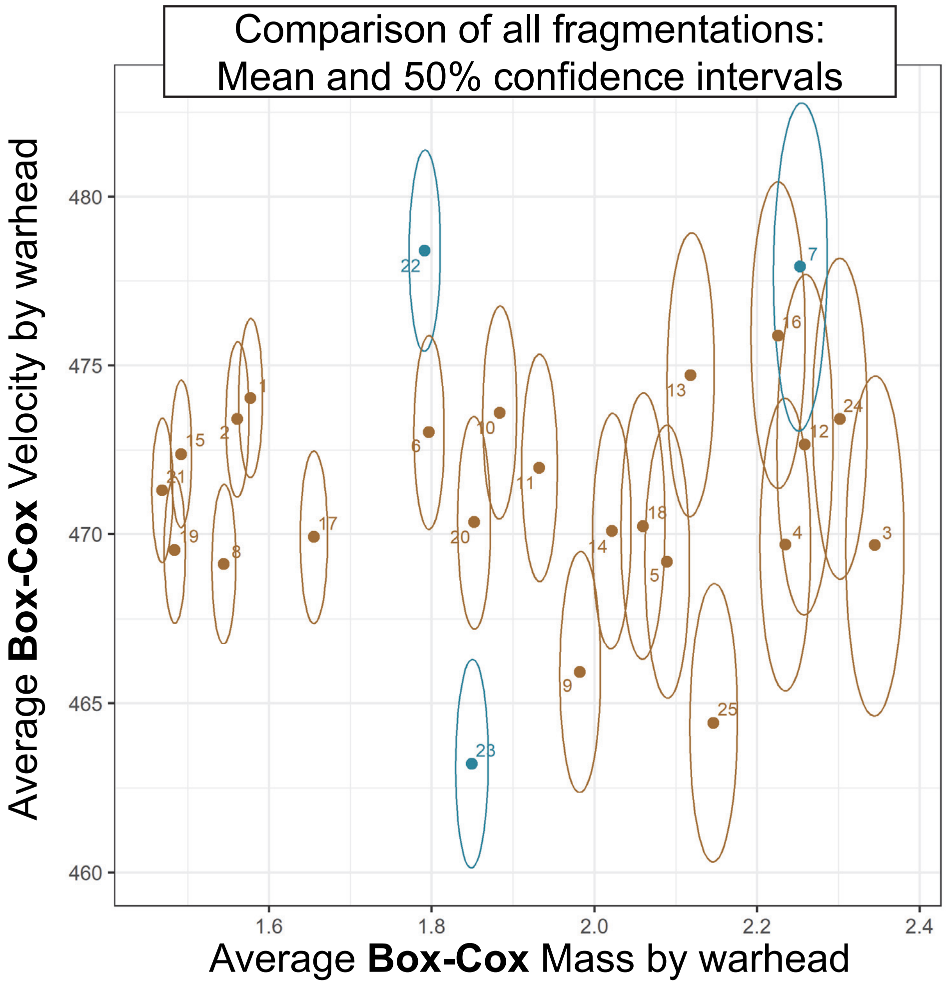
Box-Cox power transform!

Clean and beautiful data, No outliers!



Transforming reveals **negligible correlation** between Mass and Velocity (no patterns)

Clusters and correlations across all fragmentations



- Variance within and between detonations increases with mass and velocity
  - # 7 has fastest average velocity and very high average mass
  - # 22 also has a high velocity, and isn't part of a cluster
  - # 23 has lowest velocity, and differs significantly from other warheads
  - Several clusters of similar fragmentations appear

Confidence intervals are not tilted → Negligible correlation between mass and velocity

