150 YEARS FEATURING FUTURE
1872 - 2022

UNIVERSITY OF NATURAL RESOURCES AND LIFE SCIENCES, VIENNA

Comparison and Validation of Ice Throw Models

Markus Drapalik

University of Natural Resources and Life Sciences, Vienna

Institute of Safety and Risk Scienes

Institute of Safety and Risk Sciences

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- Focus on Technology Assessment and Shaping
- Roots in Nuclear Safety
- Now Energy Technologies and Biotechnology

- Comparison of safety assessment between nuclear and ice throw shows lack of validation for ice throw

- Missing standards (still in development) but also lack of knowledge/data

Safety from Ice Throw

- Started with question of minimum safety distances
- First only rough estimates available (but based on observations)

$$\text{ice throw distance} = (D + H) \cdot 1.5$$

$$\text{ice shed distance} = \frac{v(D/2 + H)}{15}$$

v … wind speed, D…rotor diameter, H…nacelle height

- Current standard: Monte-Carlo Simulation using a ballistic model usually Biswas model (simple, but solid physics)
- Recent studies prove it to be conservative with respect to maximum distance

Biswas model (2D)

$$m\ddot{x} = -\frac{1}{2}\rho A c_D v_{rel}(\dot{x} - v_w)$$

$$m\ddot{z} = -mg - \frac{1}{2}\rho A c_D v_{rel}\dot{z}$$

v_{rel} … relative wind speed, m…fragment mass, A…fragment area, C_D…drag factor, ρ air density v_w…wind speed (only in x-direction)

- Is that enough?
- Yes – in simple terrain, given enough free space, no nearby infrastructure
- Otherwise – maybe not

Open Questions

- What is the relevant safety information?
  - Maximum distance?
  - Distance at which the local risk is below a certain threshold?
  - Local risk at any point in th vicinity of the turbine?

- How can the relevant information be validated?
  - Observations?
  - Experiments?

- How can the accuracy of the models be quantified?

Experimental Validation Approach

- Validation by observation is difficult (many unknown variables)
- Experimental approach chosen

- Identical replicas of collected ice fragments thrown from wind turbines

- Measured:
  - Trajectories
  - Impact locations
  - Wind speed (1 s interval)

Experimental Validation Approach

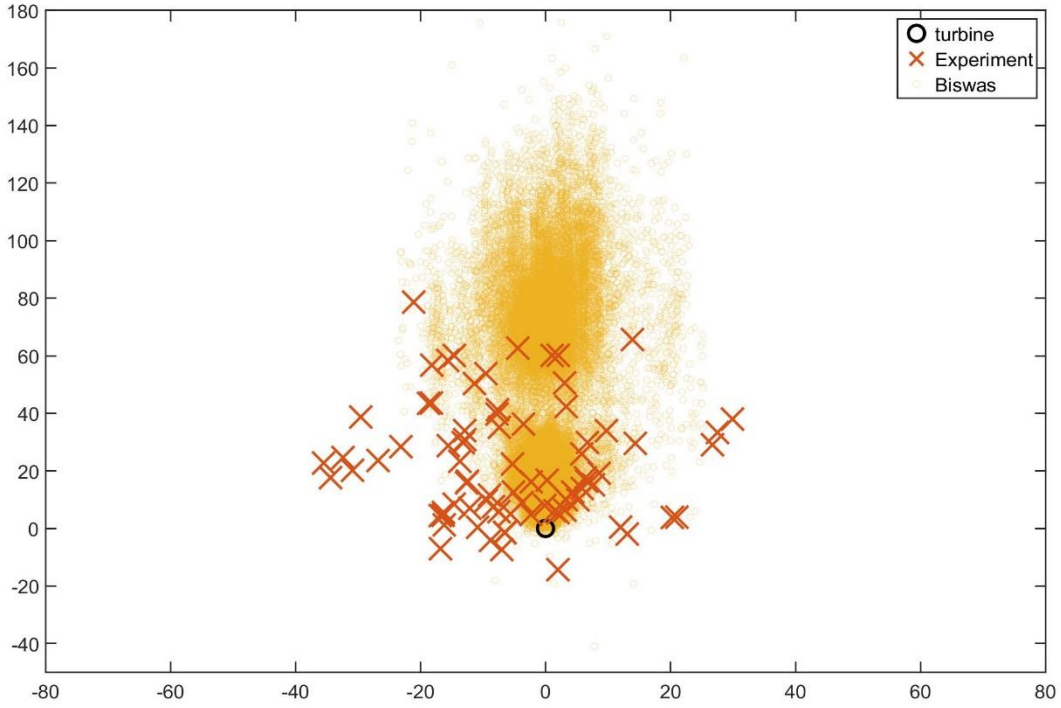
- Direct comparison with model predictions possible
- Ice fragment properties (geometry, density) well known

