EOIR Safety and Operational Suitability Metrics Analysis

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Overview

- Objective: evaluate DAA safety and operational suitability sensitivity to EO/IR characteristics to inform the MOPS
- Presented preliminary safety results in October: this slide package includes additional metrics that were collected during the EO/IR simulation runs
  - Additional metrics include operational suitability metrics such as splits, reversals and pilot workload
  - 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

- Extended parameter sweeps were performed based on feedback

EO/IR Simulation Assumptions

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

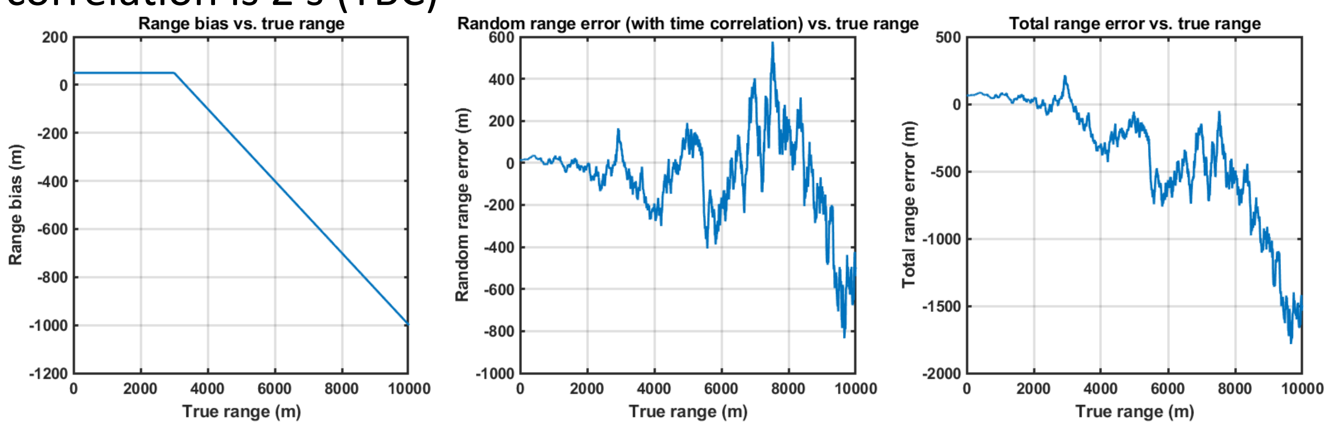
      30 seconds for Warning

      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: NASA UAS trajectories for the ownship vs. MIT LL uncorrelated encounter model for the intruder
  - 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)

      Bias not considered in default model configuration
    - $\sigma(R) = 0.03 * R$ (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)