- But if a correlation was present, we would have detected it

- ~Normal data → Analysis of Variance

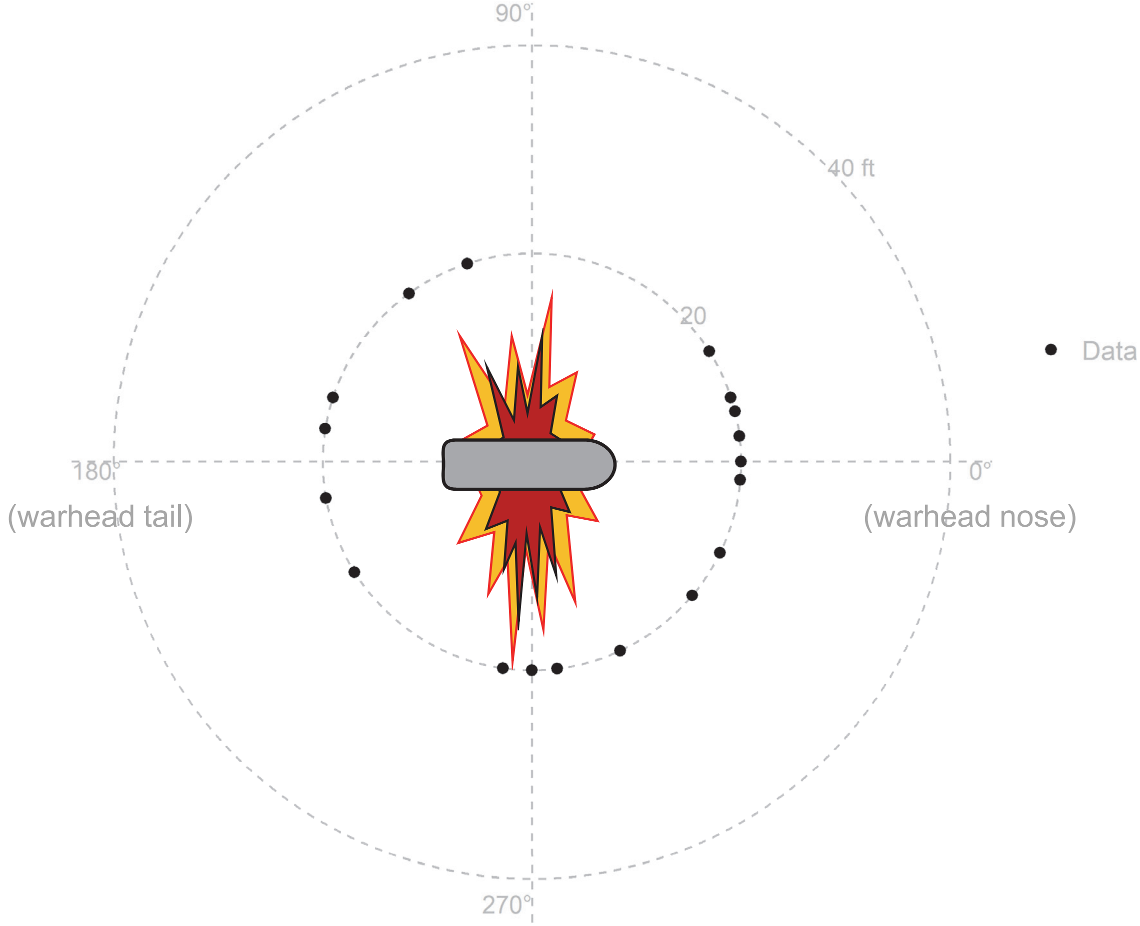
Warhead Fragmentation Model

We formulate a model to make use of full 3D data

- We propose a Bayesian Spatial Process Convolution Model
- Features of this model include:
  - Custom built, not available “off the shelf”
  - Compatible with ELSA M&S, optical tracking, and finite element method data
  - Accommodates smooth, continuous predictions across the entire factor space
  - Is adaptable, which will be useful for data fusion, and for integrating with AJEM
  - Inference is straightforward, which will be useful for comparison and validation
  - Computationally efficient for many data points and few factors

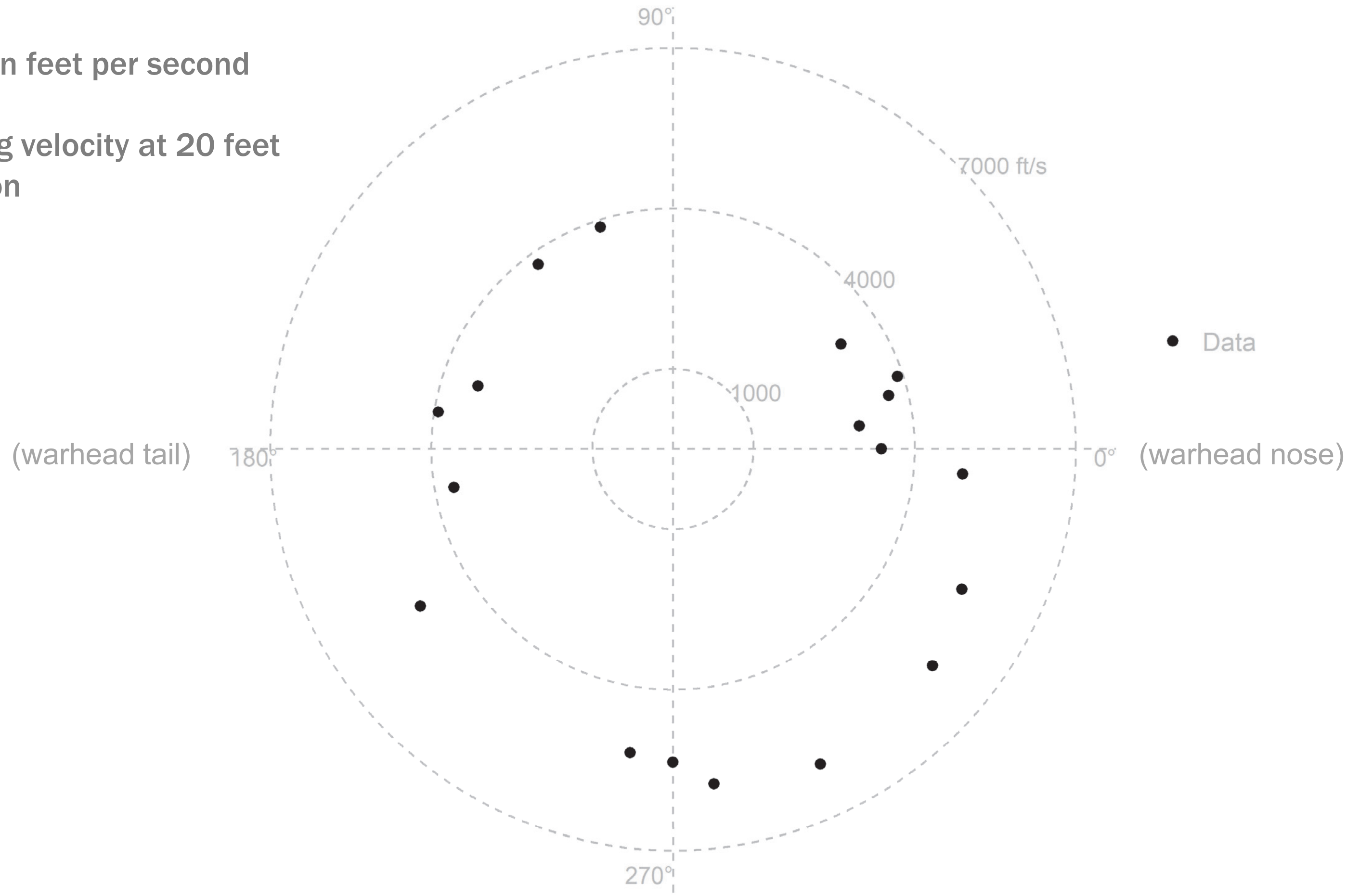
To illustrate the model, consider a simple example

- A warhead detonation disperses 18 frags
- This is a top view of an arena test
- Axes show the distance from the warhead detonation
- We want to model frag characteristics (i.e., mass, velocity, density) when the frags are 20 feet from the detonation