- For each measured experimental throw 500 simulated throws are calculated
- Initial conditions are varied according to uncertainties of experiments
- Random variations in wind field added

Biswas Model vs. Experimental Data

- Wind vector is normalized to positive y-direction
- Multiple drop heights
- One type of ice fragment (24 cm, 400 g, 147 cm²)

- **Results**
- Conservative for maximum distance in wind direction
- Low agreement with experimental distribution
- Hardly any movement normal to wind direction (model constraint)
- Possibly problematic if pronounced wind directions

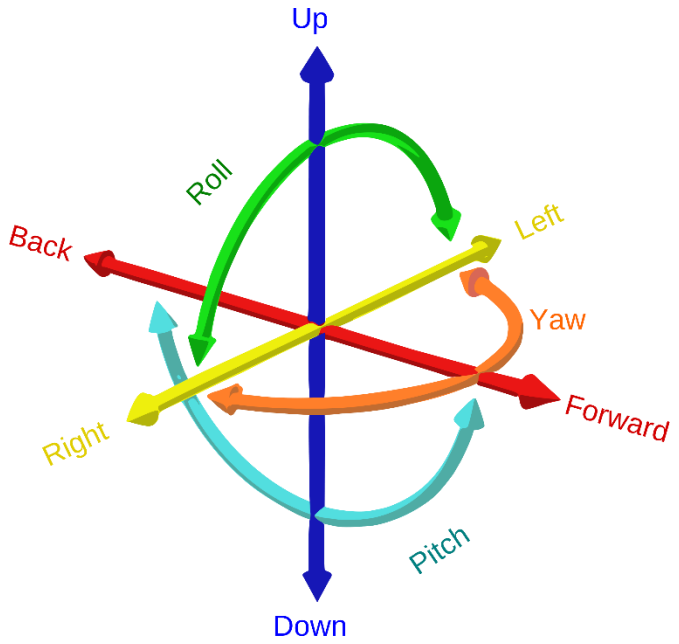


Alternative Six-Degree-of-Freedom-Model

- Allows rotation of the ice fragment
- Lift and drag change according to the apparent wind

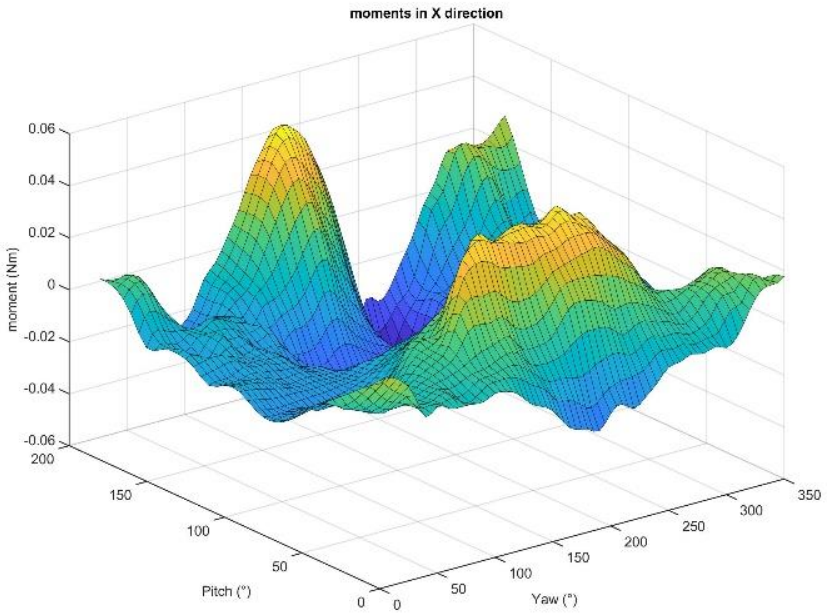
- $\ddot{X} = \frac{F}{m} + g$
- $\ddot{\theta} = J^{-1} M \cdot \exp\left(-3 \cdot \frac{\dot{\theta}^2}{{\omega_{max}}^2}\right)$

