Conjunction Assessment Risk Analysis

CARA Risk Assessment Thresholds

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CARA Threshold Types

• **Warning / remediation threshold (“Red” threshold)**
  – Pc level at which warnings are issued, and active remediation considered and usually executed

• **Analysis threshold (“Green to Yellow” threshold)**
  – Pc level at which analysis of event is indicated, including seeking additional information if warranted

• **Post-remediation threshold**
  – Pc level to which remediation maneuvers are sized in order to achieve event remediation and obviate any need for immediate follow-up maneuvers

• **Maneuver screening threshold**
  – Pc compliance level for routine maneuver screenings (more demanding than regular Red threshold due to additional maneuver uncertainty)
CARA Thresholds Development Status

• Red and Green-to-Yellow thresholds established
  – Type 1 and Type 2 error analysis
  – Imputed workload analysis

• Post-remediation threshold methodology in work
  – Rule-of-thumb in place presently
  – Analysis avenues for more robust approach

• Approach envisioned for post-remediation threshold can also be applied to maneuver screening threshold
RED AND YELLOW-GREEN THRESHOLD DETERMINATION
The CARA “Worktier” System Defined

• System for determining how much induced work a given event commanded
  – Worktier 1: e-mail contact and follow-up with O/O
  – Worktier 2: HIE package produced and briefing delivered
  – Worktier 3: RMM planning conducted
  – Worktier 4: RMM executed

• Worktier level a good proxy for seriousness of event

• Worktier level thus used as “truth” criterion to choose red and green Pc thresholds
  – Worktier 2+ recommended as particular level to use, meaning high-risk event set defined as those with a worktier level of 2 or higher
  – Plots will, however, show performance at all four worktier levels (1+, 2+, 3+, and 4)
Worktiers and Pc Threshold Circularity

- Worktiers reasonable proxy for seriousness of event
- However, Pc levels presently used to establish seriousness
  - Thus, must be careful in using historical worktier data to set Pc levels—easy to devolve into circular argumentation
- Original examination used dataset from period before Pc thresholds established and in place
  - Thus legitimate dataset from which to establish threshold set
- For this reason, updates to original values no longer easily achievable through data mining
Exploratory Analysis: Event Maximum Pc as Predictor of Worktier

- How good a predictor of the eventual work tier assignment is the maximum Pc during the event?
- Examined all events in 2011-2013
- One graph for each work tier
  - Quad-chart format shows results for each cumulative worktier level
- False alarm rate (blue line): % of cases in which the Pc indicated a serious event but the event was actually not high-risk
  - Also called a “type 1” error, and is a nuisance factor
- Missed detection rate (green line): % of cases in which the Pc indicated a non-high-risk situation but the event actually was high risk
  - Also called a “type 2” error, and is the more serious error type
Event Maximum Pc as Predictor of Worktier: Results

- Type 1 and 2 Errors for Predicting Worktier 1+ Events
- Type 1 and 2 Errors for Predicting Worktier 2+ Events
- Type 1 and 2 Errors for Predicting Worktier 3+ Events
- Type 1 and 2 Errors for Predicting Worktier 4+ Events

False Alarm Rate
Missed Detection Rate
Event Maximum Pc as Predictor of Worktier: Interpretation of Results

- Interpretive questions center on tolerable levels for the type 1 and type 2 errors
- **Type 2 error rates**
  - 0.01% to 0.1% for a 1E-05 to 1E-03 Pc threshold range—quite small
  - Events that are just below the red threshold can be promoted manually red and thus be processed as HIEs
- **Type 1 error rates**
  - Range from 10% to 0.5%—again, not very large and seemingly tolerable
- **Overall construct thus looks promising**
Individual Event CDMs as Predictor of Worktier

- A typical event consists of a chain of CDMs from 7 days to 1-2 days from TCA
- These usually begin with a smallish Pc value and increase to a maximum, then decrease somewhat rapidly
- Question now is how well each pre-max Pc value will predict the eventual worktier level of the event
  - This is the way CONOPS will actually operate
- Certain to perform worse than using only the max Pc value as a predictor
  - But may still perform quite adequately for CONOPS purposes
Individual Event OCMs as Predictor of Worktier: Results

Type 1 and 2 Errors for Predicting Worktier 1+ Events

Type 1 and 2 Errors for Predicting Worktier 2+ Events

Type 1 and 2 Errors for Predicting Worktier 3+ Events

Type 1 and 2 Errors for Predicting Worktier 4+ Events

False Alarm Rate
Missed Detection Rate
Individual Event OCMs as Predictor of Worktier: Interpretation

• As expected, performance is worse with this arrangement

• Type 2 error rates higher
  – These are between 0.5% and 1% for the 1E-05 to 1E-03 range
  – Not blissfully low, but not particularly surprising or disturbing given what is being attempted
    • Initial relatively low Pc values in an event not readily predictive of event destiny
    • Consequence is not a missed event, only that event will not be caught as early
  – Curve relatively flat, especially below 1E-04
    • Very little marginal gain from choosing a lower threshold (e.g., 1E-05)

• Type 1 error rates not very different from previous
  – Not surprising, given typically lower Pc values at the beginning of events
    • Rare that early-event Pc would exceed red threshold, not be the maximum Pc, and then drop sufficiently quickly that event would not remain an HIE
Green-To-Yellow Threshold

• Idea is to set a lower bound on Pc so that events with a Pc below this threshold will almost never become high-risk events

• Type 1 error: Pc is above this threshold but never becomes high risk
  – Not really a false alarm, as it is expected that the great majority of non-green Pc values will remain yellow and never become high risk events
  – However, to maintain parallelism with construct used for setting red threshold, appropriate to label it a Type 1 error