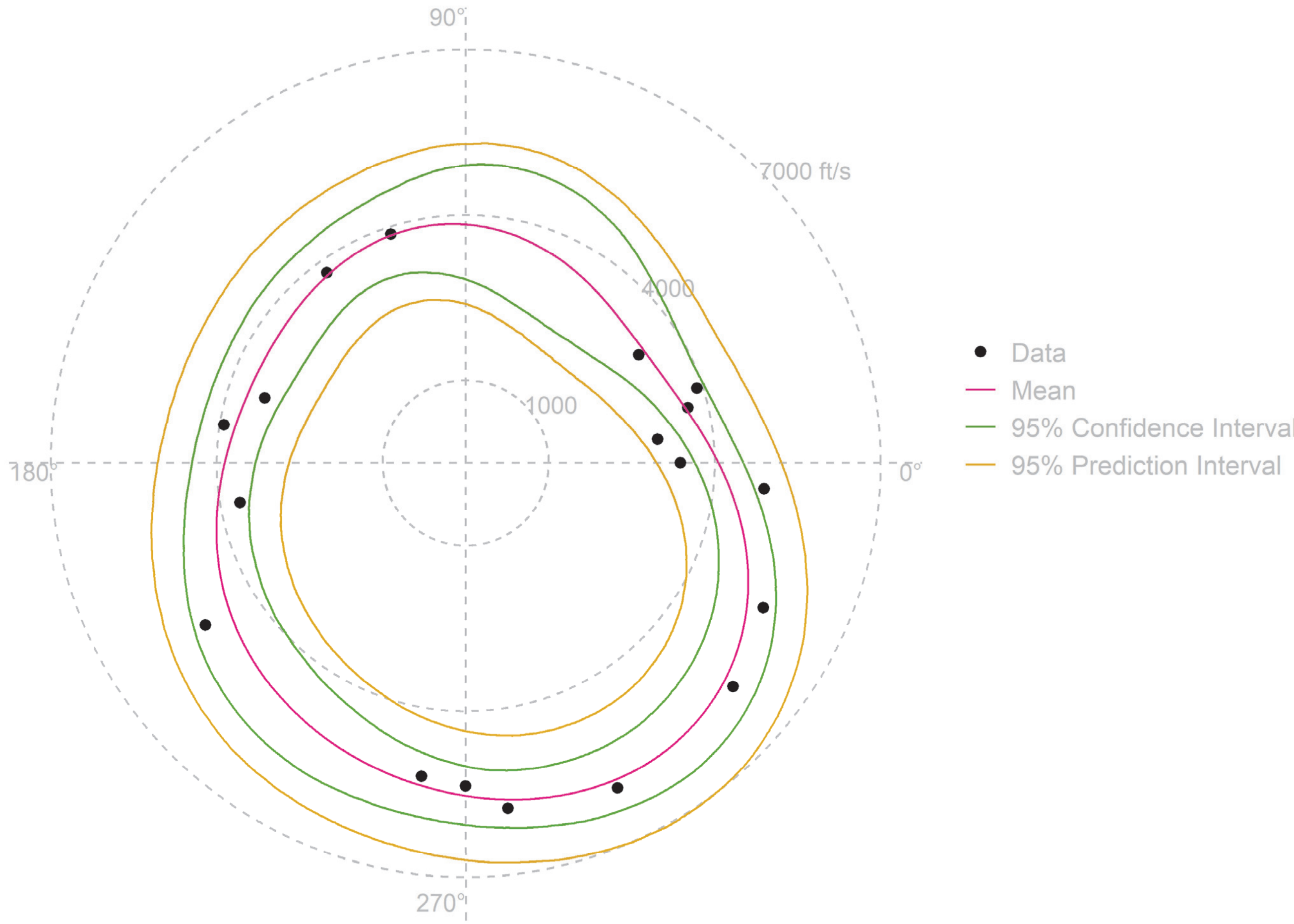
Here is the velocity of each frag

- The axes are now in feet per second
- The data is the frag velocity at 20 feet from the detonation



Here is the model fit to the velocity frag data

- The model is called a "Bayesian Spatial Process Convolution Model"[1]
- The mean is continuous from 0 to 360 degrees.
- There is a 95 percent probability that the mean would lie between the confidence interval
- There is a 95 percent probability that the data would lie between the prediction interval

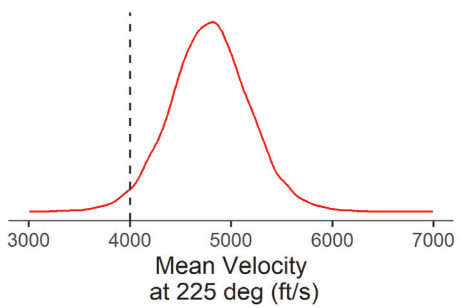


* Note that the confidence interval is actually a credible interval, and the prediction interval is a posterior predictive interval, but we've streamlined terms for this brief.