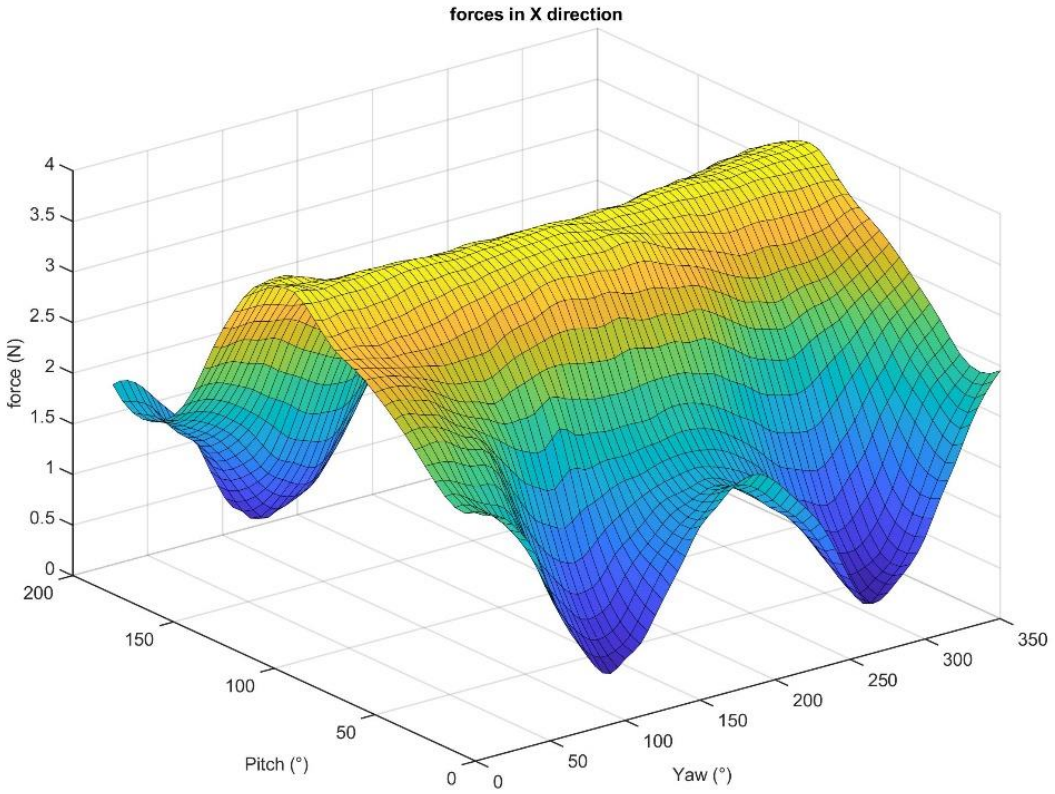
- $F(\mathrm{v_{rel}})$ and $M(\mathrm{v_{rel}})$ tabulated functions from CFD calculations
- Exp term to avoid infinite rotational velocity



Alternative Six-Degree-of-Freedom-Model

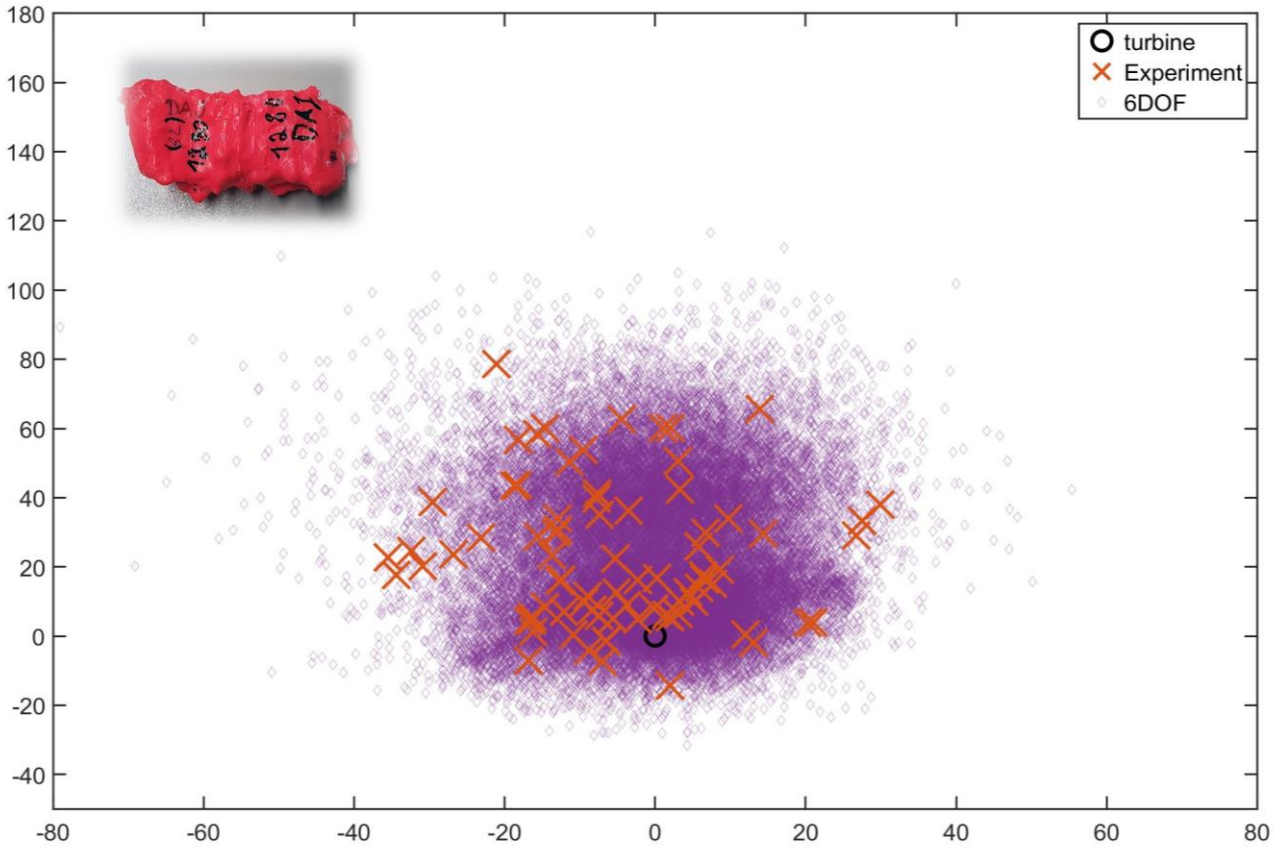
- Force and Moment are pre-calculated in a stationary setting in OpenFOAM
- Results specific for the analyzed ice fragment





