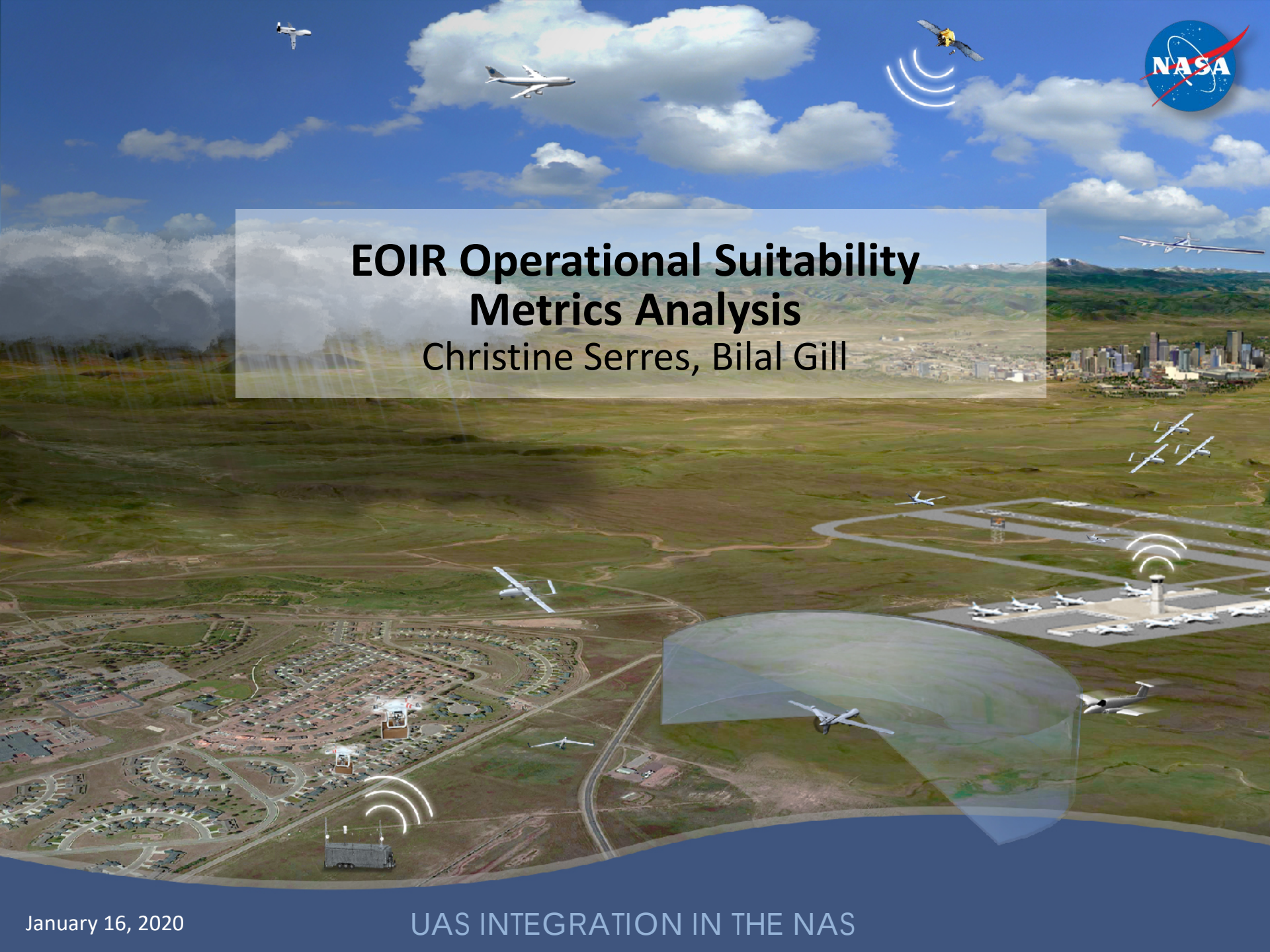


EOIR Operational Suitability Metrics Analysis

Christine Serres, Bilal Gill

Overview

- This slide package includes additional metrics that were collected during the EO/IR simulation runs
  - Additional metrics include operational suitability metrics such as splits and reversals, alert time and range
- Performed parameter sweep based on the following table:

Range error (% of σ(R))	Range rate error (% of σ)	Range Bias* (μ(R))	Angular Rate Error (% of σ)	Detection Range
50% 75% 100% (Default) 125% 150%	50% 75% 100% (Default) 125% 150%	0* As modeled (Default)	50% 75% 100% (Default) 125% 150%	1 NM 2.5 NM (Default) 3 NM 4 NM

- Additional parameter sweeps were performed based on feedback

EO/IR Simulation Assumptions

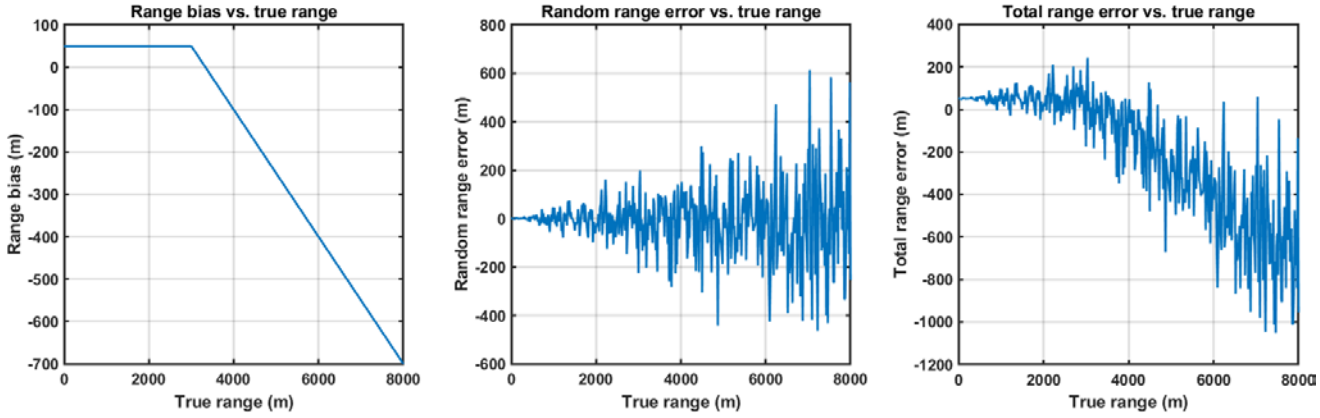
- DAIDALUS:
  - Version 1.0.1 was used in the simulation
  - Default SC-228 noncooperative well-clear definition (2200 ft, 450 ft, 0 $\boldsymbol{\tau_{mod}}$*)
  - Same configuration as low C-SWaP simulation:
    - Time to the volume for alerting (valid for Phase 1 UAS as well):

      30 seconds for Warning

      60 seconds for Corrective
    - Guidance based on 7 deg/sec turn rate
    - 4 second persistence and 2-of-4 (m of n) alerts (valid for Phase 1 UAS as well)
- SC-228 Pilot Model
  - Deterministic mode
  - Horizontal maneuvers
  - Issues 7 deg/sec turns
  - No buffer on minimum suggestive guidance
- Simulation uses low C-SWaP encounter-set
  - Ownship speed ranges from 40-100 kts; Intruder speed ranges from 0-170 kts
  - Ownship/intruder altitude: 500 AGL-10000 ft MSL

EO/IR Parametric Model

- Range estimation error[1]:
  - $\varepsilon(R) = \mu(R) + \sigma(R) * randn(1)$
    - R = range (meters)
    - $\mu(R) = 50 - 0.15 * MAX(0; R - 3000)$ (error bias at range R)
    - $\sigma(R) = 0.03 * R$ (error standard deviation at range R)
    - Randn: Matlab Normally distributed random numbers
  - Time correlation is 5 s
- Range rate estimation error[1]:
  - σ is 5% of true range rate (e.g., if range rate is 200 kts, std. dev. is 10 kt)
  - Delay is 5 s (time needed to provide information from first detection)
  - Time correlation is 2 s (TBC)



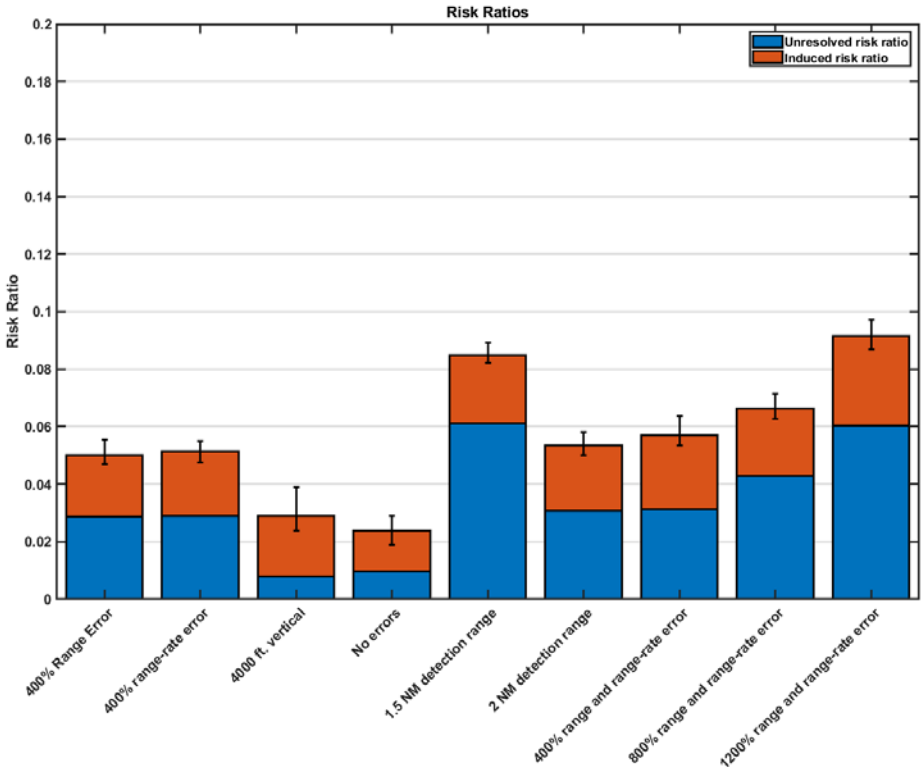
1. Farjon J., "White paper EO/IR sensor model", SAFRAN ED, 2019

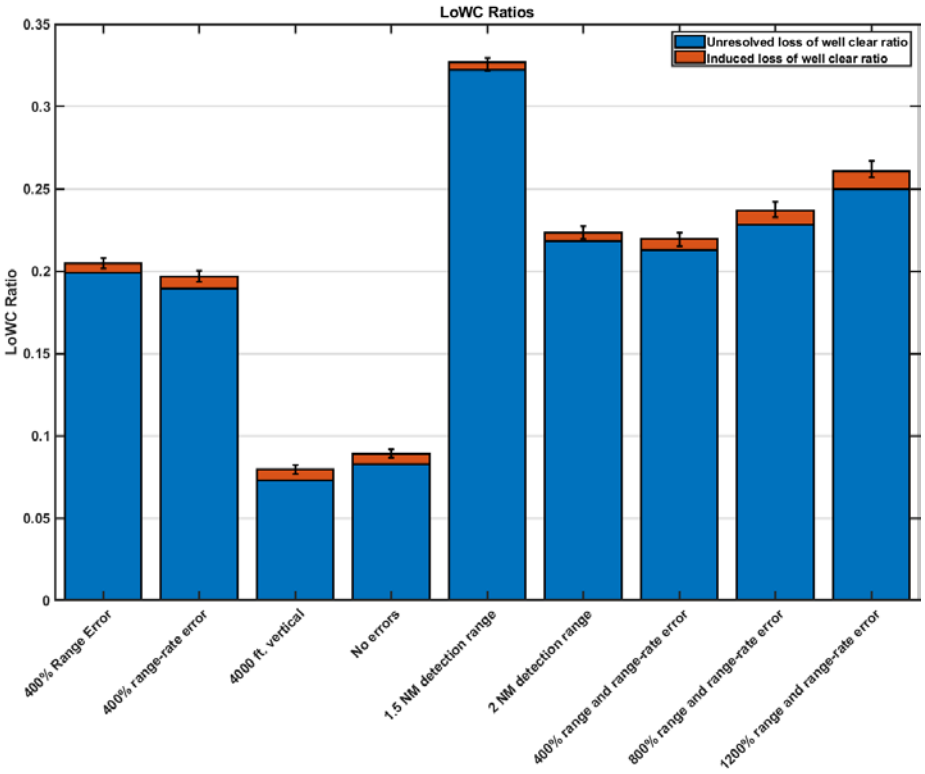
EO/IR Parametric Model (Cont.)