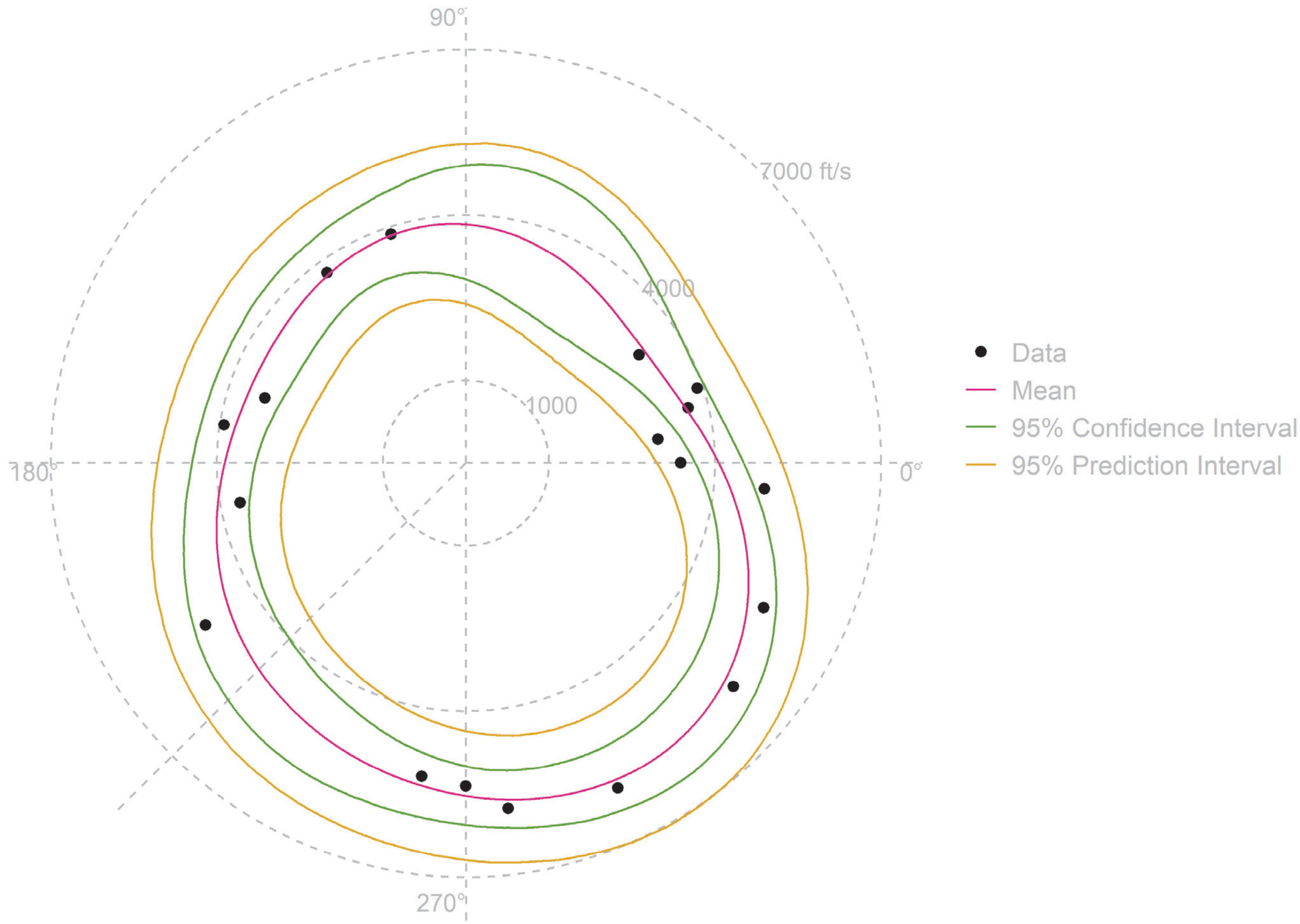
[1] Higdon, Dave. "Space and space-time modeling using process convolutions." In *Quantitative methods for current environmental issues*, pp. 37-56. Springer, London, 2002.

Inference and uncertainty quantification is built into this model

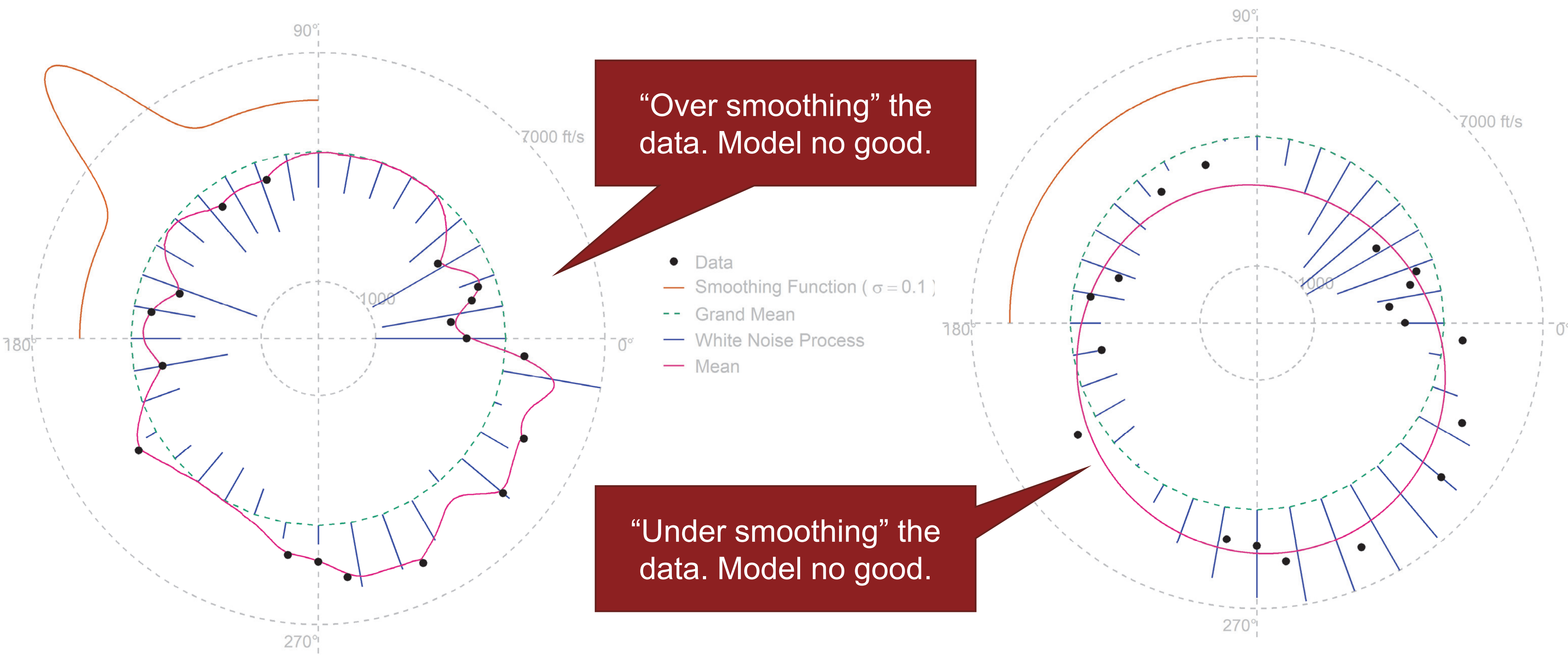
Is the mean velocity at 225 deg greater than 4000 ft/s?