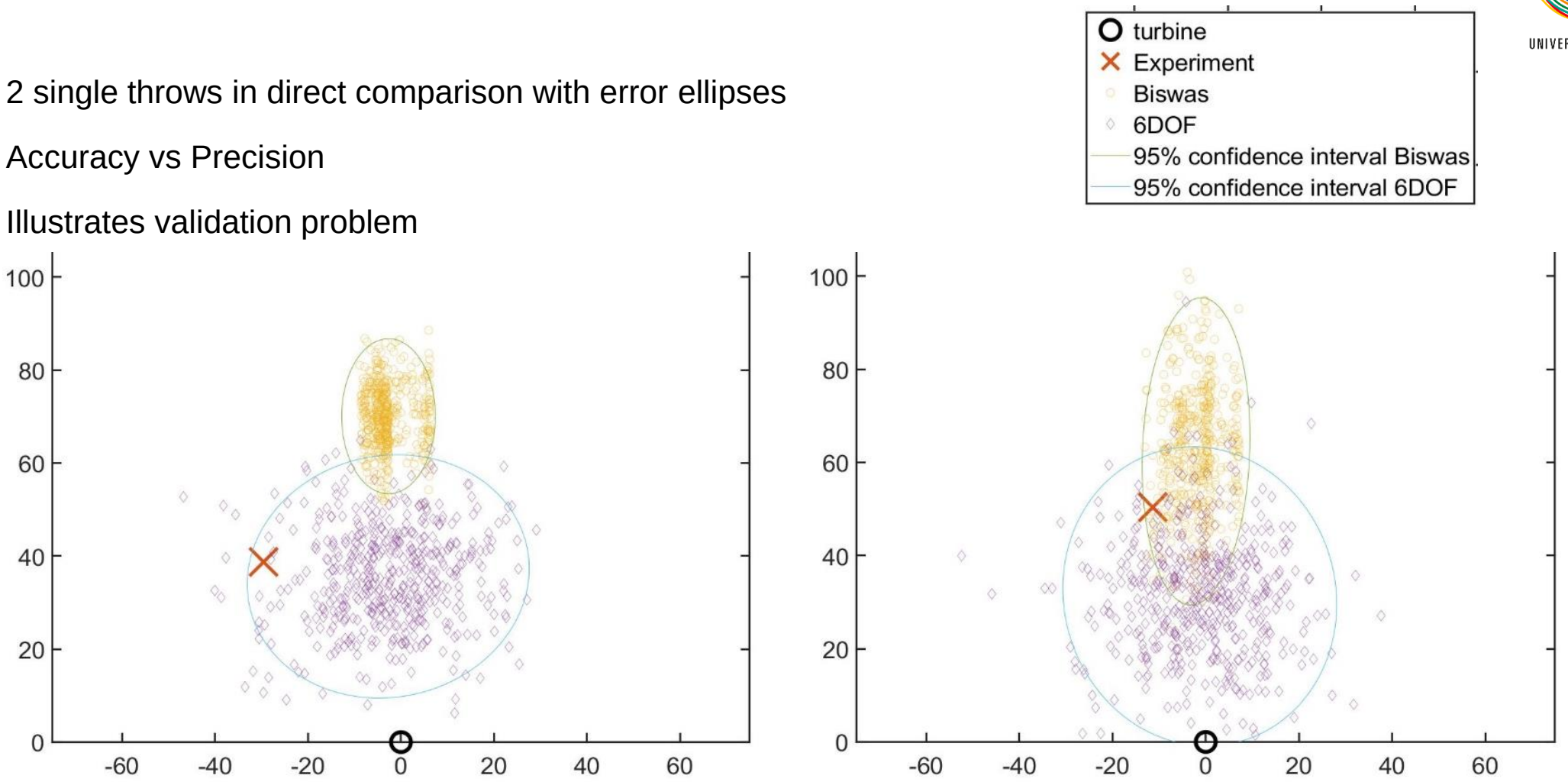
6DOF-Model vs. Experimental Data

- not necessarily conservative (depends on choice for maximum distance)
- reproduces distribution acceptably
- Results much more realistic