- Bearing and elevation error[1]:
  - Angle measurement error is Gaussian white noise
  - $\sigma < 1$ mrad (standard deviation)
  - Measurements are not time correlated
- Bearing and elevation rate error[1]:
  - Angular rate error is Gauss-Markov noise
  - $\sigma < 1.4$ mrad/s (standard deviation)
  - Temporal decay time is approx. 10 samples
- No field of regard (FOR) limits for azimuth and elevation
- 2.5 nautical mile detection range

1. Farjon J., "White paper EO/IR sensor model", SAFRAN ED, 2019

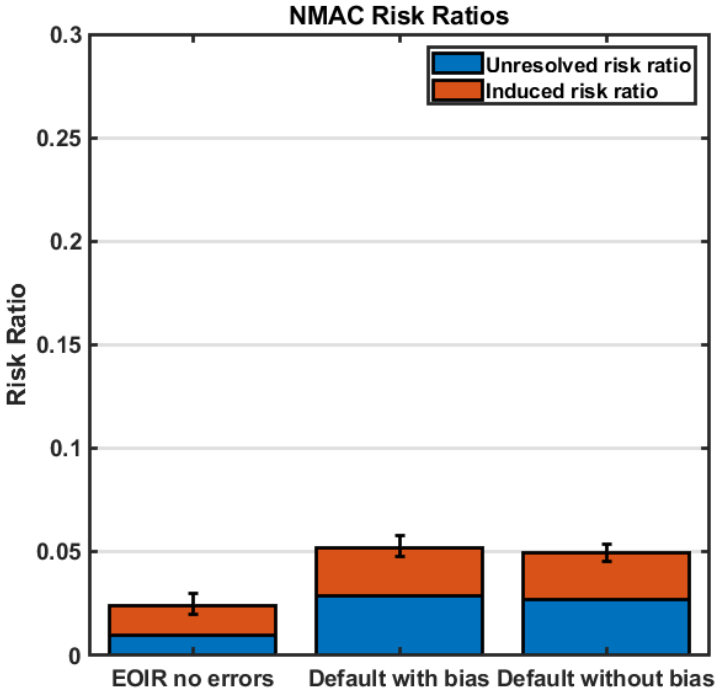
Risk Ratio and LoWC Ratio of additional runs

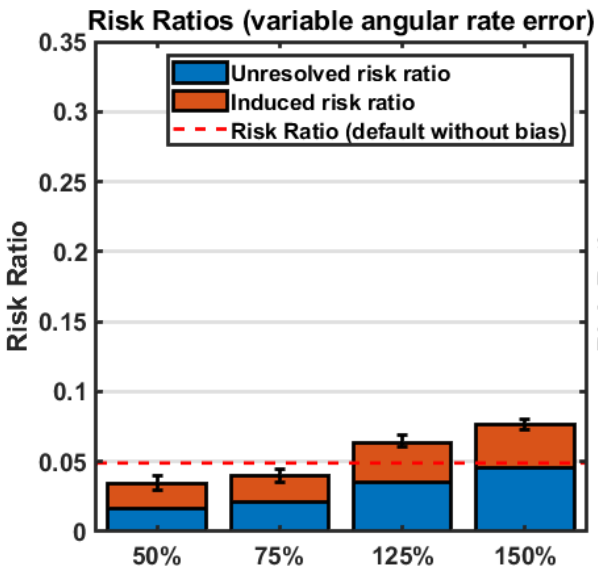


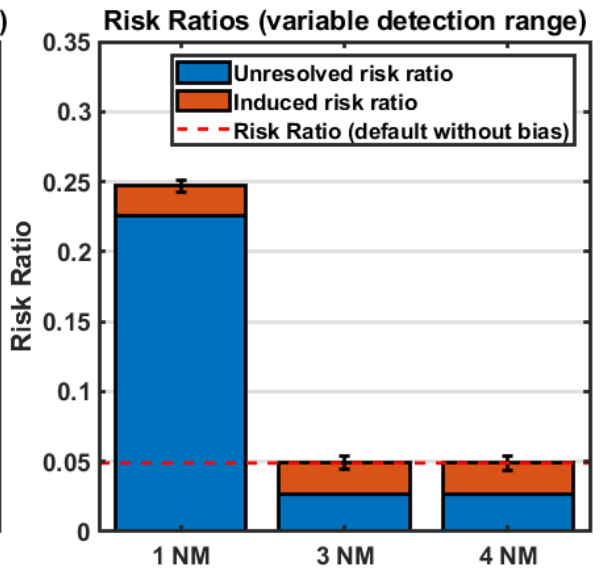


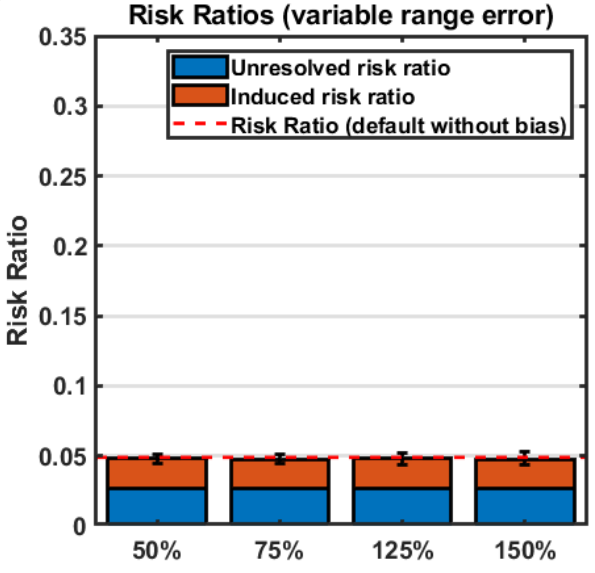
- These graphs show the risk ratios and LoWC ratios of the new configurations that were run
- The greatest increase in both risk ratio and LoWC ratio for the additional cases is for the 1.5 NM detection range case
  - Risk ratio for the 1200% range and range-rate error case is the highest among the additional configurations
- The 4000 ft. vertical case configuration has the vertical alerting threshold of DAIDALUS set to 4000 ft. (similar to the MOPS recommendation for encounters with non-cooperative aircraft)

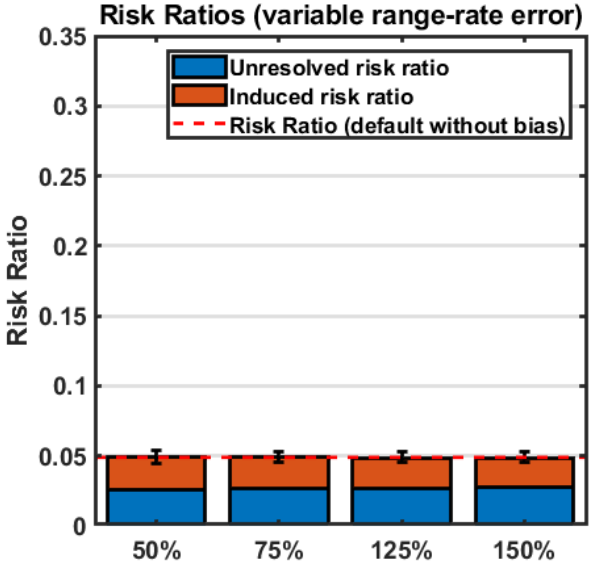
Risk Ratio from previous configurations





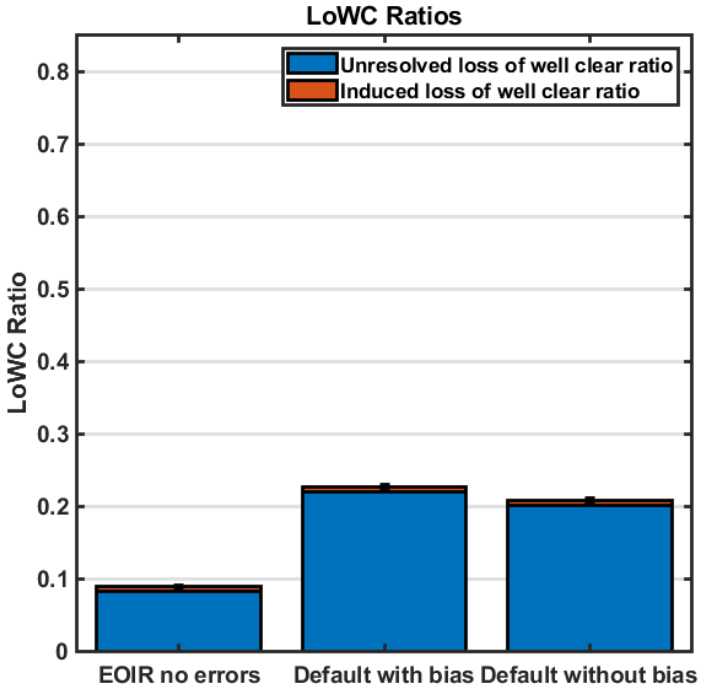


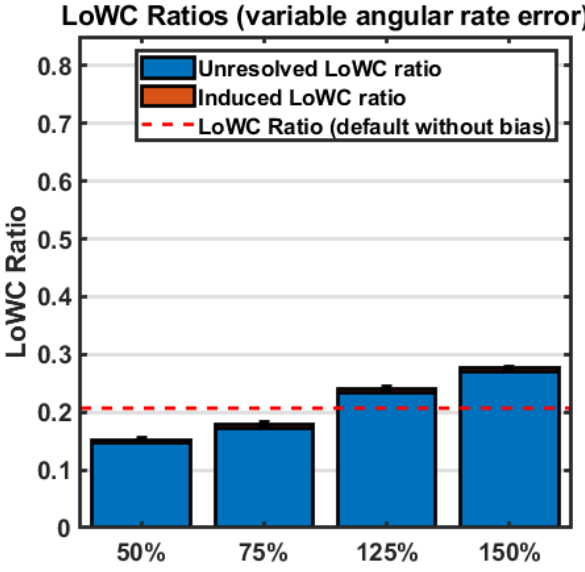


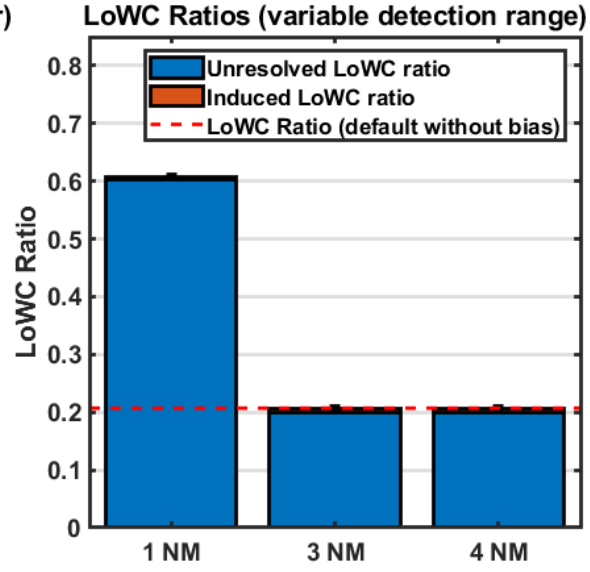


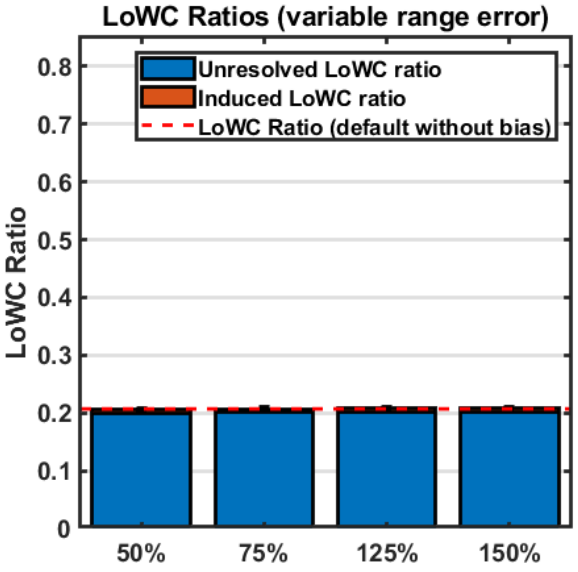
- These graphs show the risk ratios grouped by the different error parameters of the EOIR model that were varied
- The risk ratio is sensitive to angular rate and detection range

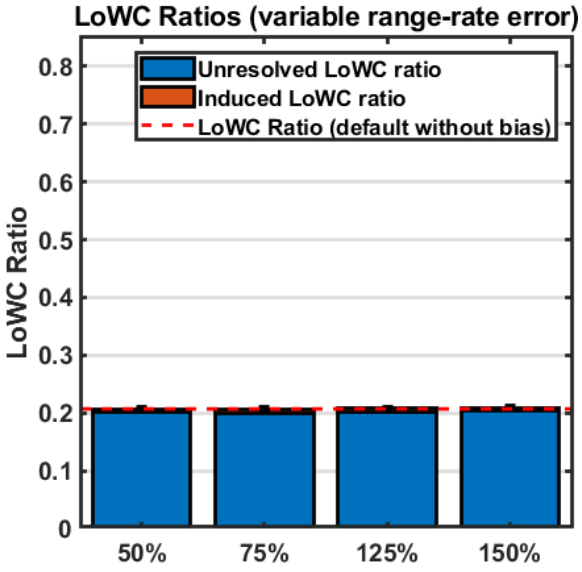
LoWC from previous configurations









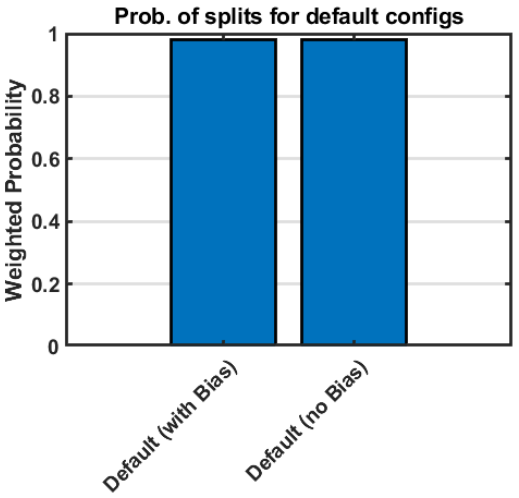


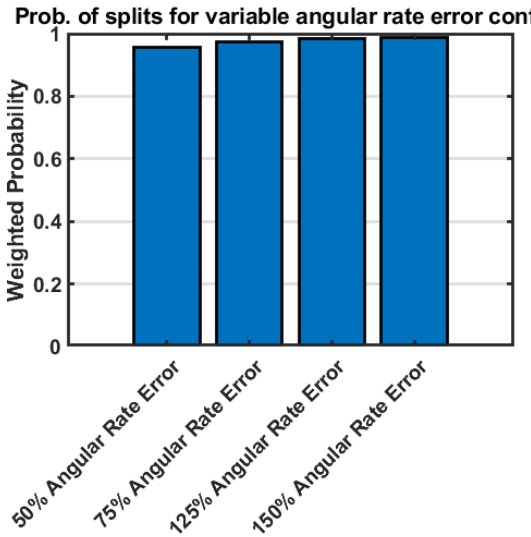
- These graphs show the LoWC ratios grouped by the different error parameters of the EOIR model that were varied
- The LoWC is sensitive to angular rate and detection range, similar to the risk ratio