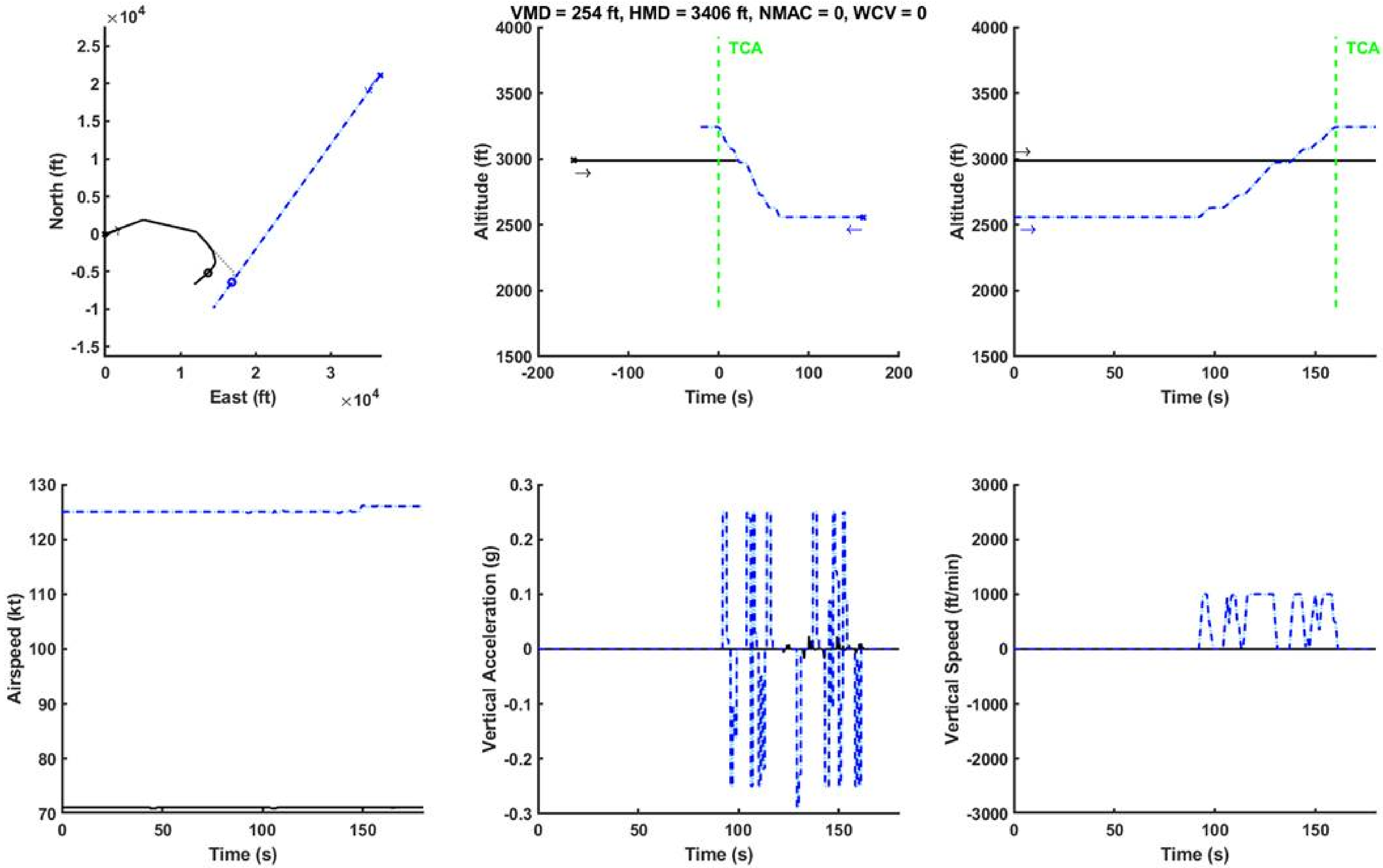
  Temporal decay time is approx. 10 samples

- No field of regard (FOR) limits for azimuth and elevation
- 2.5 nautical mile detection range