6DOF- Model vs. Biswas-Model

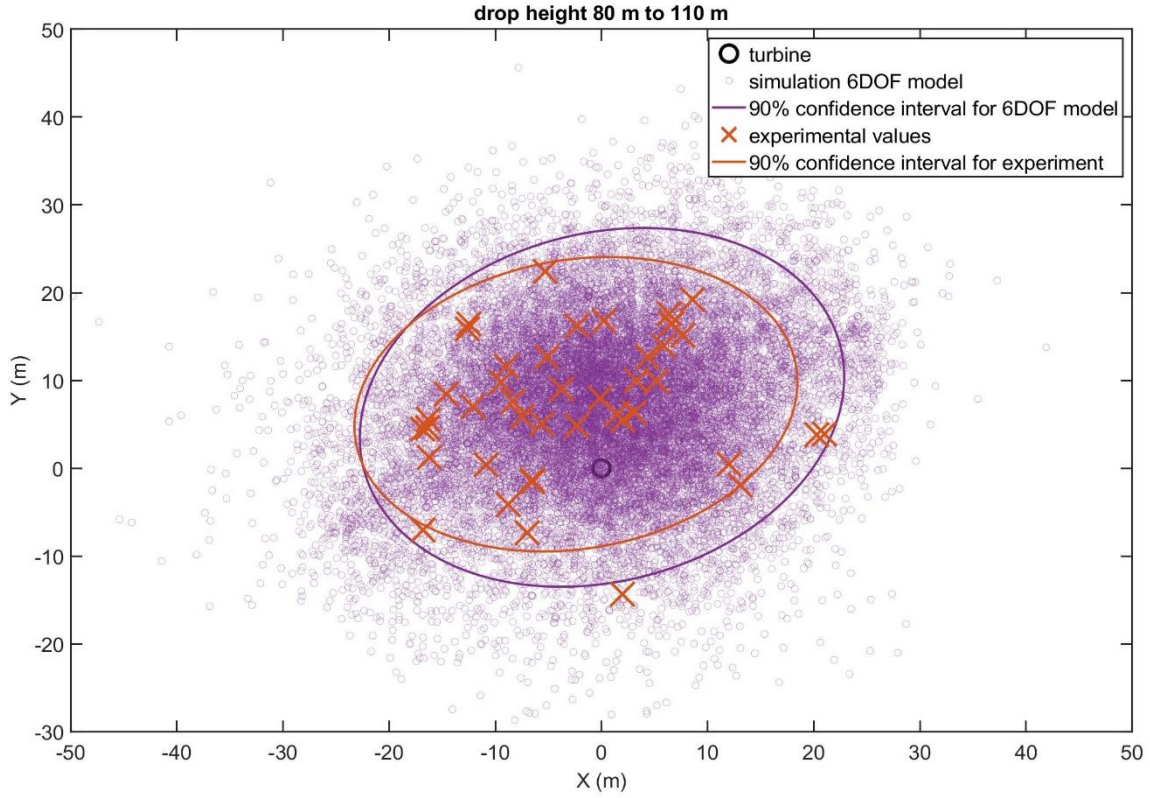
- 2 single throws in direct comparison with error ellipses
- Accuracy vs Precision
- Illustrates validation problem