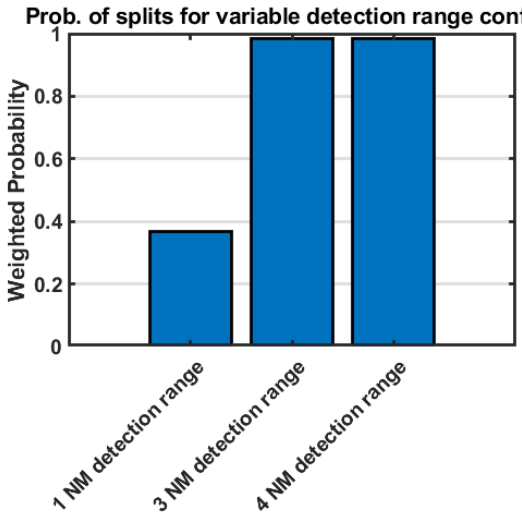
Operational Suitability Metrics

- Reversals
  - Reversals are based off of commanded headings from the pilot model
    - An encounter has a reversal if the commanded heading changes sign (e.g., from turn left to turn right)
- Splits
  - Splits are based off of the alert level from DAIDALUS
    - An encounter has a split if DAIDALUS issues an alert of any type, the alert clears, and then DAIDALUS issues another alert of any type
    - Note: preventive alerts are suppressed in the simulation so this metric is not impacted by preventive alerts
- Pilot workload
  - Pilot workload is approximated as the total number of maneuvers performed over all encounters for a given configuration

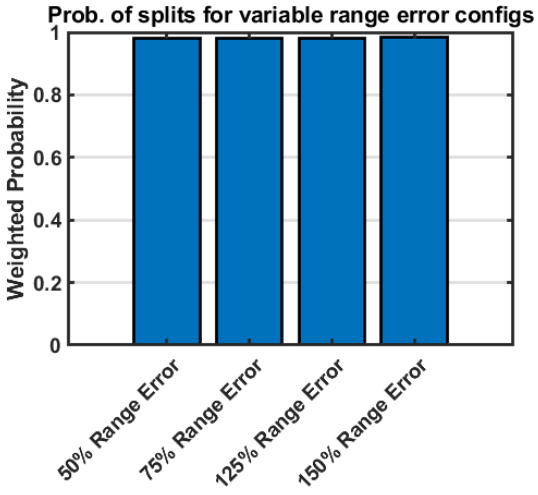
Operational Suitability Metrics (Splits)

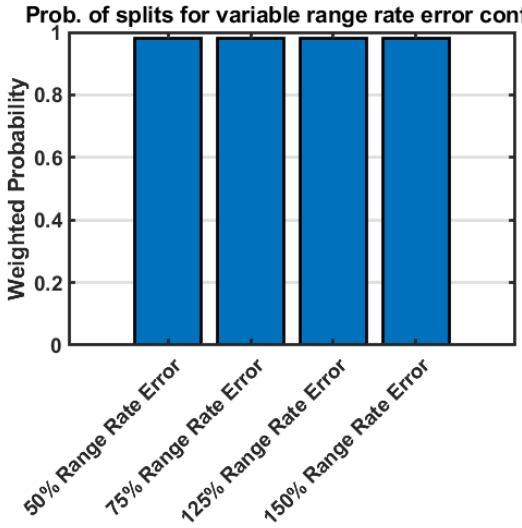




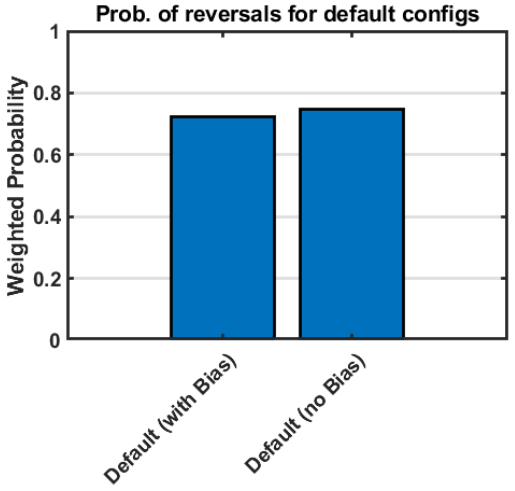


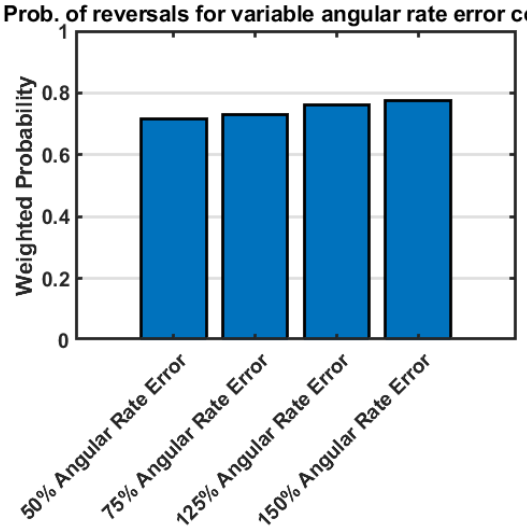
- These plots show the probability of a split alert occurring in an encounter
  - These metrics are only for encounters where there was a nominal LoWC
- The parameters that have the largest effect on splits are variable angular rate and variable detection range
  - Almost every encounter with a nominal LoWC had a split alert

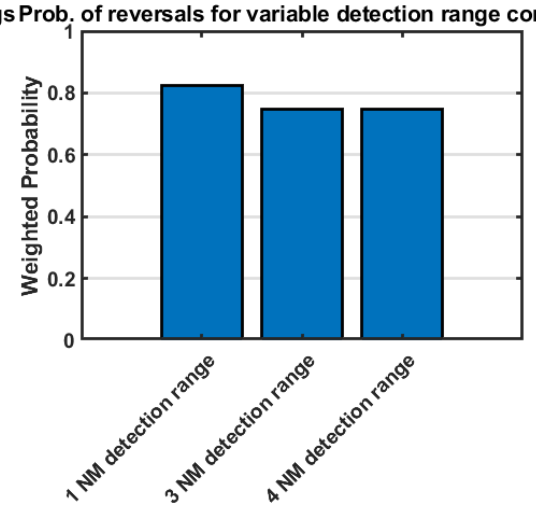




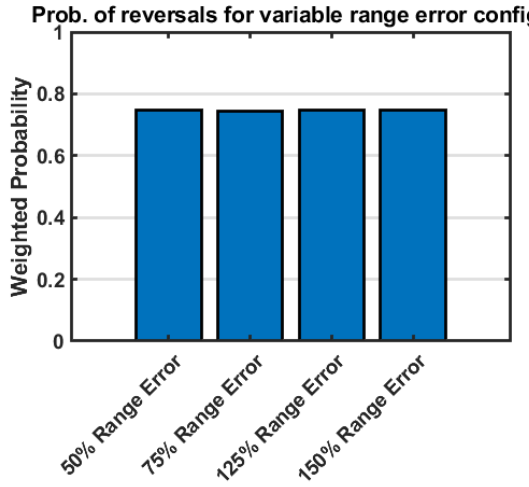
Operational Suitability Metrics (Reversals)

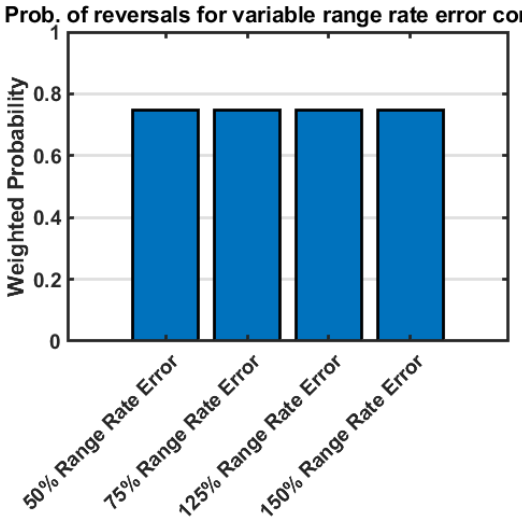




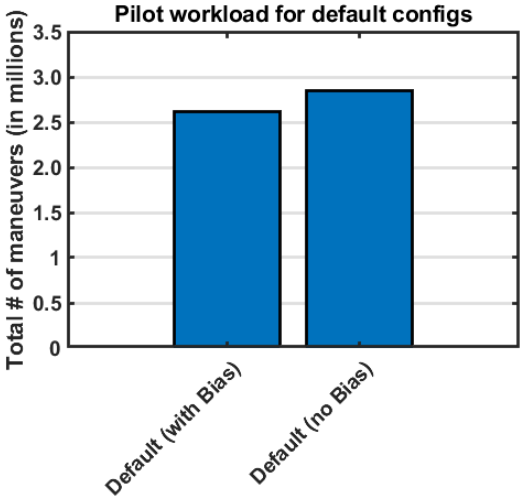


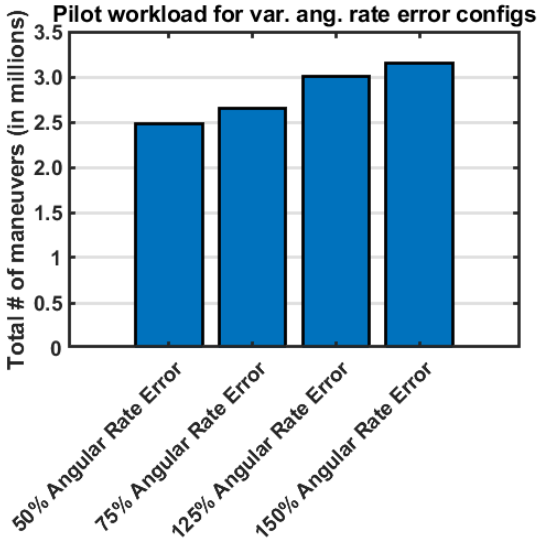
- These plots show the probability of a reversal occurring in an encounter
  - These metrics are only for encounters where there was a nominal LoWC
- The parameters that have the largest effect on reversals are variable angular rate and variable detection range
  - Range bias also has some effect on reversals
  - There are reversals for a large majority of encounters with a nominal LoWC



