Debris Avoidance

A Delicate Balance of
Risk, Emotion, and Mission Success

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Outline

- **Risks and Decisions**
- **The Debris Avoidance Risk Problem**
- **Proposal: A Direct and Novel Investigation**

Risks and Decisions

Decision Making is Always Based on Risk

Risk – What is it Really?

- Risk – Has two parts
  - The Probability of a Failure or Error
  - The Consequence of the Failure or Error
- Three Classical Formulations of Risk

Classical Risk Factor I

- $R_f = P_f + C_f - P_f * C_f$, where
  - R_f is Risk Factor
  - P_f is Probability of Failure
  - C_f is Consequence of Failure, normalized to be between 0 and 1
- R_f – Always between 0 and 1
  - Low Risk - $0 < R_f < 0.3$
  - Medium Risk - $0.3 < R_f < 0.7$
  - High Risk - $R_f > 0.7$
- Risk Management Activities Depend on Calculated Level R_f

Classical Risk Factor II

- $R_f = P_f * C_f$
- C_f has arbitrary units, thus R_f has arbitrary units
- Very Problem Specific
- Works Very Well in Insurance Industry where Consequence is Always Measured in Dollars
- Used as an Alternative to Risk Factor I when Too Many Risk Items Compute as High Risk Category
- Can Make Risk Management and Decision Making More Subjective, and Dangerous

Classical Risk Factor III

- Statistical Error Types
  - Type I - Rejecting a True Hypothesis
  - Type II - Accepting a False Hypothesis
- Based on Frequentist Statistics
  - Significance Level α – Acceptable Probability of Committing a Type I Error, Based on Consequences
  - Little Correlation with Probability of Committing a Type II Error
  - p-Value – Provides Estimate of Bound on α, loosely based on data
- Recent Literature Questions Validity of p-Values
- Simulations Support Recent Literature, p-Values too High

The Special Case:
Low Probability Event, High Consequences

- **Risk Factor I - Always Results in R_f= 1**
- **Risk Factor II - Results Very Subjective, Relative Measures Unclear**
- **Risk Factor III - Flat Probability Space, Frequentist Statistics Based**

None of these Allow Good Decision Making!

A Classic Example: DoE Order 3002

- P_f Normalized to 0, 1, 2, or 3
  - Normalization Subjective (Very Unlikely up to Very Likely) with Unenforceable Guidelines
  - Guideline for P_{fn}= 0, Probability of Failure <10-5
  - Guideline for P_{fn}= 3, Probability of Failure >0.8
- C_f Categorized as 0, 1, 2, 3
  - 3 is the Worst Consequence
  - No Consideration of Intangibles
  - Subjective
- $R_f = P_f*C_f$
  - Risk Factor Values range from 0-9
  - R_f = 0: Omit as Risk Item – do nothing, Eliminate Risk Documentation

Idaho National Engineering and Environmental Laboratory (INEEL) Accident

- **Risk Item: Unexpected Discharge of CO_2 Fire Suppression System during Maintenance, $P_f<10^{-6}$**
- **Analyzed in Accordance with DoE Order 3002**
  - **$P_f<10^{-6}$, so $R_f=0$ – Omitted as Risk Item from Risk Management and Safety Procedure Training**
  - **Risk Item Forgotten, Documentation Lost (except for CYA by some employees)**
- **Event Occurred Summer 1998**
  - **During Routine System Maintenance in Non-nuclear Facility at INEEL, CO_2 Fire Suppression System Unexpectedly Activated**
  - **Killed One Maintenance Worker, Permanently Injured Another**

INEEL Accident Consequences

- **Event was an Ordinary Industrial Accident**
  - **Loss of Life and Injury on the Job**
- **Emotional Overreaction: Event Occurred at Nuclear Lab (but in non-nuclear building)**
  - **Bad Press for DoE**
  - **Estimated 3,000 Man-years labor lost due to Work Stoppages for Investigation and Future Prevention Efforts**
  - **Instituted Universal Worker Safety Training for Event, Even Though only a Handful of Employees at Risk**
  - **Lockheed Martin Excluded from Contract Rebid**

Lessons to Be Learned

- Never, Ever Omit an Identified Risk Item from a Risk Management Plan, Regardless of How Low the Probability of Failure
- Low Probability Events with High Consequences Need Special Attention
  - More Analysis of Modes of and Probability of Failure
  - Better Definition and Understanding of Consequences, Including Impact of Emotional Response and Intangibles