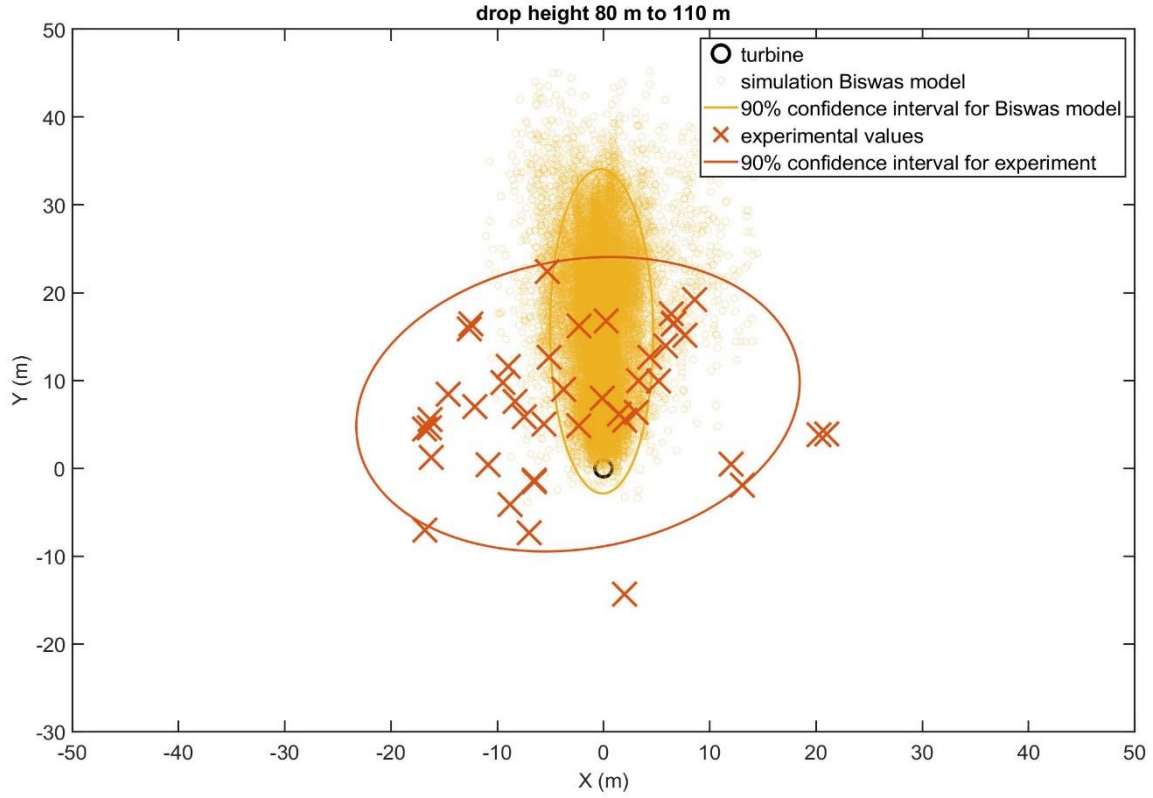


6DOF- Model vs. Biswas-Model

- Split by drop height (here: < 110 m)
- Apply normal distribution
- Error ellipses can be compared to compare distributions

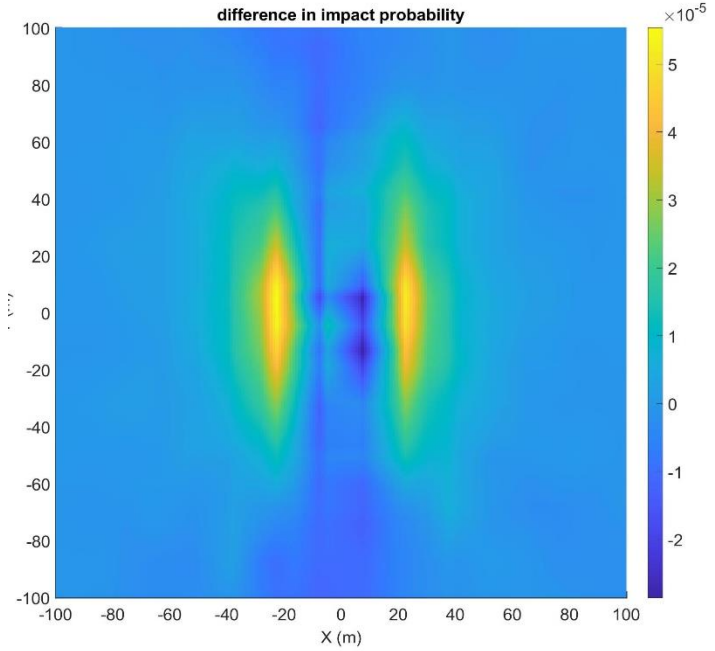
- Ellipse overlap Biswas-Experiments: 20%
- Ellipse overlap 6DOF-Experiments: 99%