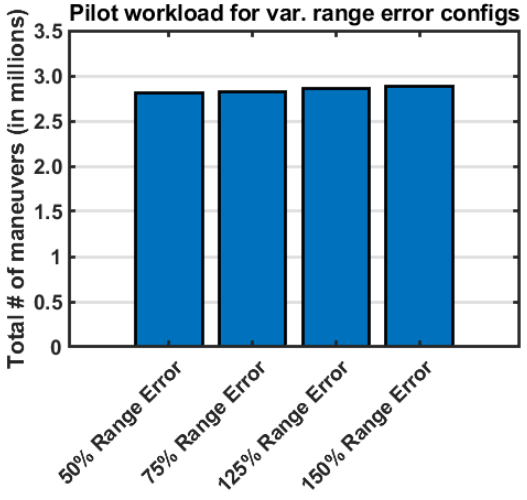


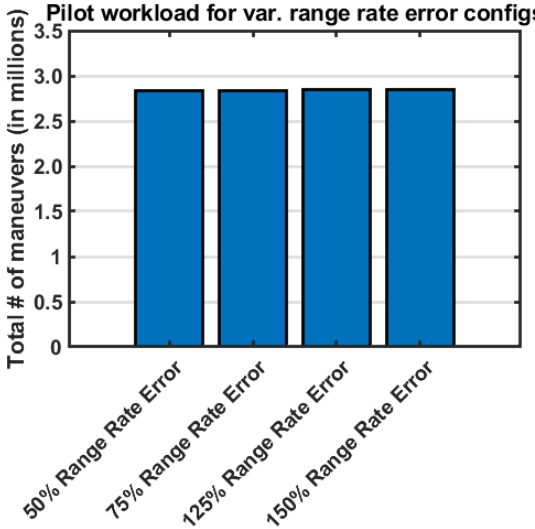
Pilot Workload



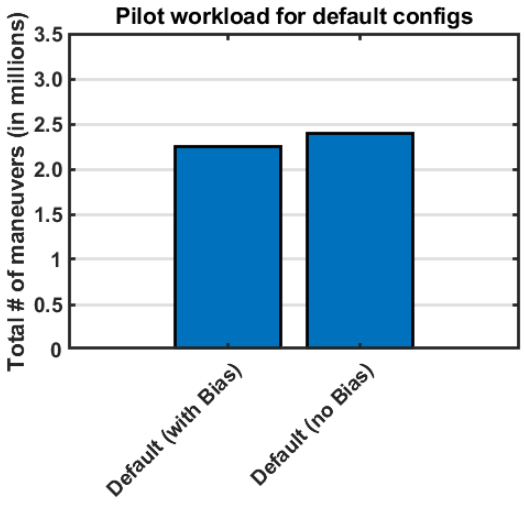


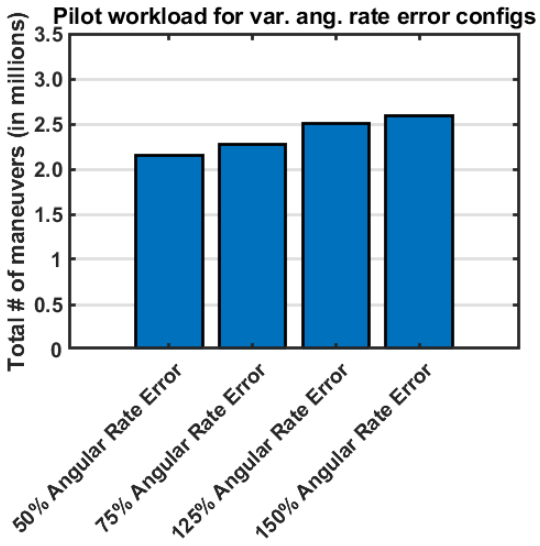
- Results are for all encounters
- Angular rate and detection range have the largest effect on pilot workload
  - Range bias also has some effect on pilot workload

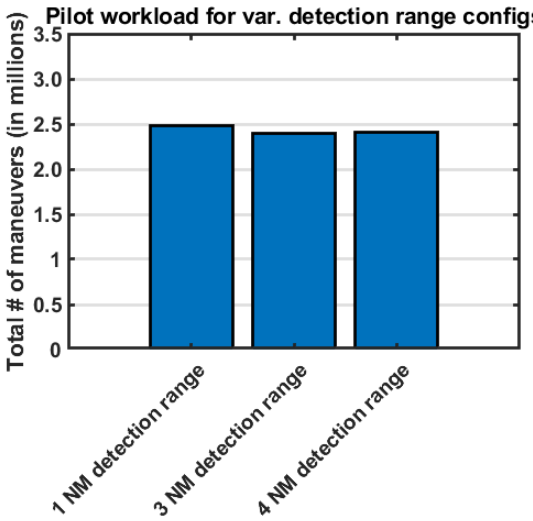


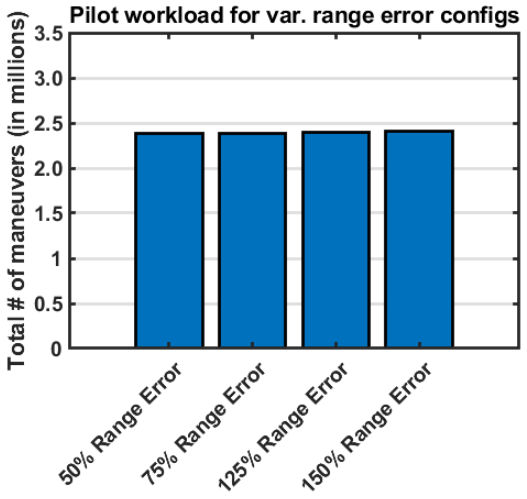


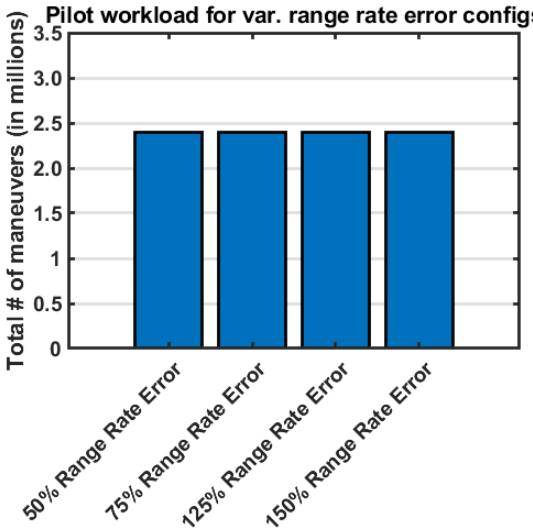
Pilot Workload (Nominal LoWC)





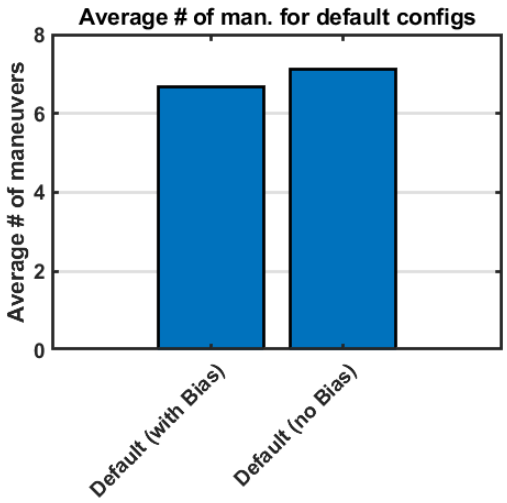


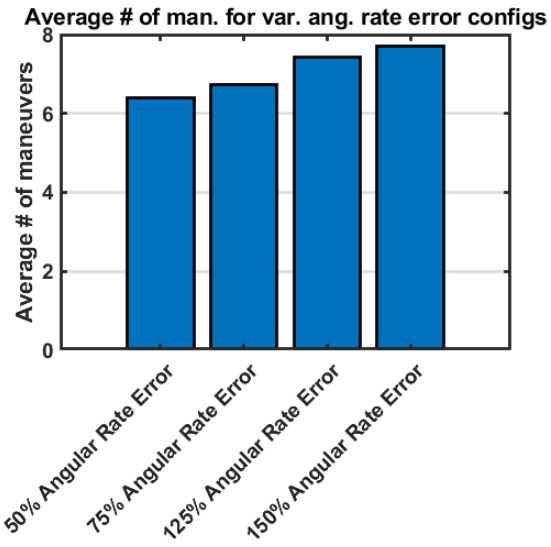


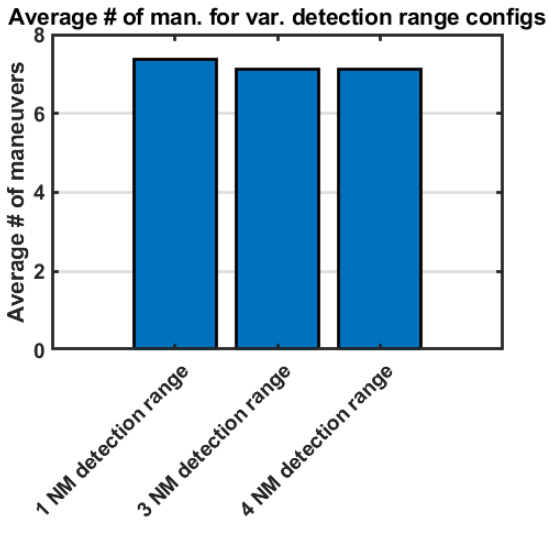


- Results are for encounters that had a nominal LoWC
- The parameters that have the largest effect on pilot workload are variable angular rate and the range bias for the default case
  - Variable detection range also has a small effect on pilot workload

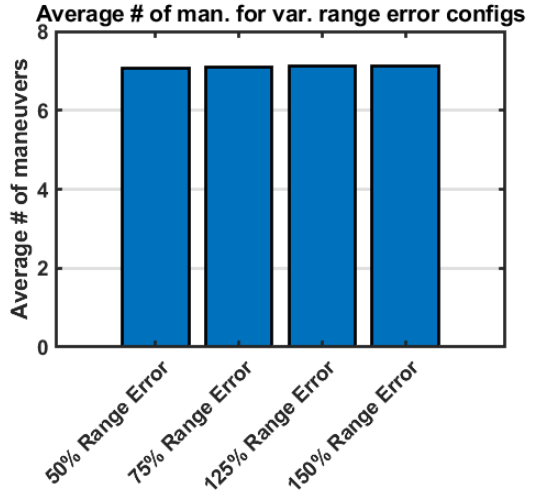
Average number of maneuvers per nominal LoWC

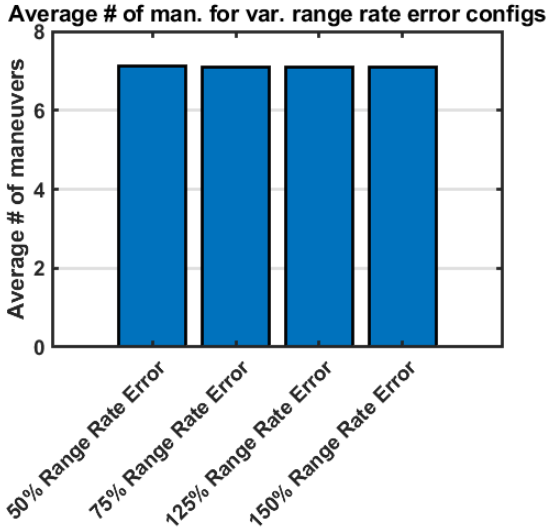




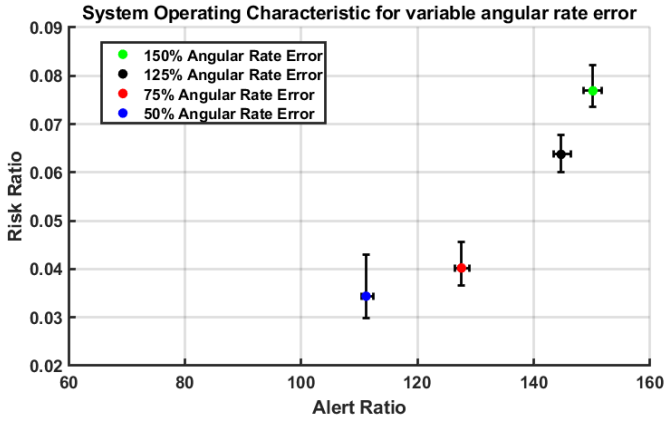


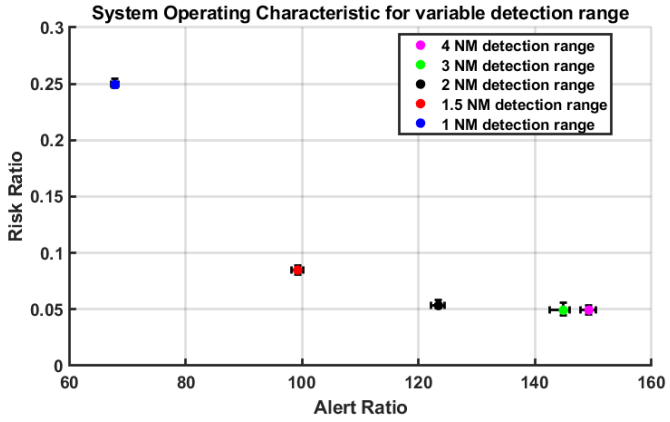
- Results are for encounters that had a nominal LoWC
- These graphs show the average number of maneuvers for encounters where there was a nominal LoWC
  - The parameters that have the largest effect on the number of maneuvers is the angular rate

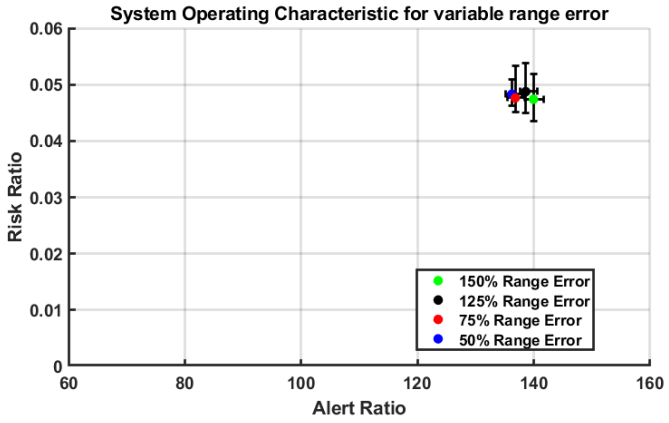


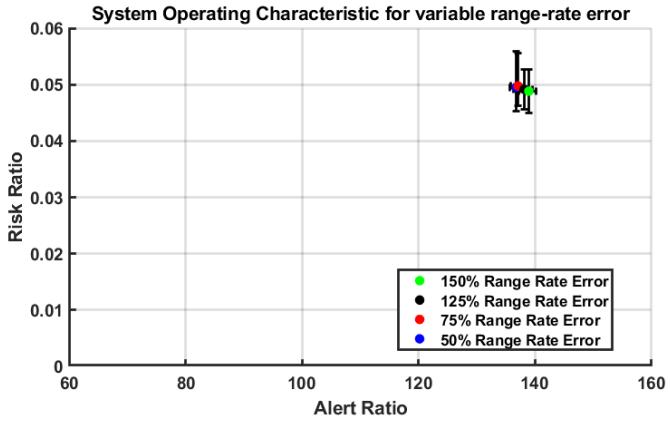


System Operating Characteristic









- There is a common trend among all configurations, where a larger error leads to a larger alert ratio
  - For detection range, a smaller detection range leads to a smaller alert ratio