There's a 98 percent chance that the mean velocity at 225 deg is greater than 4000 ft/s.



How do we know which model is a good fit? Two extremes:



"Over smoothing" the data. Model no good.

"Under smoothing" the data. Model no good.

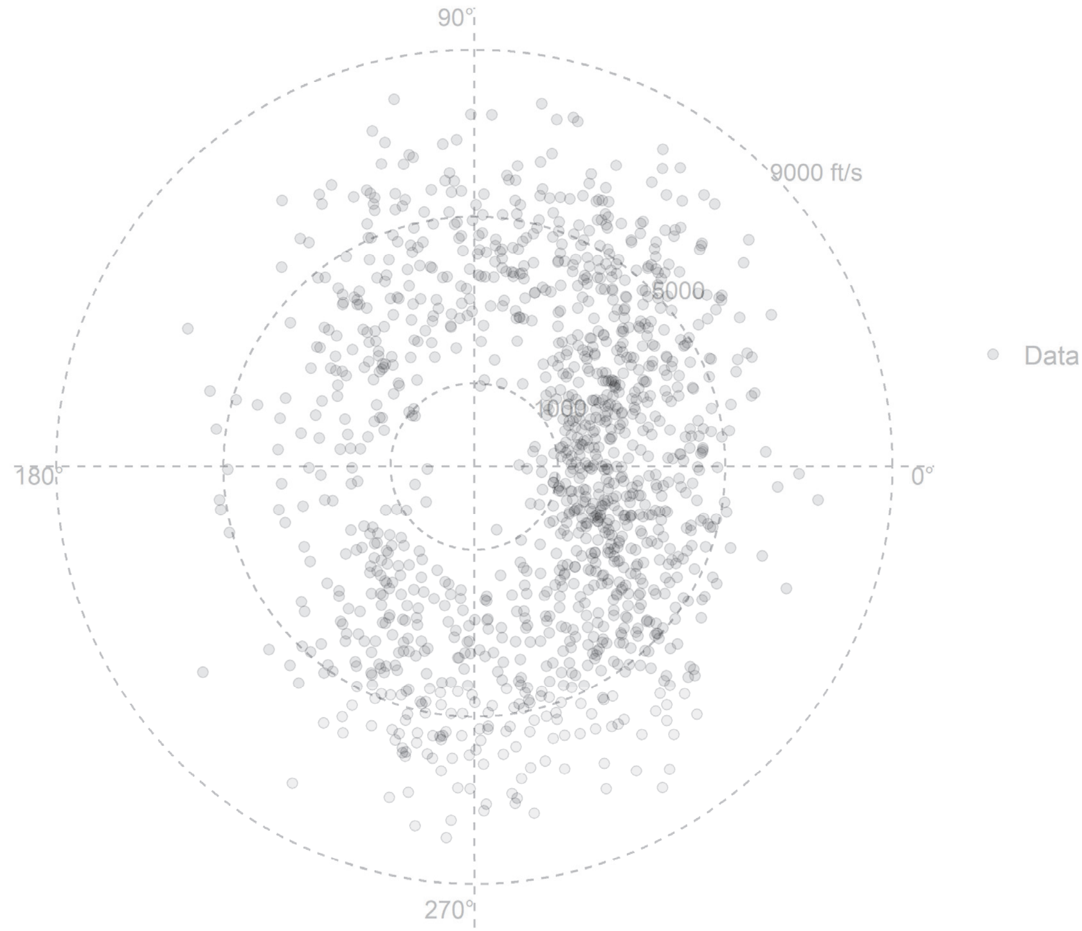
We optimize a Bayesian probability to find a good compromise.

Circular Warhead Fragmentation Model

Fit to ELSA Data

Here is the ELSA velocity data

- Data is from detonation #7
- There are 1,256 fragments
- Velocities are observed at 20 feet from the detonation
- In its original form, the data is spherical, but we've projected it to a circle (i.e., collapsed it to a top-down view)