The Debris Avoidance Risk Problem

Another Low Probability, High Consequences Event

The Debris Environment

- **Debris does not Include Micrometeoroids, Manmade Only**
- **Three Classes of Debris**
  - **Very Small - < 1cm, mostly paint flecks and sand grain sized, Many and Totally Undetectable!**
  - **Medium - between 1 and 10 cm, Average Mass 7gm, Fewer, and Mostly Undetectable**
  - **Large - > 10 cm, Average Mass 455 kg, about 900 objects below 270 nmi, All Tracked by USSPACECOM Routinely!**

Debris Class Risk Assessment Shuttle and ISS

Debris Class	Probability of Collision	Consequences	Risk Level	Mitigation Methods
Small	Very high	Slight, Critical Components All Shielded	Low	Improve Shielding for Non-critical Components
Medium	~1.5%/year	Some Damage, Critical Components Mostly Shielded	Medium	Improve shielding for Critical Components
Large	0.5%/year	Catastrophic, Loss of Vehicle and Crew, Intangibles	Serious	Avoidance Maneuvers Virtually Eliminate Risk

Debris Avoidance History

- Not Performed Before Challenger Accident
- Salyut and Mir have almost 30 years of Exposure without a Collision
- Shuttle Flight Rule Both Overly Conservative and Subjective
- International Space Station Flight Rule is Probability Based
- STS Has Executed 5 Maneuvers to Date
- ISS Has Executed 1 Maneuver to Date

STS and ISS Debris Avoidance Scenario

- T_{ca}*-24 to 48 hours:
  - USSPACECOM Performs “Computation Of Misses Between Orbits” (COMBO)
  - Object Predicted to Penetrate an “Alert Box” (currently ±5 x 25 x 5 km about vehicle)
  - USSPACECOM Starts High Intensity Tracking and Special Perturbations Processing
  - Notifies JSC of Alert
- Subsequent 3-6 hours Intervals:
  - USSPACECOM Obtains Additional Data
  - Performs New COMBO
  - Notifies JSC of Status of Conjunction

* T_{ca} – Time of Closest Approach

Debris Avoidance Scenario Continued

- T_{ca} - 3 to 6 hours:
  - If Alert Box Penetration Still Predicted, Flight Director Uses Flight Rule to Decide whether to Order Maneuver Execution or not
- Not Later than T_{ca}-1.5 hours:
  - If Needed per Flight Rule, Avoidance Maneuver Performed
- Post T_{ca}:
  - Conjunction Analyzed at JSC and USSPACECOM

STS Flight Rule

- **Based on a "Maneuver Box"**
  - **If Debris Object Predicted to Penetrate a ±2 x 5 x 2 km (UVW centered on Shuttle) box, Flight Director "May" order Execution of Avoidance Maneuver if Does Not Compromise Mission Operations**
- **Size of Box Determined to Result in Greatest Lower Bound Risk**
  - **Computed for Direct Head-On Collisions only, Worst Case**
  - **Probability of Collision Max of 10^{-5}**
  - **Maneuver Box Penetrations can and usually Have Much, Much Lower Probabilities of Collision, Head-on Collisions Very Rare**
  - **Classic Overreaction**

ISS Flight Rule

- **STS Flight Rule would result in 60-100 Avoidance Maneuvers per Year for ISS**
- **ISS Flight Rule Developed to Reduce ISS Debris Avoidance Maneuvers with No Increase in Risk**
  - **Probability of Penetration of 60 m radius Sphere about ISS (P_c) Computed from Covariances for Debris Object (from USSPACECOM) and ISS (from GPS)**
  - **"Yellow" Criterion Exceeded (P_c ¤ 10^{-5}): Prepare Avoidance Maneuver, Execution at Flight Director's Discretion**
  - **"Red" Criterion Exceeded (P_c ¤ 10^{-4}): Prepare and Execute Avoidance Maneuver, No Flight Director Discretion**

Advantages of ISS Flight Rule

- **Better Foundation than STS – Probability Based as a Function of Specific Conjunction Geometry**
- **Reduces Predicted ISS Annual Maneuver Rate to about 5-6 with No Reduction in Risk**
- **Frequentist Statistics Based, Yet No Computation of Probabilities of Type I and Type II Errors**
- **Currently Being Considered for Replacing STS Flight Rule, Should Happen Soon**
- **Still Overly Conservative**