Conclusion

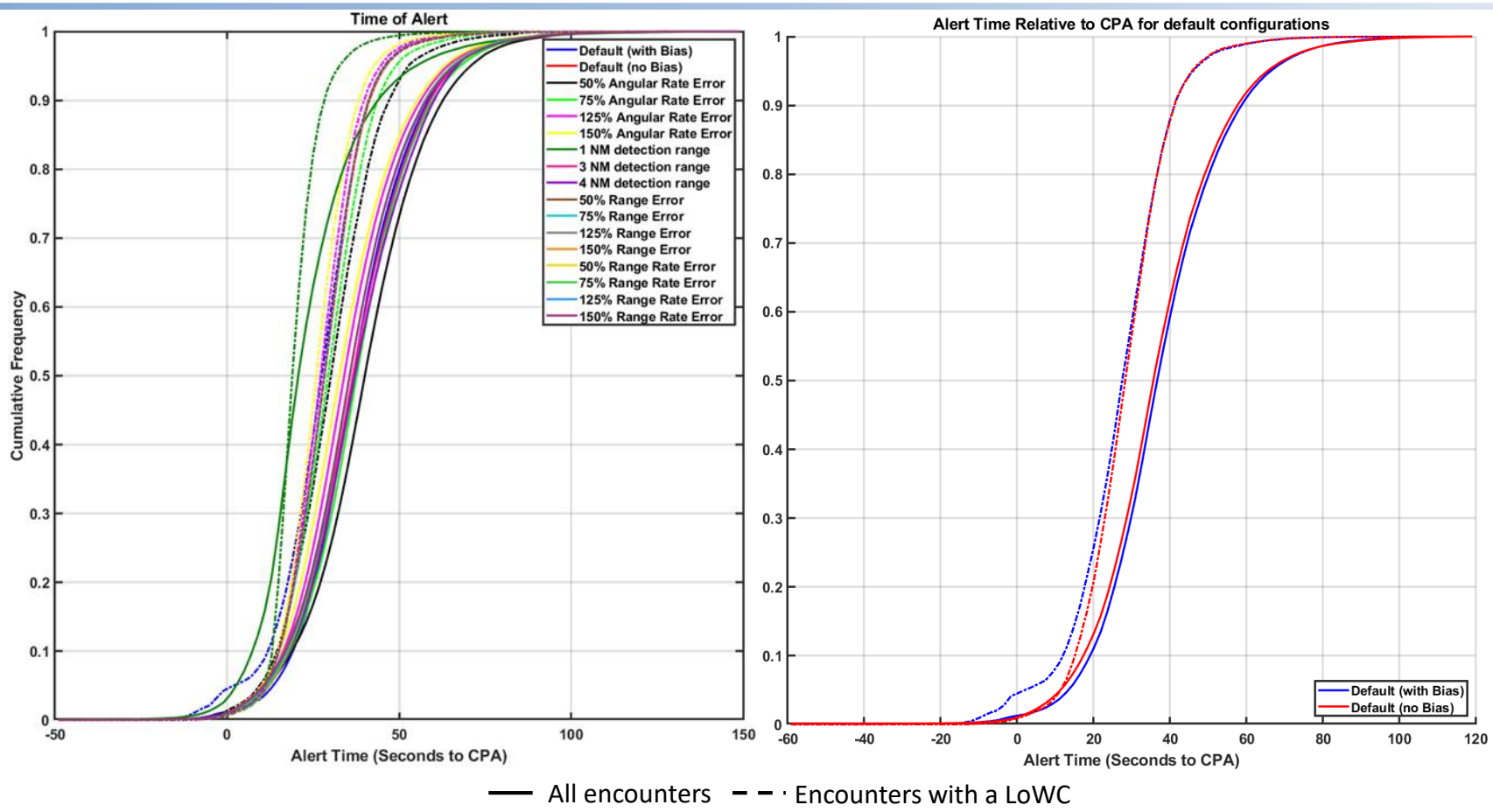
- Variable angular rate error and variable detection range have the greatest effect on operational suitability metrics, especially alert ratio and workload
  - Reversals and splits are largely unaffected by EOIR parameters
- Require EO/IR WG feedback: are the results presented thus far sufficient to establish associated MOPS requirements, or are additional data required?

Backup Slides

Alerting Time and Range

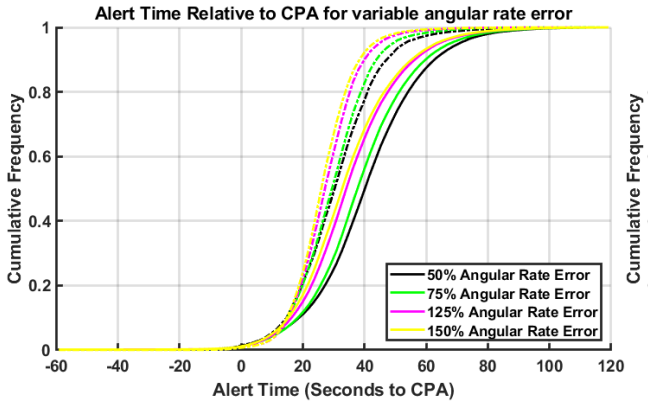
- These graphs on the next few plots show results for encounters **with response to DAIDALUS guidance**
  - Dashed lines show the alert time for cases where there is a LoWC even with mitigation
  - Solid lines show the alert time for all encounters

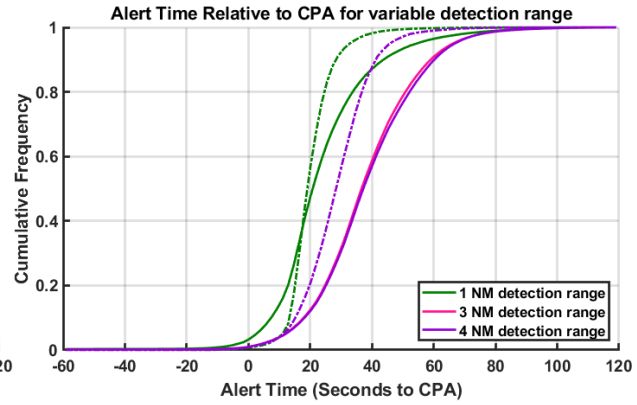
Time of Last Alert

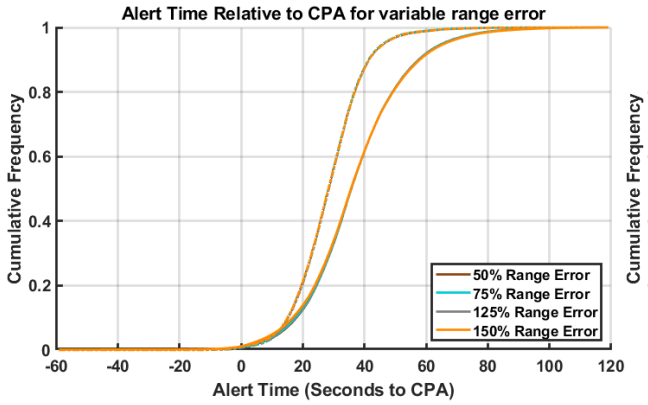


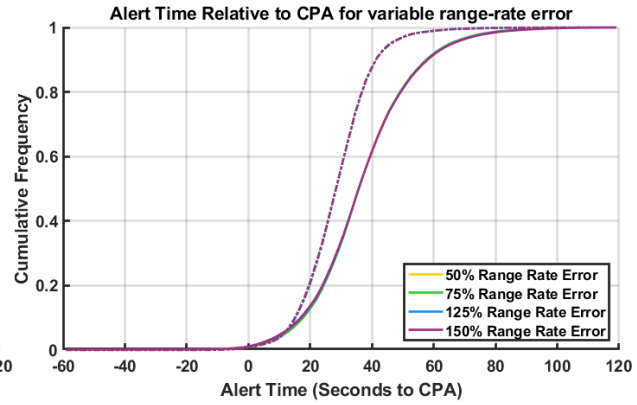
- Time of last alert is the time of last transition from no alert to any alert before a maneuver is made

Time of Last Alert





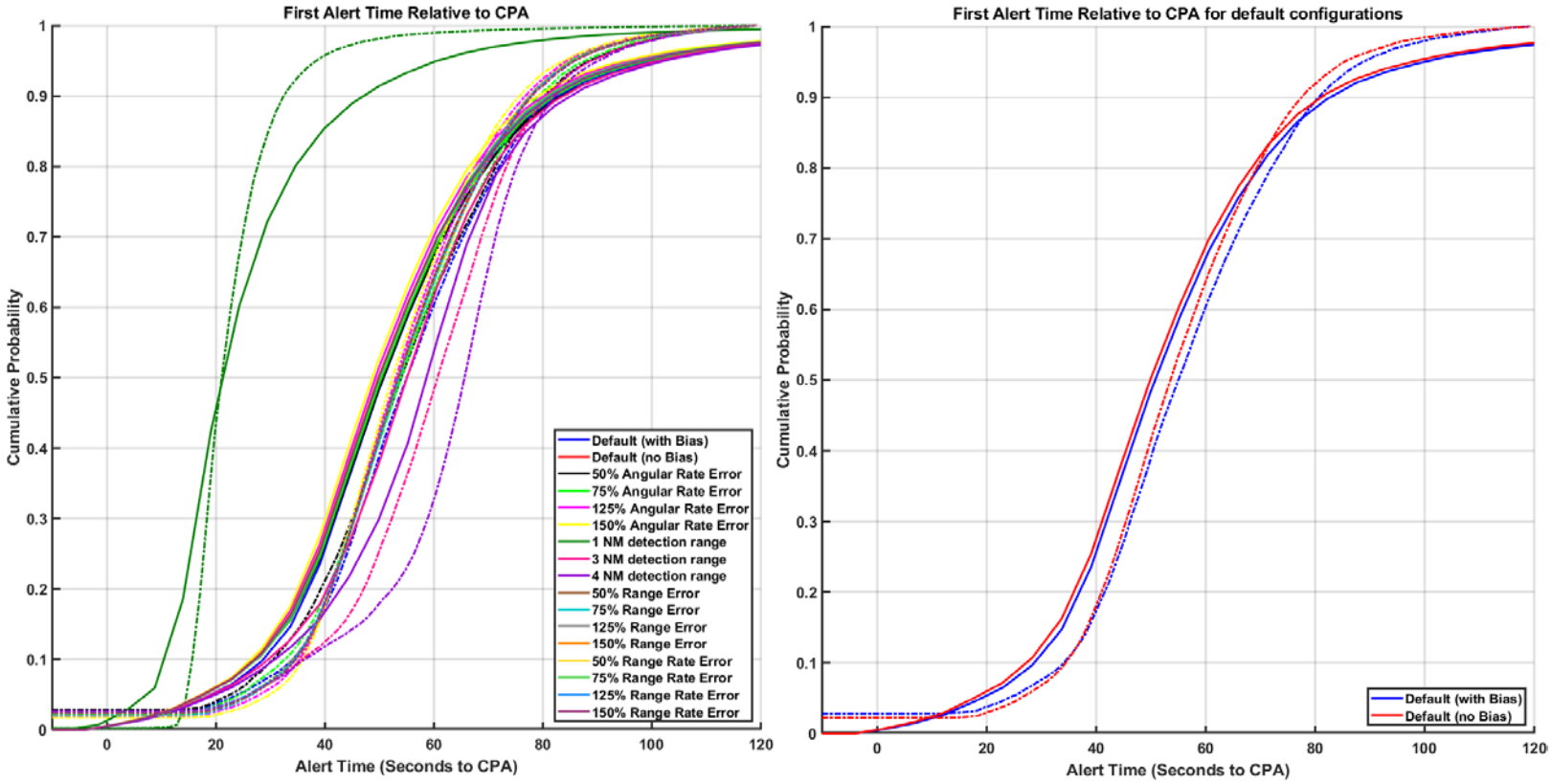




All encounters Encounters with a LoWC

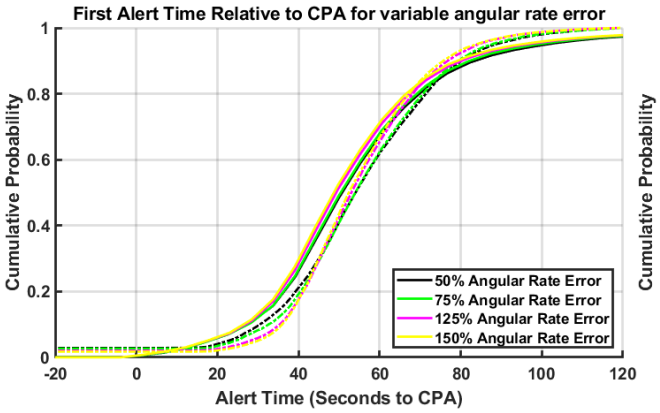
- The variable angular rate error cases show that the ownship alerts later for higher angular rate errors
- The variable detection range alert time only changes for the 1 NM alerting range