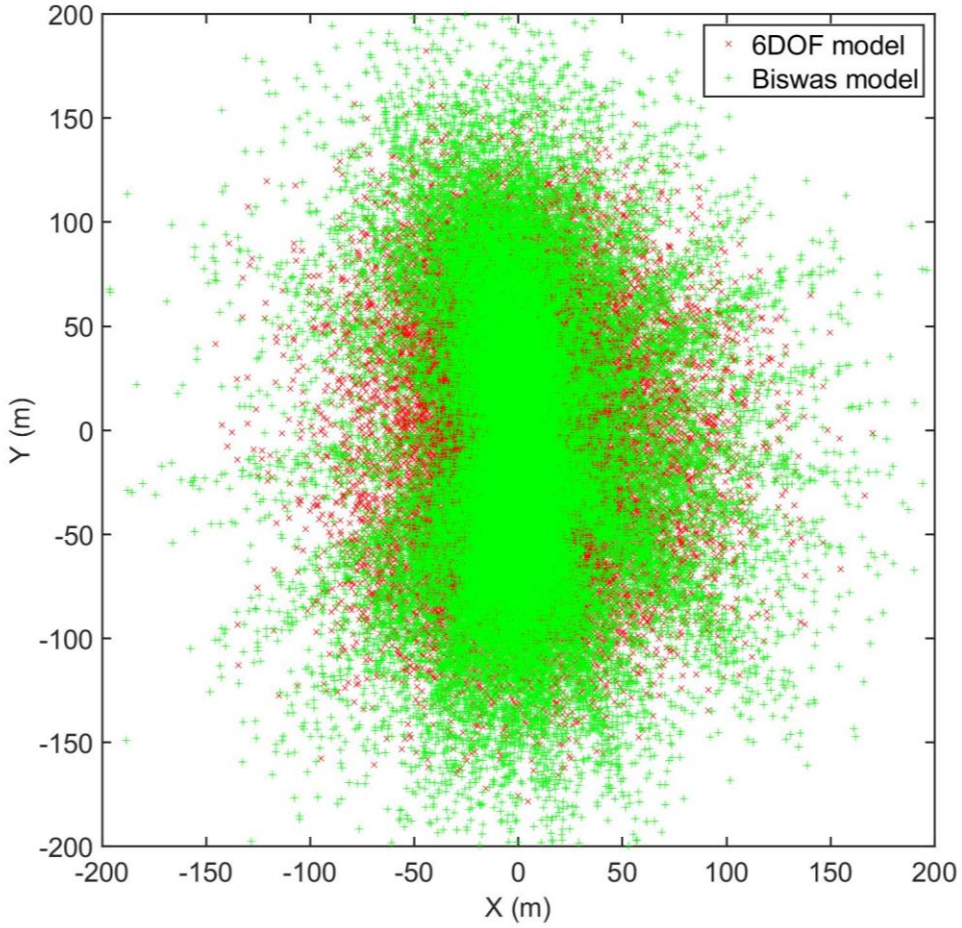




Comparison for multiple directions

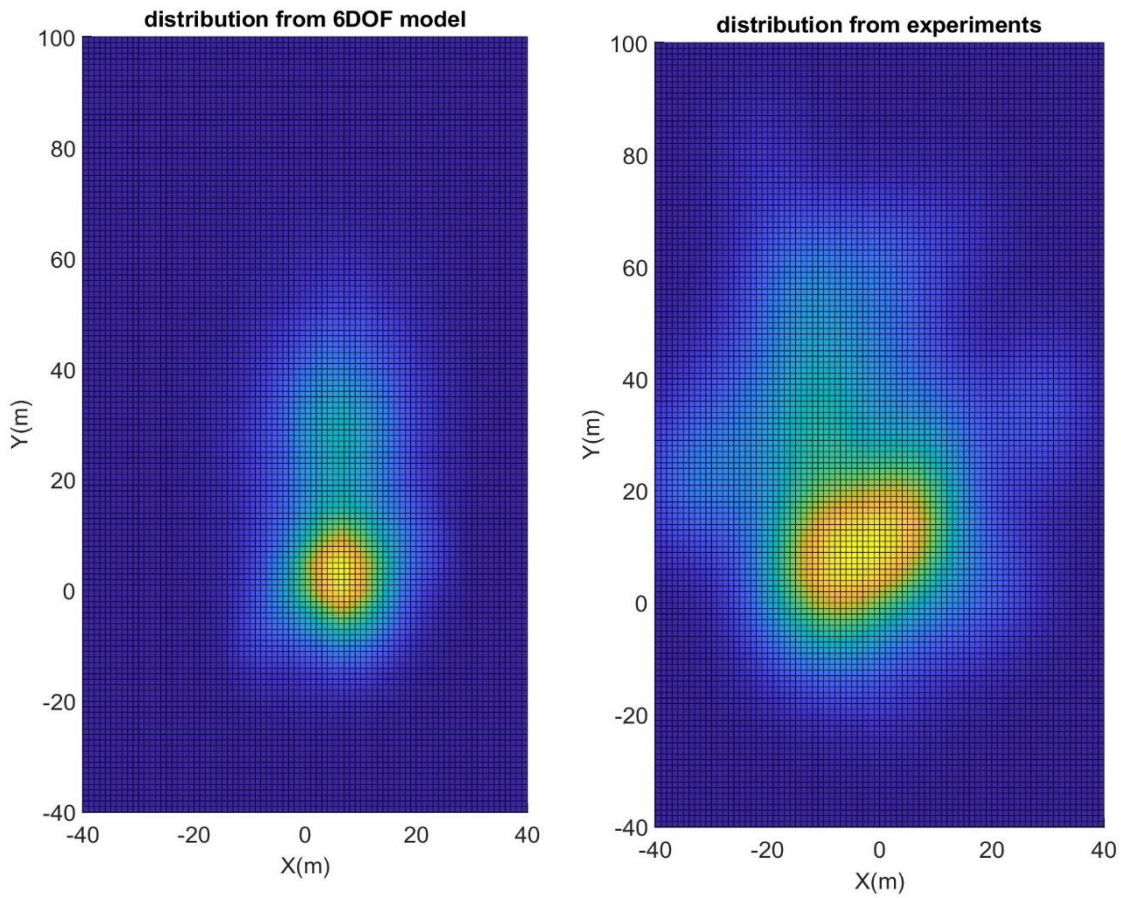
- Realistic wind directions and speeds, points on rotor (150 m diameter)
- Overall higher distances in Biswas model
- More even distribution in 6DOF model





