Uncertainty in Risk to Aircraft From Space Vehicle Operations

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Background

- Space vehicle accidents can generate lots of debris, initiating above aircraft altitudes
- Aircraft, due to their speed and thin skin, may be vulnerable to smaller debris than objects on the ground
- Space vehicle launches and re-entries sometimes necessitate significant mitigations of risk
- The relationship between uncertainties in the inputs to the risk calculation and the resulting risk measures has not been previously evaluated quantitatively

Aircraft risk measures

- Probability of
  - Impact above certain mass threshold
  - Potentially casualty-producing impact
  - Potentially catastrophic impact
- Calculated for either
  - An aircraft flying a particular trajectory
    - A four-dimensional calculation, since aircraft is moving and debris is falling
    - Useful for assessing a mission support aircraft
    - Can be used to evaluate a flight path, but requires aircraft flying at different times
  - A particular location (approximation)
    - Aircraft flies straight and level the entire time debris is in the air
    - Aircraft stays at the same position, but has a forward speed
    - Useful for developing keep-out areas

Uncertainties in Risk Calculation Inputs

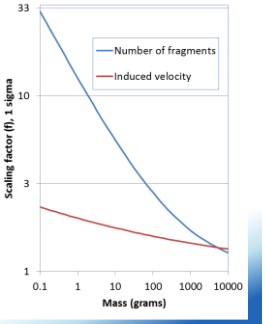
- Debris resulting from the accident
  - Number of fragments
  - Fragment masses
  - Break-up induced velocity
- Probability of failure
- Aircraft characteristics: size, speed, etc.
- Aircraft vulnerability model
  - RCC 321-07 contains models of casualty and catastrophe area for commercial jets as a function of fragment mass

Approach

- Develop input datasets that are samples from the range of uncertainty
- Compute risk measures for a sample mission, with variants representing sampled inputs
- Evaluate resulting uncertainties
  - How large is the uncertainty in aircraft risk?
  - What input uncertainties are most important?

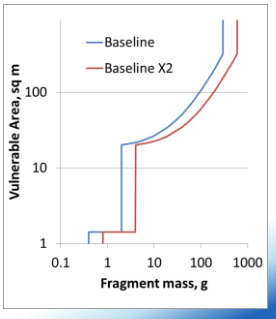
Input uncertainty: fragment list

- Method to produce samples
  - Start with nominal fragment list that has reasonable representation of small fragments
  - Scale the number of fragments up or down, and the breakup induced velocity
    - Scaling factor is larger at smaller masses
    - Scaling factor is randomly sampled once for whole debris and once for each fragment group
  - Adjust fragment mass to conserve total vehicle mass



Input uncertainty: vulnerability

- Used RCC 321-10 commercial jet casualty model as baseline
- Apply scaling factors to the mass
  - Bias: factor of two
  - One-sigma: 50%



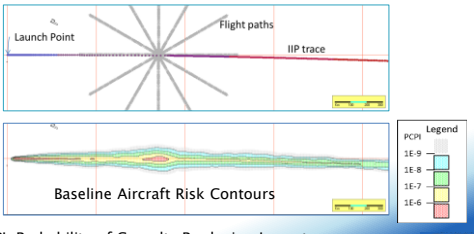
Other input uncertainties

Parameter	Mean	Standard deviation
Speed (km/hr)	830	48
Altitude (m)	11,000	610
Area (m^2)	Top: 1000 Front: 140	5%

Failure probability uncertainty was not modeled; risk measures are directly proportional to failure probability

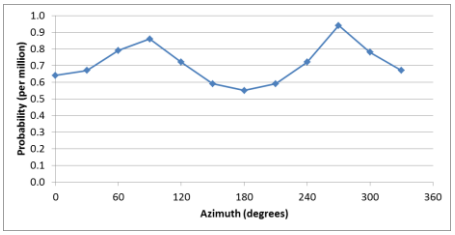
Mission

- Realistic LEO nominal trajectory for two stage vehicle
- Hypothetical launch location and azimuth



PCPI: Probability of Casualty Producing Impact

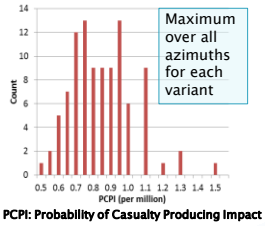
Results: Baseline vs azimuth



- Chart shows maximum risk over all planes flying at each azimuth, crossing the IIP trace at different times
- Risks vary by azimuth of crossing by a little less than a factor of two

Statistics of risks for input variants

Azimuth	Mean	Std. dev.	COV (%)
0	0.55	0.10	18%
30	0.69	0.14	20%
60	0.69	0.13	18%
90	0.77	0.15	19%
120	0.67	0.13	19%
150	0.56	0.10	18%
180	0.52	0.09	18%
210	0.54	0.10	18%
240	0.64	0.12	19%
270	0.85	0.18	21%
300	0.69	0.14	20%
330	0.57	0.11	19%



- Variant statistics are consistent at all azimuth: given input uncertainties, coefficient of variation in risk is ~20%
- Looking only at maximum azimuth, risk uncertainty appears to follow a log-normal distribution

Sensitivity of output risk to input uncertainty

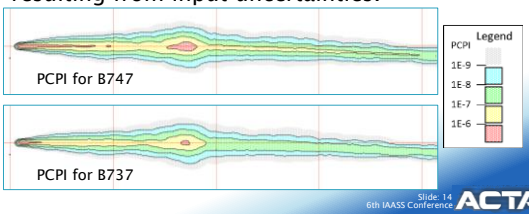
Baseline PCPI: 0.95 (per million)

Parameter (% change)	PCPI when Increased	PCPI when Decreased
Speed (7%)	0.96	0.93
Altitude (20%)	0.89	0.90
Area (25%)	1.10	0.78
Vuln. Model (100%)	1.00	0.85
Fragments (100%)	1.00	0.77

- The aircraft area uncertainty is most important, followed by the fragment list uncertainty
- Raising or lowering altitude both reduced risk

Comparison of uncertainty to different aircraft

- Boeing 737 is three times smaller than 747.
- Maximum PCPI for Boeing 737 with baseline models is 0.4 (vice 0.95).
- This is much larger than uncertainties resulting from input uncertainties.



Conclusions

- The size of the aircraft resulted in a greater effect on the resulting risk than any of the uncertainty in the computation.
- The variation of risk as a function of the azimuth of crossing the risk region is also greater than the uncertainty at a given azimuth.
- Caveat: uncertainties in inputs are highly speculative