• Type 2 error: Pc is below this threshold but becomes high risk
  – Even here, the problem is not particularly serious: events are not missed but just have their true severity discovered somewhat later

• Investigate against all pre-max-Pc OCMs in each event
Green Threshold Performance: Pre-max-OCMs in each Event

- **Green Threshold Performance:**
  - Pre-max-OCMs in each Event

- **Type 1 and 2 Errors for Predicting Worktier 1+ Events**
  - Missed Detection Rate
  - False Alarm Rate

- **Type 1 and 2 Errors for Predicting Worktier 2+ Events**
  - Missed Detection Rate
  - False Alarm Rate

- **Type 1 and 2 Errors for Predicting Worktier 3+ Events**
  - Missed Detection Rate
  - False Alarm Rate

- **Type 1 and 2 Errors for Predicting Worktier 4+ Events**
  - Missed Detection Rate
  - False Alarm Rate

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Green Threshold Performance: Interpretation

• **Type 2 error performance**
  – Stable at 0.015% for 1E-08 to 1E-06
  – Numbers quite low

• **Type 1 error performance**
  – Ranges from 30% to 20%
  – Numbers seem high, but actually have little significance
    • Essentially # of yellow events that never become red—this is expected
Concurrent Events

• If an event’s Pc exceeds the red threshold, it becomes an HIE
  – Usual dynamics is for the event to remain at this level until TCA
• Can thus determine the number of concurrent HIEs implied by a particular red threshold
  – # of concurrent HIEs per day over the 2011-2013 period
  – Summarized by 50th, 68th, and 95th percentiles
  – Separate lines for all satellites and maneuverable satellites only
• Graph on next slide
Concurrent Events: Interpretation

- Workload becomes problematic around 5E-04 with current staffing
- Must also consider imputed workload on missions with more frequent HIEs
Satellite Lifetime Conjunction Risk

- Aerospace study developed factor for satellite lifetime conjunction risk calculation
  - $1 \times 10^{-8}$ per $10 \text{ m}^2$ of spacecraft projected area per day
  - Based on older version of ORDEM and not orbit regime dependent, so a durable result would require re-execution of the study
  - However, factor can be used to produce results to provide orientation

- Contour plot gives composite satellite conjunction risk as a function of spacecraft size and years on orbit
  - Colors represent $\log_{10}(P_c)$
Lifetime Conjunction Risk Contour Plot

Lifetime Payload Conjunction Risk Against All Objects > 1cm

- Time on Orbit (years)
- Payload Projected Area (m²)

-7 - 7
-6.5 - 6.5
-6 - 6
-5.5
-5.5
-5.5

-3 - 3
-3.5 - 3.5
-4 - 4
-4.5 - 4.5
-5 - 5
-5.5 - 5.5
-6 - 6
-6.5 - 6.5
-7 - 7

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Satellite Lifetime Conjunction Risk: Interpretation

- Satellites with a reasonable lifetime on orbit (~10 years) and a non-trivial size (~4m²) have a lifetime conjunction risk of ~3E-04
- Does not make sense to remediate conjunctions with a risk much smaller than this
Overall Summary

- Analysis does not point to single value for red or green threshold
- However
  - Region between 1E-04 and 5E-04 seems to be a reasonable choice for red threshold
    - Type 2 error rates OK (0.05% or so)
    - Type 1 error rates OK also (~5%)
  - Not much improvement in situation in choosing a smaller threshold
    - Type 2 error curves relatively flat
  - Workload, however, does increase substantially when smaller threshold chosen
    - Smaller thresholds begin to approach lifetime conjunction risk values, most of which is due to untrackable small debris
- CARA ~4E-04 choice, while not made inevitable by this analysis, is reasonably supported by it
POST-MANEUVER THRESHOLD DETERMINATIONS
CARA Post-Remediation Threshold

• Current recommendation is to choose maneuver to reduce cumulative $P_c$ to $1E-10$
  – Rule of thumb that has arisen over the years
  – Intent is essentially to eliminate need for follow-up maneuver because original maneuver inadequately sized

• Many missions now push back against this conservative value
  – Can put missions outside of control box
  – Even if executable, can consume large amount of fuel
  – No rigorous justification at present for value

• Sketch of expected approach to resolution to follow
Pc Uncertainty and Post-Maneuver Remediation

- Pc Uncertainty construct pursued by CARA for years; briefed recently at AAS (paper 16-241)
- Considers all of the uncertainties in the input parameters to generate a PDF of Pc values, rather than a single value
- Can use to determine likelihood of obtaining a Pc of a certain value or higher at a given percentile point
  - E.g., 5% or lower chance that the Pc will exceed 1E-04
- Can incorporate into Maneuver Trade-Space functionality
  - Function presently produces contour plot of Pc as a function of maneuver size and maneuver execution time (phasing)
  - Pc uncertainty can be used instead to give the likelihood of the post-maneuver Pc exceeding a specified threshold
    - Perhaps 4.4E-04 or 1E-05 (red and maneuver planning thresholds)
    - Graph could show likelihood of Pc exceeding 1E-05; perhaps choose 2% or less
  - Frames output in terms of likelihood of post-maneuver high risk
  - Works best if maneuver execution error incorporated into construct
CARA Maneuver Screening Threshold

• Same approach as for RMM sizing can be used
• Both canonical threshold and percentile point could be different
• Setting of percentile points can be informed by regular operational practice
  – i.e., percentile point to be used when evaluating red threshold under regular conditions