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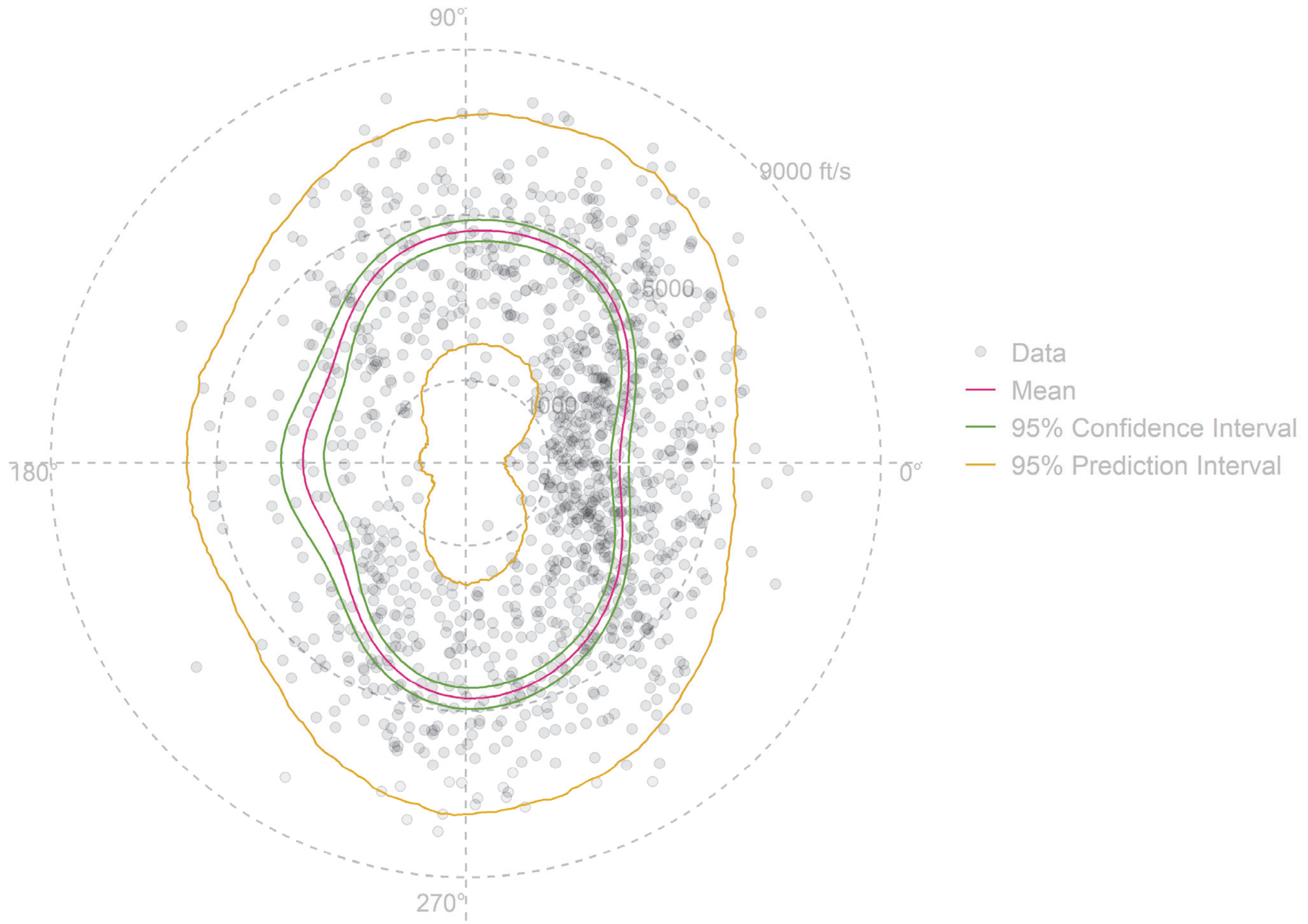
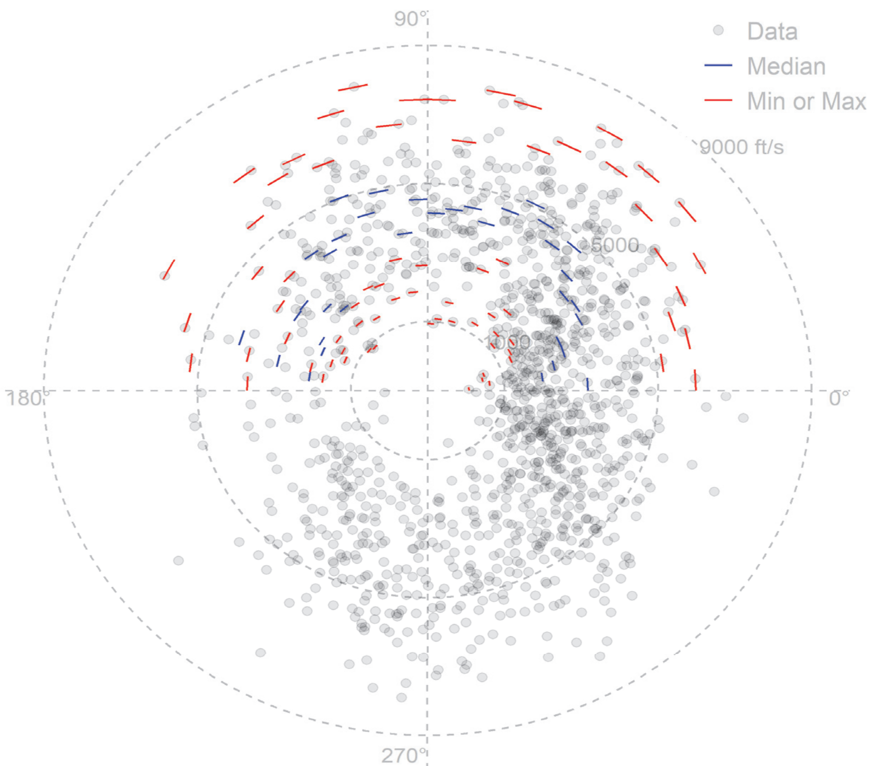