The Validation Problem

- Experiments provide at least limited data for qualitative model validation
- Limited statistical assessment of model quality possible, if experimental data can be assumed normal distributed
- This is usually not the case for thrown ice fragments
- Comparison of distribution densities is possible (e.g. 2D Kolmogorv-Smirnov-test, energy statistic)
- Still no way to „draw some errorbars“



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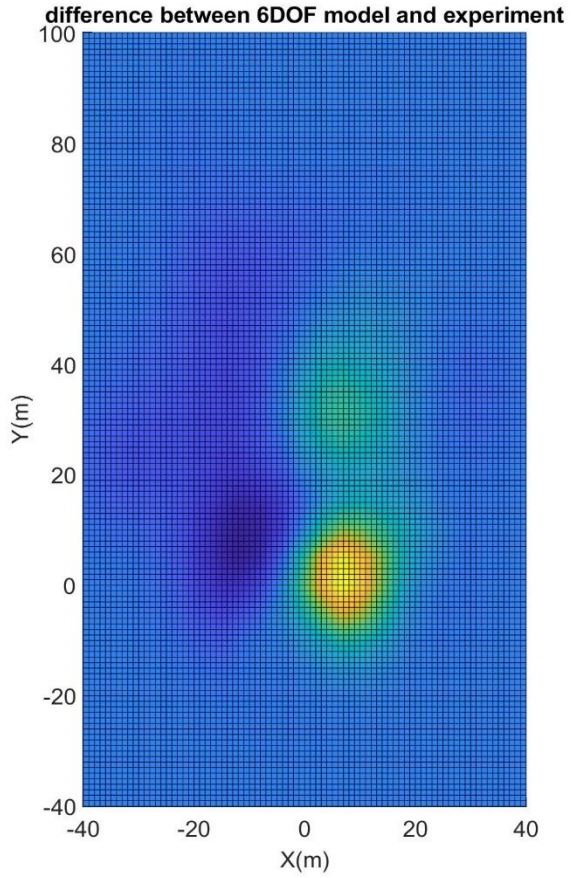

Summary

- Goal of model needs to be well defined (only maximum or realistic)
- Biswas model is conservative for maximum distance but unrealistic, limited use for strong variation in wind directions
- Six degree of Freedom models give more realistic results but require high effort to set up
- The range of validity of the models can still not be determined in a useful way
- Experimental data for validation purposes and an implementation of the 6DOF-model are available at: http://www.risk.boku.ac.at/forschung/forschungsschwerpunkte/erneuerbare-energie/eisball/

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UNIVERSITY OF NATURAL RESOURCES AND LIFE SCIENCES, VIENNA

University of Natural Resources and Life Sciences, Vienna

Department of Water, Atmosphere, Environment
Institute of Safety and Risk Sciences

Dänenstraße 4, A-1190 Vienna
Tel +43 47654 81811
Email: markus.drapalik@boku.ac.at