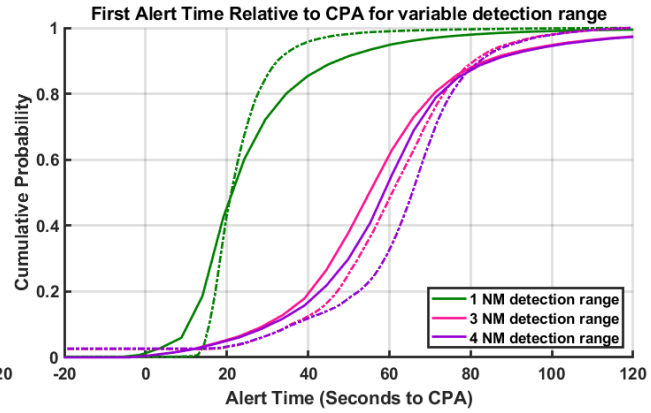
First Time of Alert

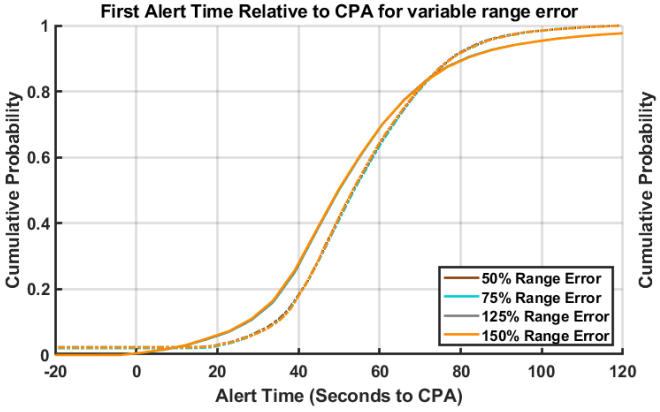


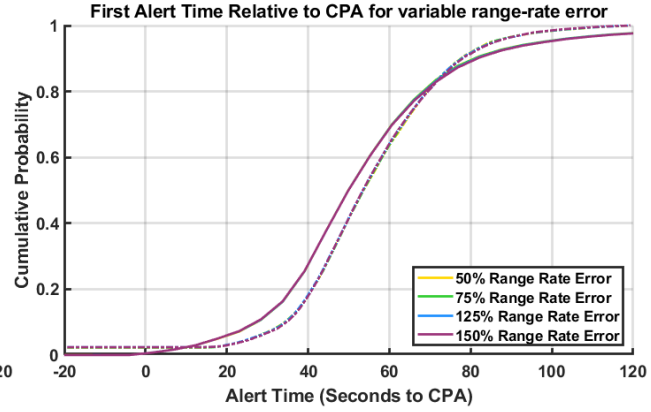
- First time of alert is the first time in the encounter where there is an alert of any kind, relative to the time of nominal CPA
- The ownship alerts earlier in encounters where there is a LoWC even with mitigation
- In general, the first time of alert is slightly earlier for the Default with bias case than for Default without bias case

First Time of Alert





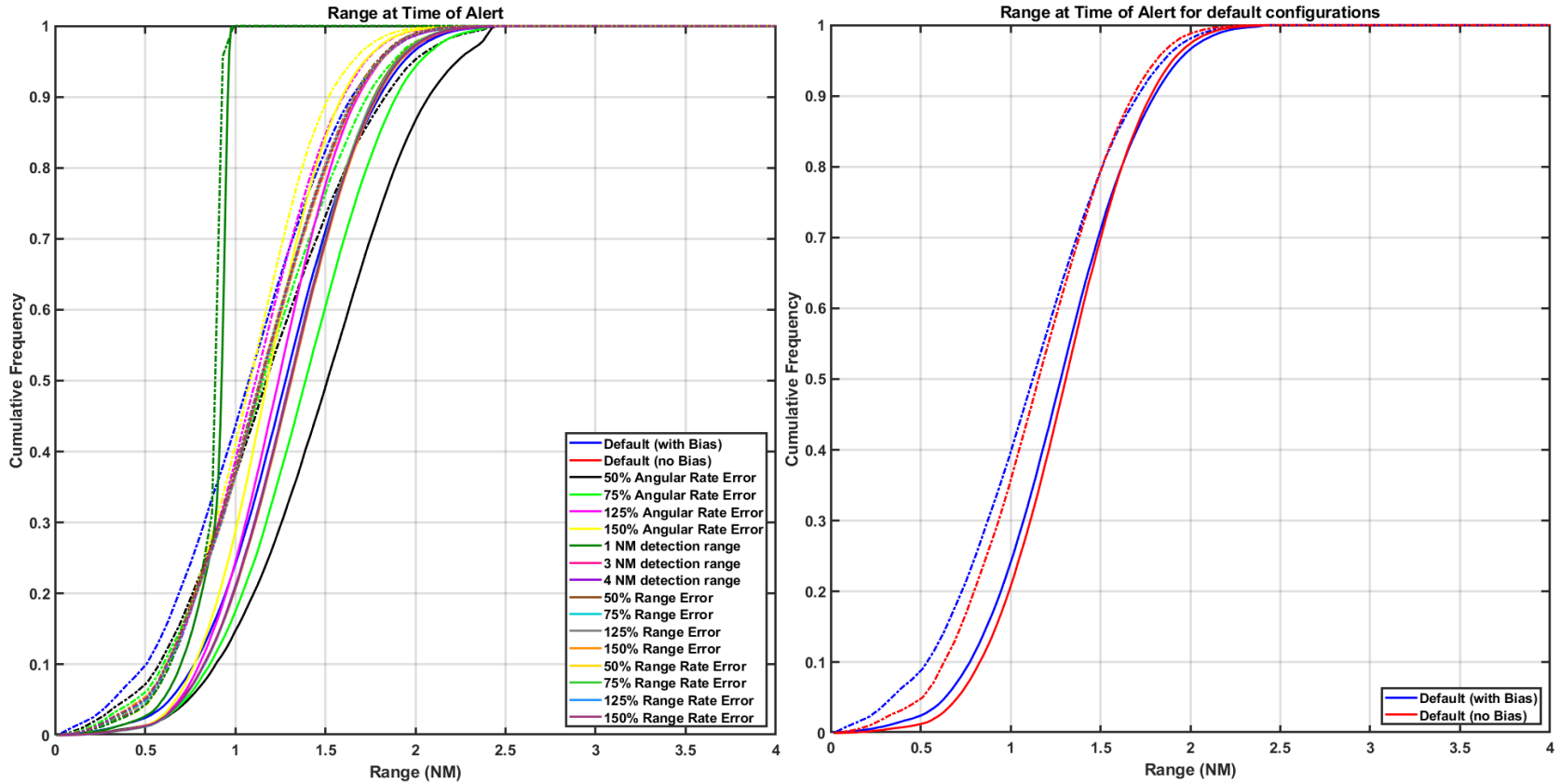




All encounters Encounters with a LoWC

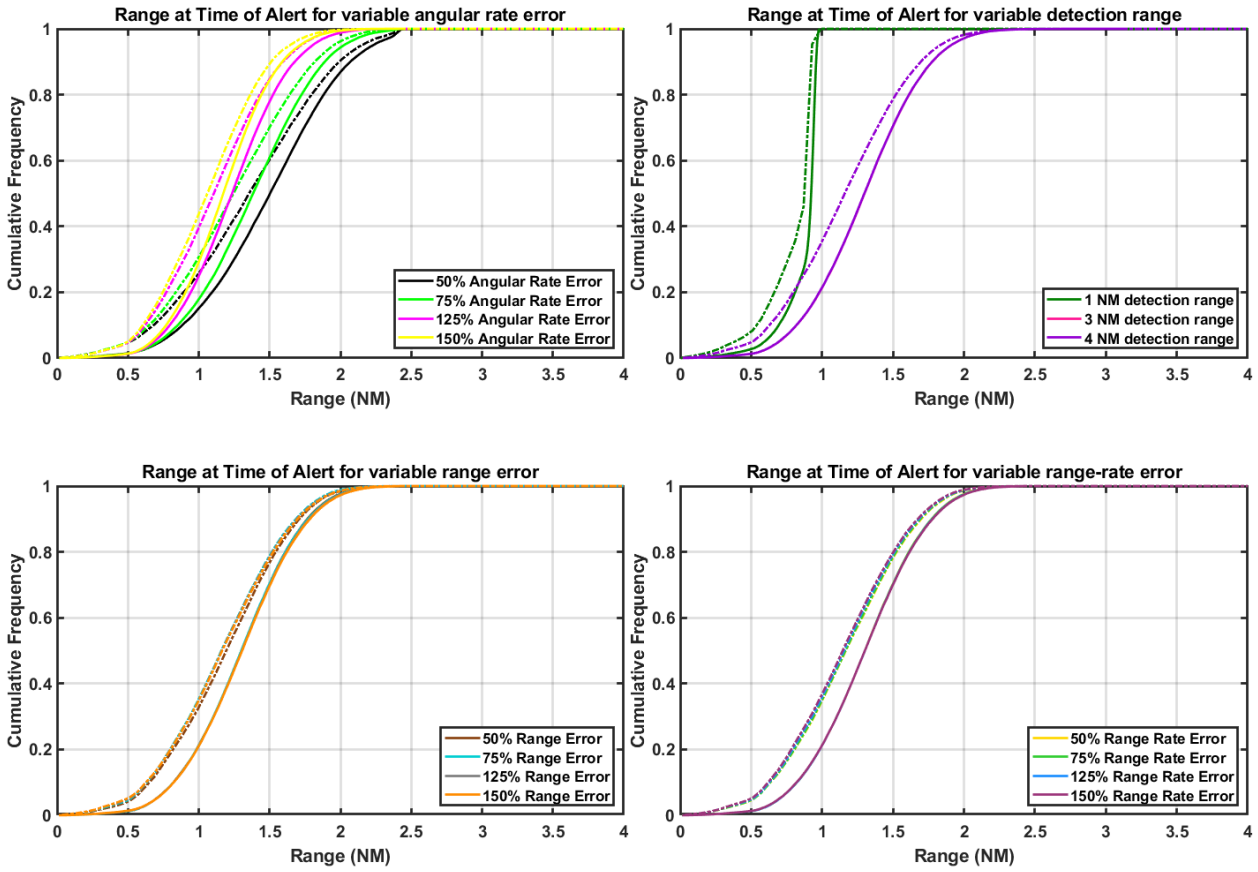
- The only cases where there is variability in the graphs are the cases where the angular rate error and detection range are being varied

Range at Time of Alert



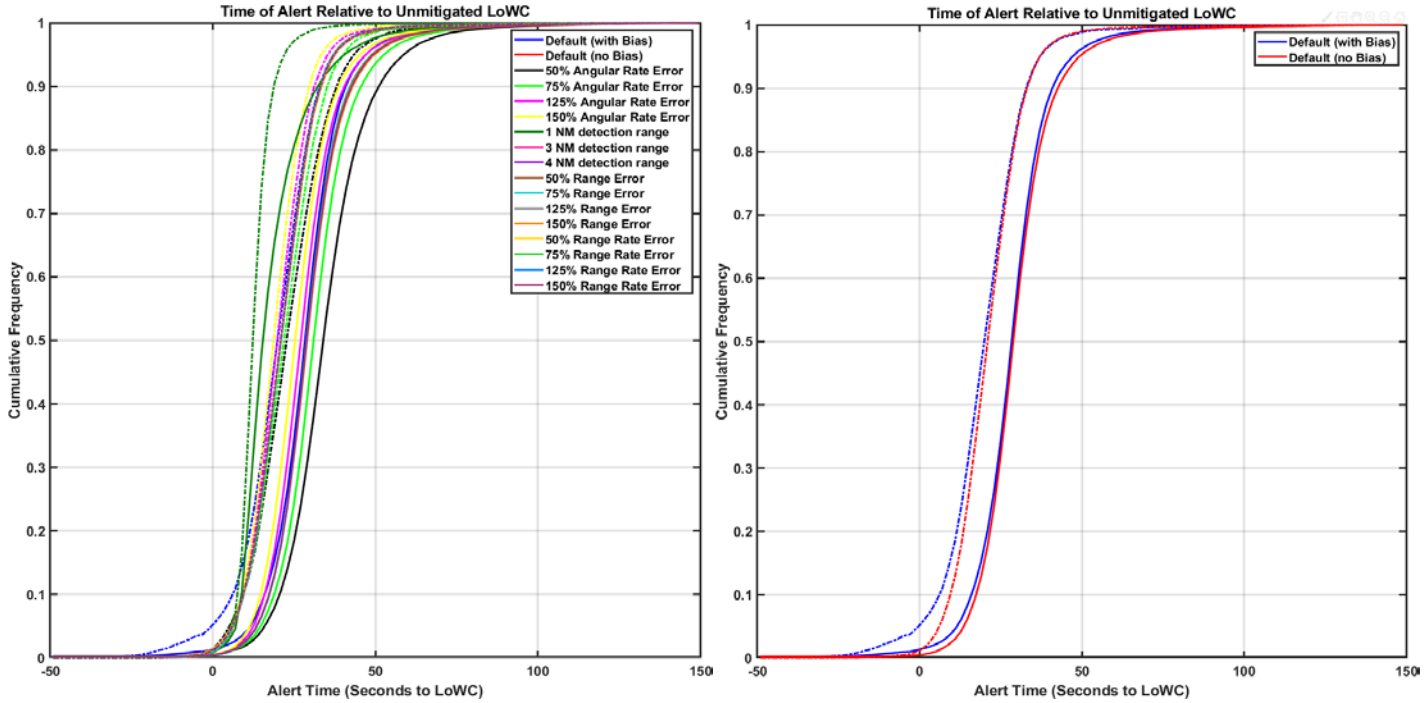
- Plots show range at time of last alert
- 50% angular rate error alerts at the furthest range, followed by 75% angular rate error
- In general, the default without bias case alerts at a slightly further range than the default with bias case