ISS Debris Avoidance: A Continuing Problem

- ISS Mission is to be Microgravity Laboratory
- Annual Microgravity Mission Requirement – 180 days per year of Microgravity in no less than 30 day periods
- Satisfaction of Annual Microgravity Mission Requirement Complicated by Planned and Random Periods of Disturbances
  - Vehicle Dockings: Shuttle, Soyuz, ESA, Japan
  - Control Moment Gyro Desaturations
  - Routine and Unplanned Maintenance and Repairs
- Predicted Maneuver Rate is a Mean Rate, Poisson Statistics Govern
  - A Single Maneuver Expected Per Year Results in Probability of 92% of Completing Annual ISS Microgravity Mission
  - Five Expected Maneuvers Per Year Result in Probability of <70% of Completing Annual ISS Microgravity Mission
- Annual Number of Debris Avoidance Maneuvers Needs Further Reduction Without Increase in Risk

Solutions Considered

- Debris Elimination or Deflection
  - Formation Flyers to Destroy or Deflect Debris – Summarily Eliminated in 1990
    - Very Expensive, both in Capital and Ops
    - May Increase Risk rather than Reduce it
  - Ground Based Lasers to Destroy or Deflect Debris
    - May not be Possible
    - May Increase Risk rather than Reduce it
    - Very Expensive, both in Capital and Ops

More Solutions Considered

- Passive, Increase Vehicle Shielding
  - Can Help with Small and Medium Sized Debris for ISS
  - No Help for Large Debris, not Possible for Shuttle
- Reduce Probability of Collision
  - Improve USSPACECOM Detection and Tracking
    - USSPACECOM Mission – Assets Closing Down
    - Minor Expenses in Ops, Major Expenses in Capital
  - MADCAT – Proposed Improvement in Contemporaneous Atmosphere Estimates, Better Short Term Predictions for Debris

Proposal

A Direct and Novel Investigation

A Bayesian Approach

Scope of Investigation

- Literature Search Reveals Many Articles on Debris Avoidance, All from Three Distinct Classes
  - Debris Environment Analysis and Predictions
  - Calculations of Aggregate Risk due to Environment
  - Calculations of Probability Integral for Conjunction
- Objectives:
  - Develop Realistic Probability Computation using Bayesian Statistics to Reduce Annual Number of Maneuvers and Overall Risk for STS and ISS
  - Formulate Suitable Risk Factor Calculation for Low Probability, High Consequence Risk Items to Allow Good Decision Making

Research Approach

- **Revisit Past Shuttle and ISS Maneuvers and Conjunctions to Establish Credible Baseline**
  - **Where Possible, Compute Actual Frequentist Probabilities of Type I and Type II Errors**
  - **Formulate Decision Data**
- **Formulate Bayesian Calculations of Probability of Collision; Consider as a minimum:**
  - **Historical Data**
  - **USSPACECOM/JSC Operations – updated Covariances**
  - **Predicted Risk Reduction Post Maneuver**
  - **Predicted Risk to other Debris As a Result of Maneuver**

Research Approach
(cont.)

- **Formulate Consequences, both for Maneuver and no Maneuver Situations**
  - **Collision**
  - **Mission**
  - **Operations**
  - **Mission Planning**
- **Investigate Bayesian “Formulations” for Computing Risk Factors for the General Low Probability, High Consequence Risk Item Problem**
- **Apply if Possible to STS and ISS for Risk Factors**

Research Approach
(cont. 2)

- Revisit Past STS and ISS Debris Conjunctions
  - Determine if Flight Rules using new Bayesian Probability Calculations would omit a Maneuver that was Executed
  - Determine if Flight Rules using new Bayesian Probability Calculations would Call for a Maneuver that was not Executed
  - Determine if Flight Rules' "Red" and "Yellow" Criteria Probabilities could be Reduced by Using new Bayesian Probability Calculations

Anticipated Results

- **Appreciable Reduction in Annual Number of Predicted Maneuvers for STS and ISS at Same Risk Level**
- **Potential Reduction of STS and ISS Flight Rule Risk Levels, with Reduction in Annual Number of Maneuvers**
- **Potential Reduction of “Alert” Box Size, Reduced Operations for both USSPACECOM and JSC**
- **Rapid Implementation of Bayesian Technique at NASA/JSC for both STS and ISS – No Flight Rule Changes needed**
- **Development of Workable Risk Management Process for Low Probability/High Consequence Risk Items**

Synopsis

- **Risk Management for Low Probability, High Consequence Risk Items Very Difficult**
- **Shuttle and ISS Debris Avoidance Problems, in this Class of Risk Problem**
- **Bayesian Approach to Shuttle and ISS Debris Avoidance looks Promising for Reducing Annual Maneuver Rate with No Increase in Risk of Collision**
- **Area of Investigation may lead to Better Risk Management Approach for Such Problems**