A Z-data file is a worse model of the data

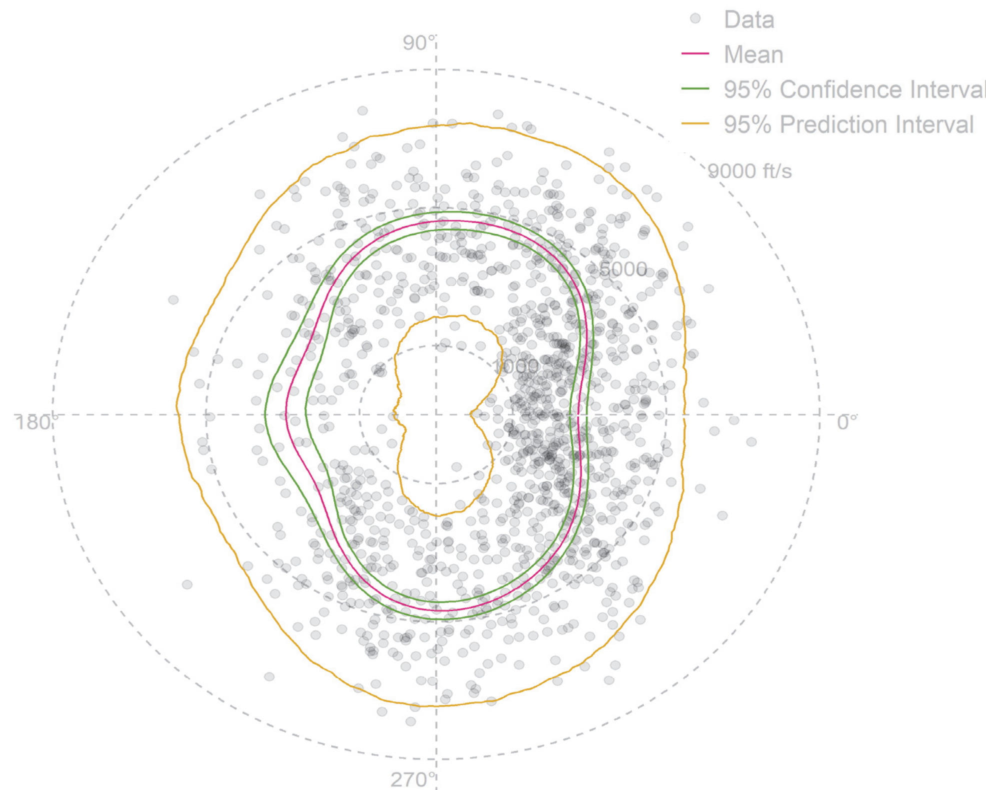
Z-data Representation of Fragment Velocity

- Z-data files bin the data, and compute median, min
- No statistical inference, poor uncertainty quantification
- Assumes symmetry, susceptible to over-fitting



New Model Representation of Fragment Velocity

- This model is fit across all the data
- Enables statistical inference, better prediction accuracy, and better uncertainty quantification



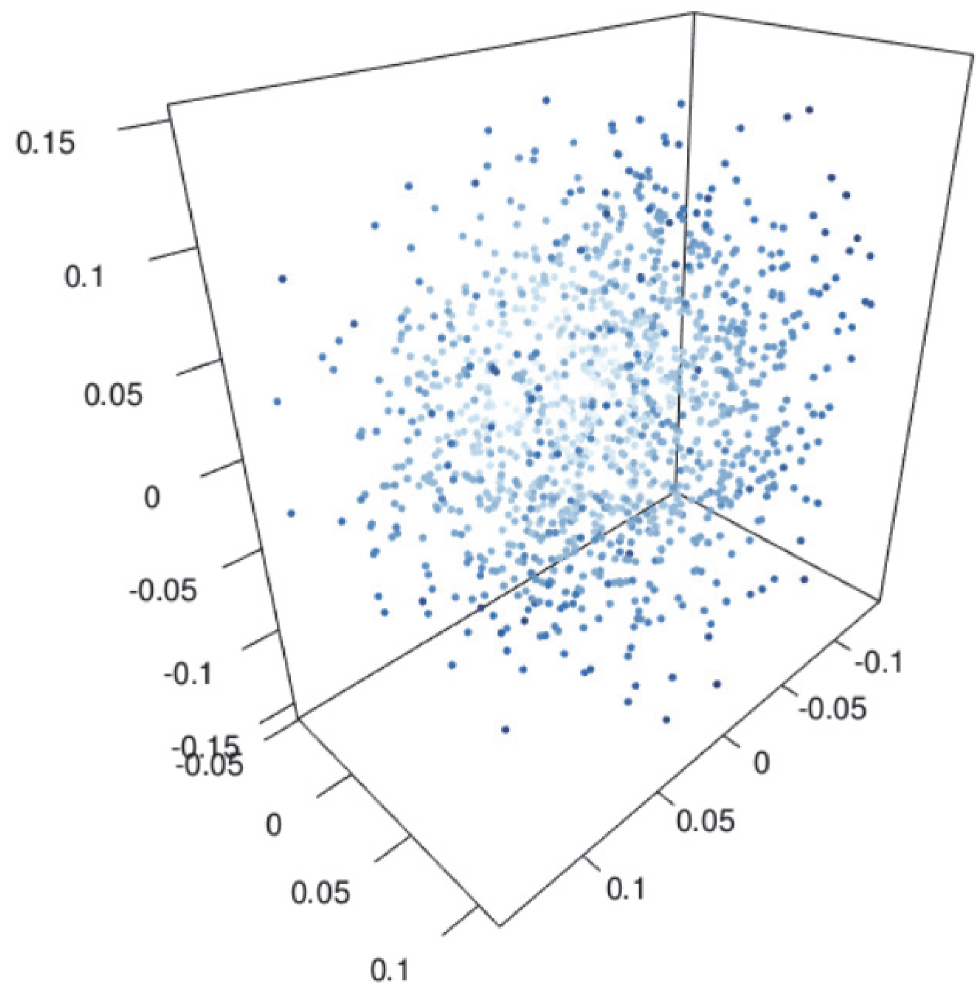
Spherical Warhead Fragmentation Model

Fit to ELSA Data

Raw data from detonation #7

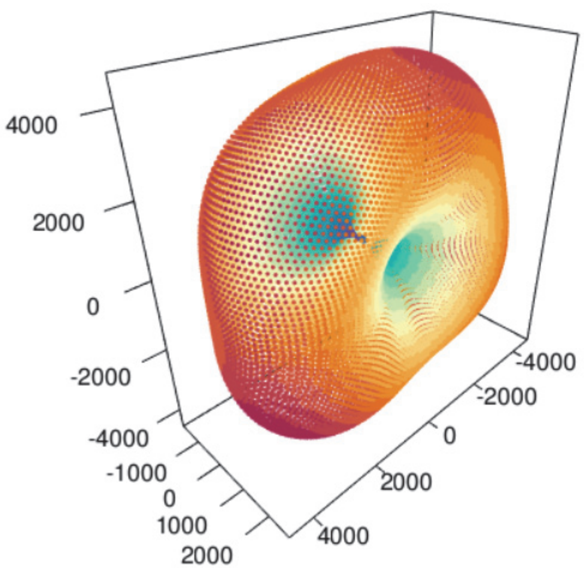
Three-dimensional fragmentation data

- X,Y,Z coordinates of the positions of fragments
- The positional data is hard to interpret
- Statistical models reveal patterns in data