Range at Time of Alert



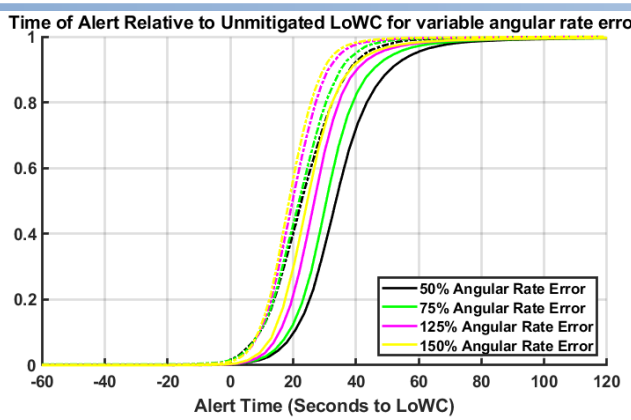
- Range at time of last alert follows the trend where there is significant difference when the angular rate is varied
- For detection range, the 3 NM and 4 NM cases typically do not alert before 2.5 NM due to noisy measurements from the EOIR sensor

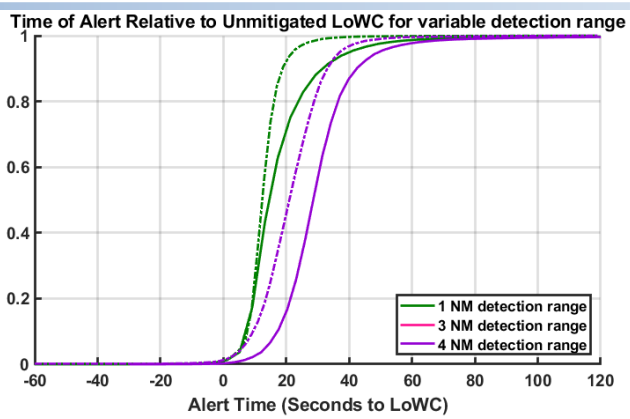
Time of Last Alert relative to LoWC

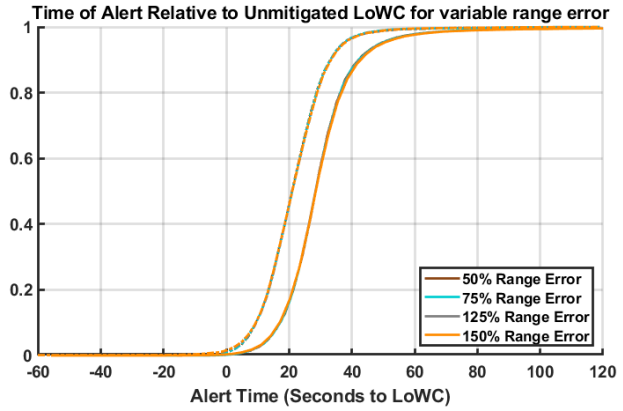


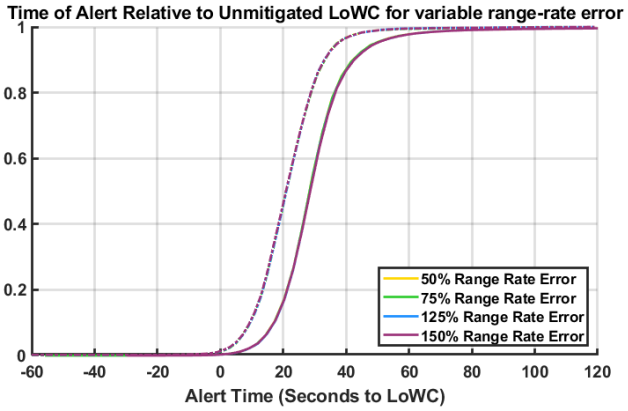
- These graphs show the time of last alert relative to unmitigated LoWC

Time of Last Alert relative to LoWC









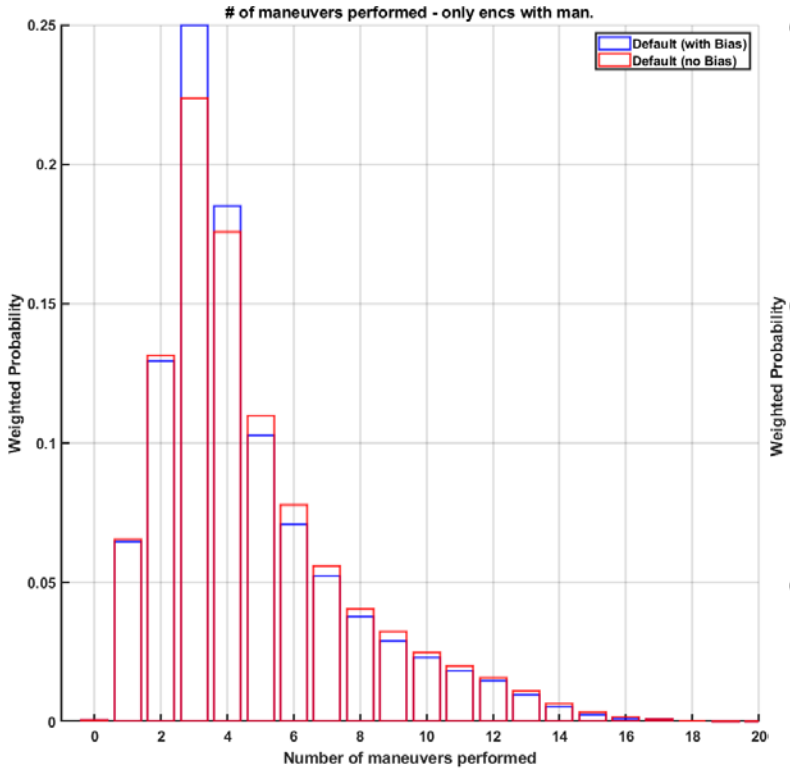
- These graphs show the time of last alert relative to unmitigated LoWC
  - Less angular rate error leads to an error alert relative to LoWC

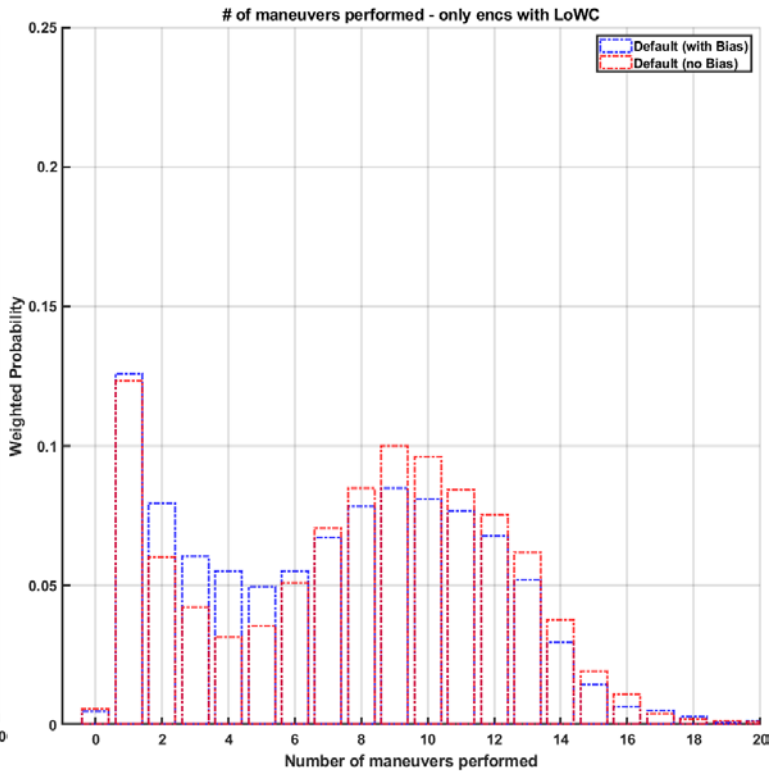
Pilot Response Model

- Use SC-228 pilot model created by Lincoln Laboratory
  - Executed in deterministic mode
    - Always maneuvers horizontally in the direction of the minimum suggested maneuver; turns left if minimum suggestion is inconclusive
    - Follow guidance bands without buffer
  - Timing:
    - Decision updated according to alert state
    - Execution delay after decision: 3 sec
- Analyze horizontal maneuvers only
  - Low-SWAP turn rate: 7 deg/sec

Alert State	Decision Update Periods (s)
No Alert	24
Proximate Traffic	24
Preventive Alert	15
Corrective Alert	9
Warning Alert	9
Loss of Well Clear	3

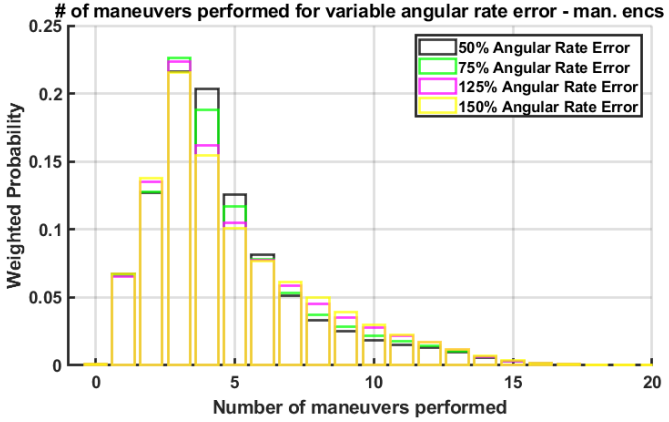
Number of maneuvers performed

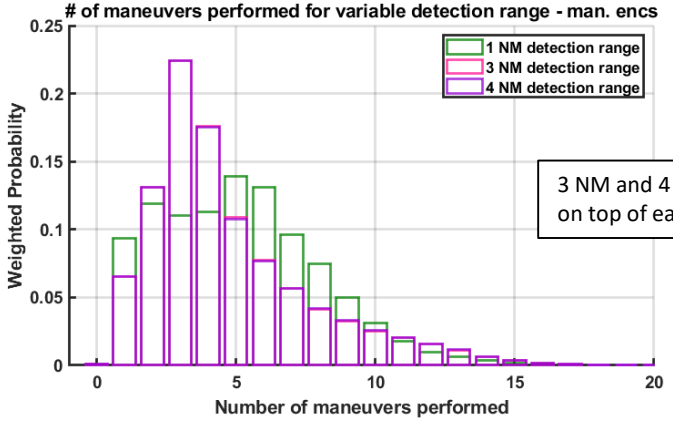




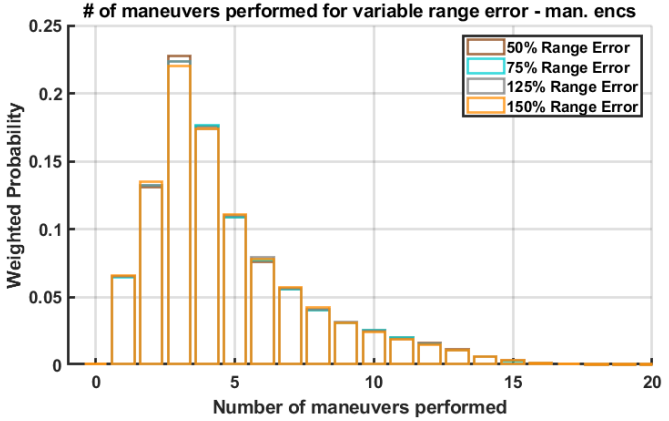
- In encounters where there is a LoWC despite maneuvering, the ownship tends to maneuver up to 10 times or more
- The default with bias configuration maneuvers less than the without configuration case (in cases where there is at least 1 maneuver)

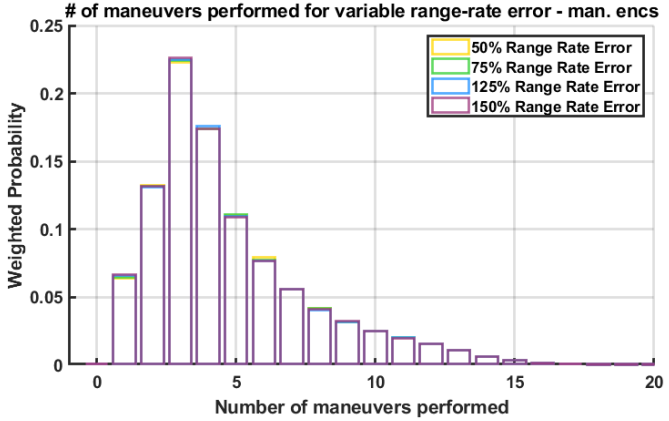
Number of maneuvers performed





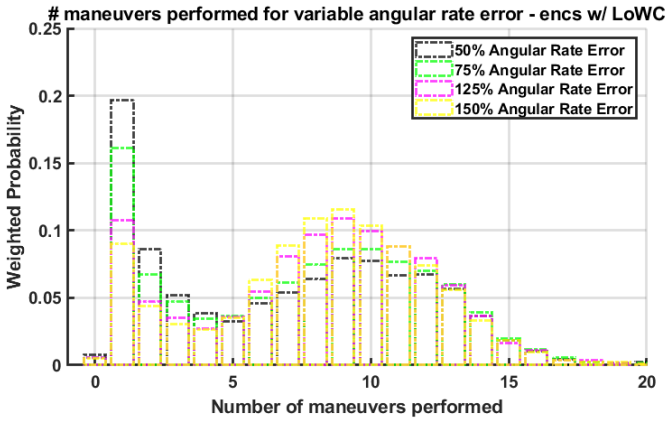
3 NM and 4 NM bars are on top of each other

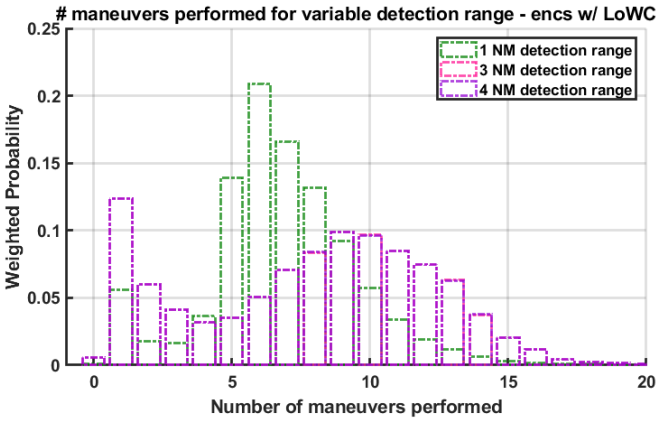


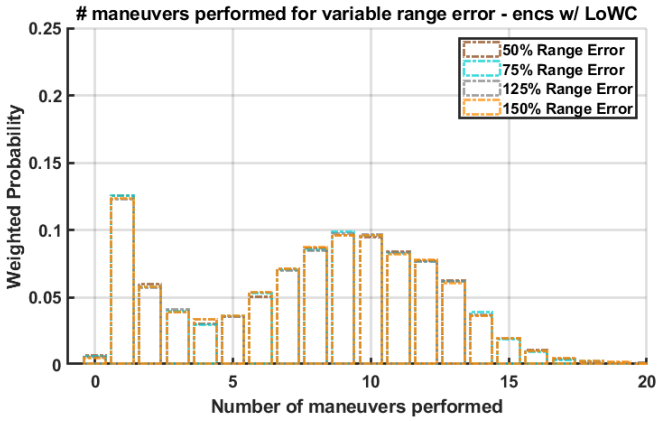


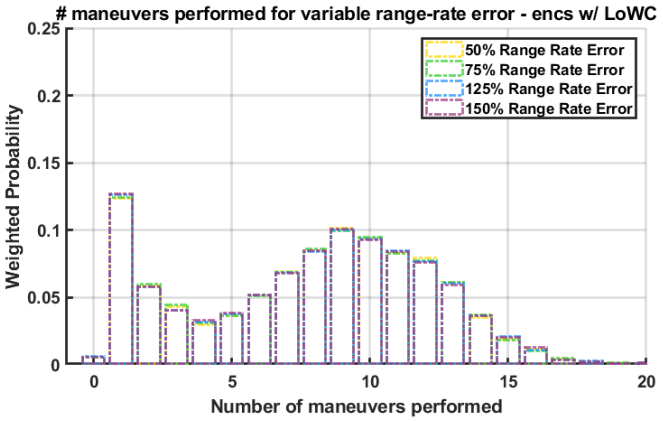
- The greatest variability in maneuvers is for the variable angular rate error and variable detection range cases
  - The larger the angular rate error is, the more the ownship tends to maneuver
  - These metrics only include maneuvers where at least one mitigation maneuver was performed

Number of maneuvers performed



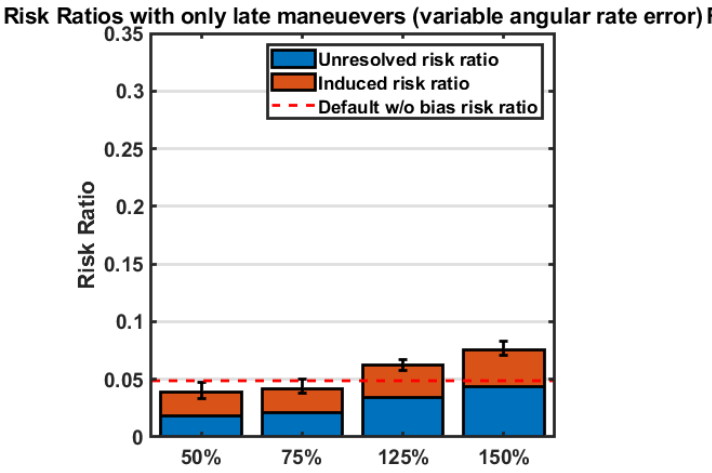


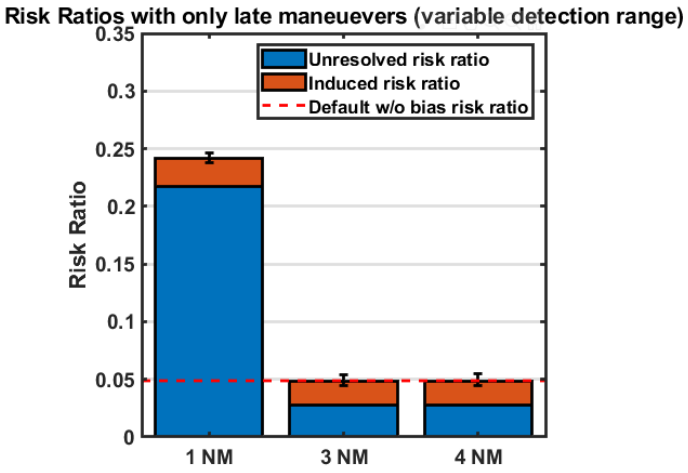


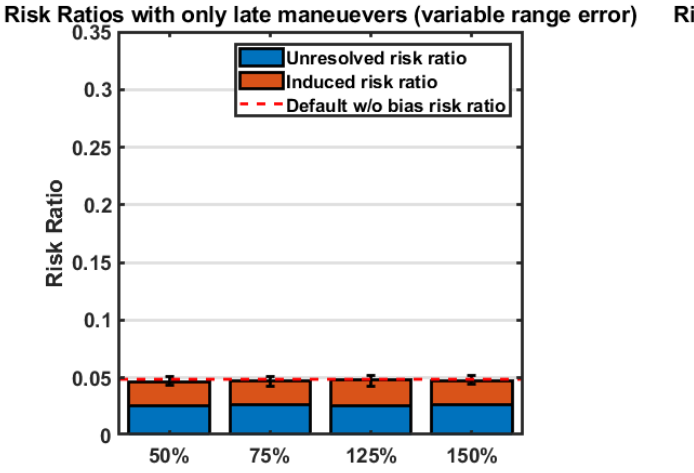


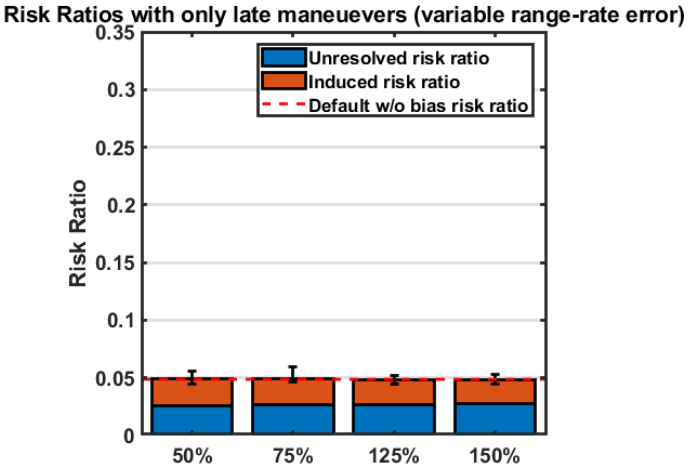
- The trend for the variable range and range-rate error matches that of the default configurations
- The trend for the variable angular rate error and variable detection range follows that of the no LoWC case

Risk Ratio with late maneuvers comparison



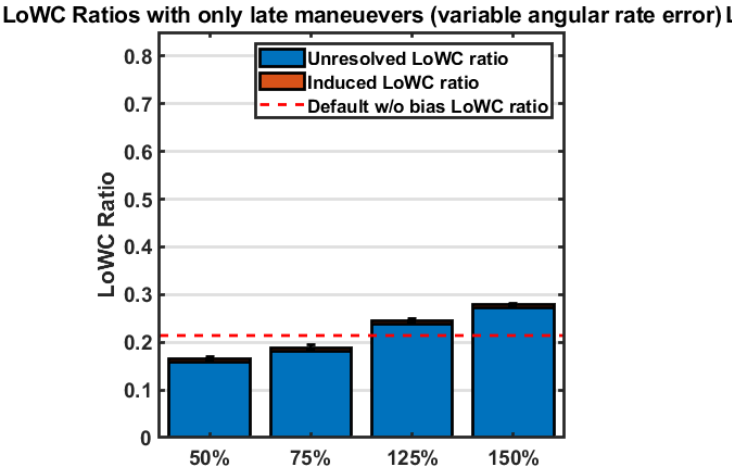


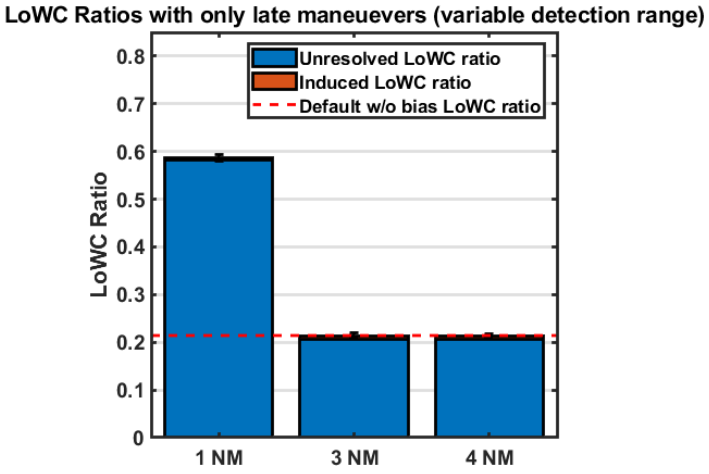


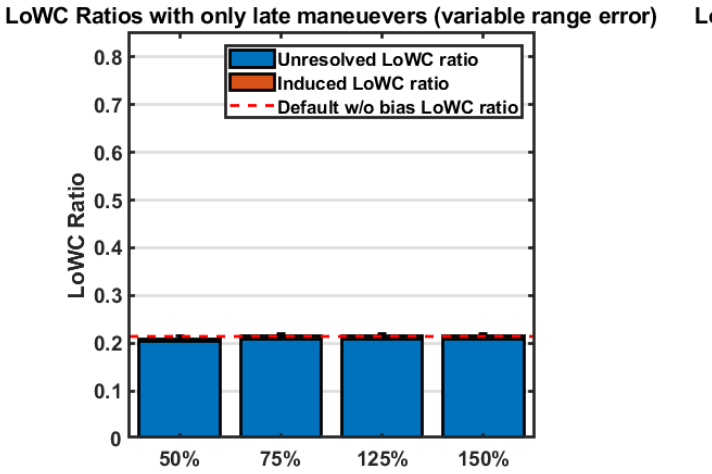


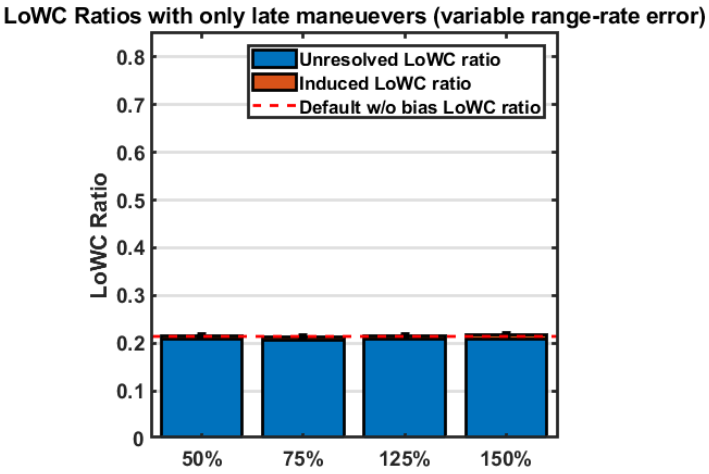
- The risk ratios for late maneuvers is virtually identical to the risk ratio for all encounters

LoWC Ratio with late maneuvers comparison









- The LoWC ratios for late maneuvers is virtually identical to the risk ratio for all encounters