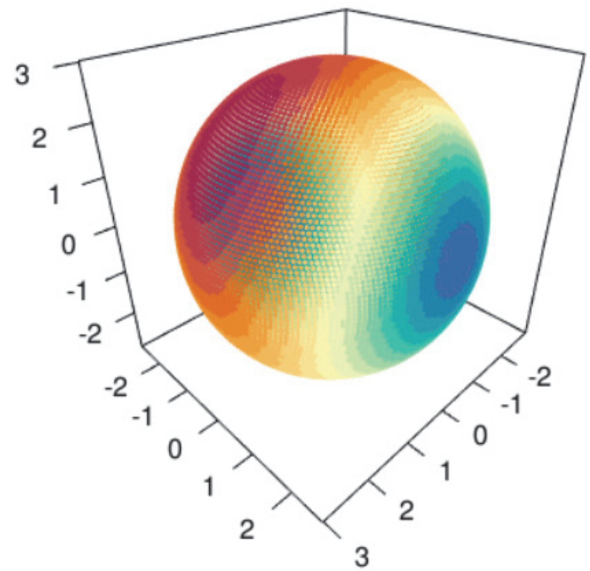
Spherical model fit results – predicted fragment mass, velocity, density

Fragment Velocity



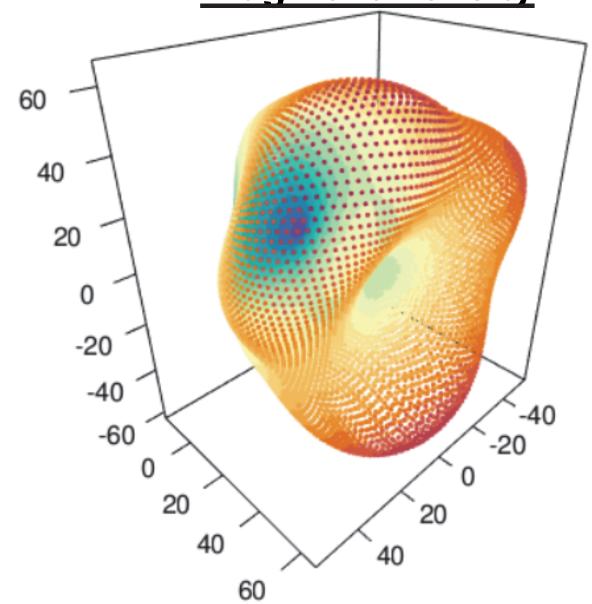
Square Donut

Fragment Mass



Sphere

Fragment Density



Dutch Baby?

Summary and Impact

- Without better data analysis methods, optical tracking improvements may not be realized in our evaluations
- Improving analysis means improvements to lethality & vulnerability M&S fidelity

Future Work

- Sample size determination
- Confidence bands that preserve physical properties
- Model checking strategies
- Easy to use R package for the above

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*
12-04-2021

2. REPORT TYPE
Presentation

3. DATES COVERED *(From - To)*

4. TITLE ANDSUBTITLE
DATAWorks 2021: Warhead Arena Analysis Advancements

5a. CONTRACT NUMBER
Separate Contract

5b. GRANT NUMBER
____ ____ ____

5c. PROGRAM ELEMENT NUMBER
____ ____ ____

5d. PROJECT NUMBER
C9107

5e. TASK NUMBER
C9107

5f. WORK UNIT NUMBER
____ ____ ____

6. AUTHOR(S)
John T. Haman (OED); Thomas H. Johnson (OED); Mark A. Couch (OED); Heather M. Wojton (OED); Kerry N. Walzl (OED); Higdon, David (N/A); Thomas Hatch-Aguilar (N/A)

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Institute for Defense Analyses
4850 Mark Center Drive
Alexandria, Virginia 22311-1882

8. PERFORMING ORGANIZATION REPORT NUMBER
NS-D-11038
H 2021-000047

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Institute for Defense Analyses
4850 Mark Center Drive
Alexandria, Virginia 22311-1882

10. SPONSOR/MONITOR'S ACRONYM(S)
IDA

11. SPONSOR/MONITOR'S REPORT NUMBER
____ ____ ____

12. DISTRIBUTION / AVAILABILITY STATEMENT
Approved for Public Release. Distribution Unlimited.

13. SUPPLEMENTARY NOTES

14. ABSTRACT
Fragmentation analysis is a critical piece of the live fire test and evaluation (LFT&E) of the lethality and vulnerability aspects of warheads. But the traditional methods for data collection are expensive and laborious. New optical tracking technology is promising to increase the fidelity of fragmentation data, and decrease the time and costs associated with data collection.
However, the new data will be complex, three-dimensional “fragmentation clouds,” possibly with a time component as well, and there will be a larger number of individual data points. This raises questions about how testers can effectively summarize spatial data and use it to draw conclusions about warhead performance for sponsors.
In this briefing, we will discuss Bayesian spatial models that are effective for characterizing the mass and velocity fragmentation distributions, along with several exploratory data analysis techniques that help us make sense of the data. Our goals are to:
- Produce simple statistics and visuals that help the live fire analyst compare and contrast warhead fragmentations.
- Characterize important performance attributes or confirm design/spec compliance.
- Provide data methods that ensure higher fidelity data collection translates to higher fidelity modeling and simulation down the line.
This talk is a version of the first-step feasibility study IDA is taking – hopefully much more to come as we continue to work on this important topic.

15. SUBJECT TERMS
Bayesian Statistics, Energy Statistics, Live Fire Test and Evaluation, Modeling and Simulation

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
					Mark Couch (OED)
Unclassified	Unclassified	Unclassified	Unlimited	31	**19b. TELEPHONE NUMBER** *(include area code)* (703) 845-2530

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI std. Z39.18