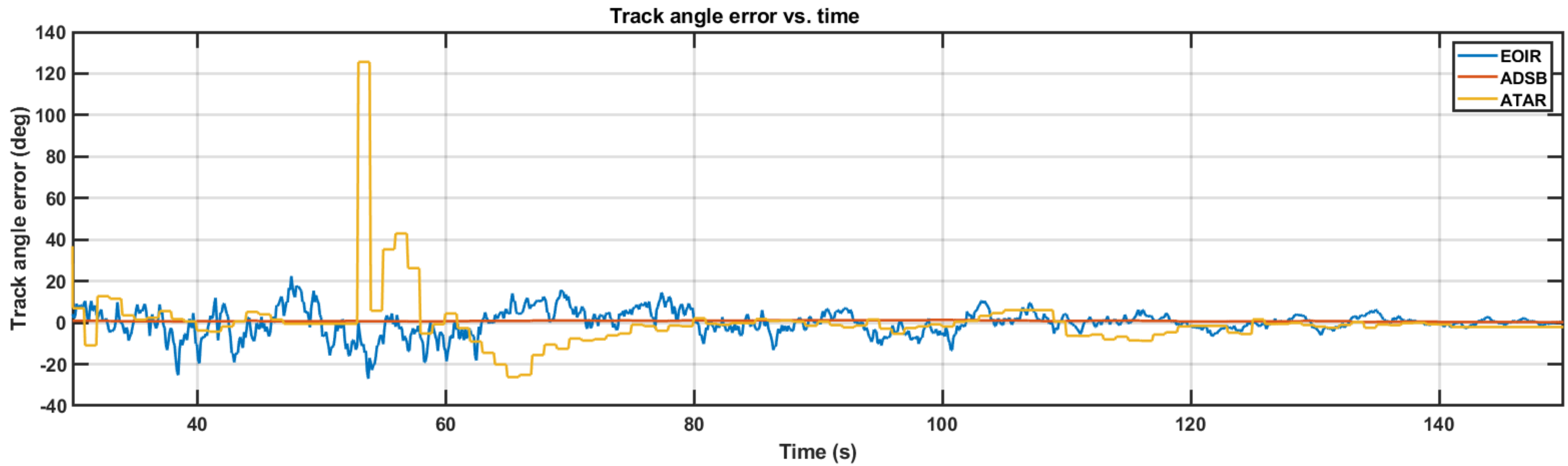
1. Farjon J., “White paper EO/IR sensor model”, SAFRAN ED, 2019

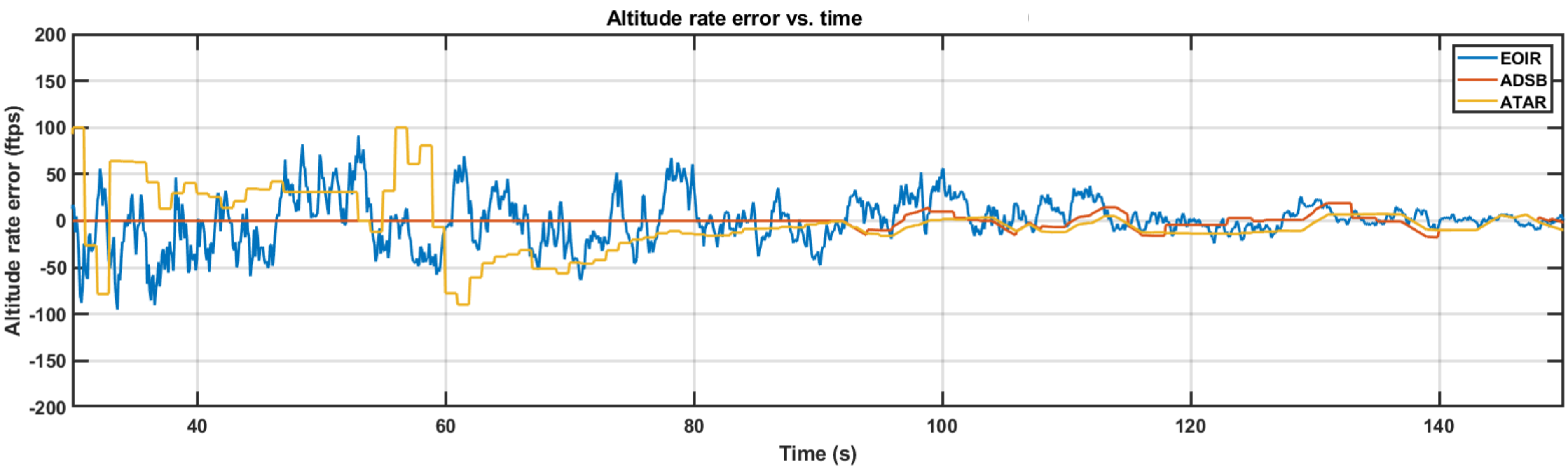
Example Encounter 1

Black line is ownship; Black dotted line is ownship nominal trajectory; Mitigated trajectory uses EOIR for DAA
Blue dashed line is intruder

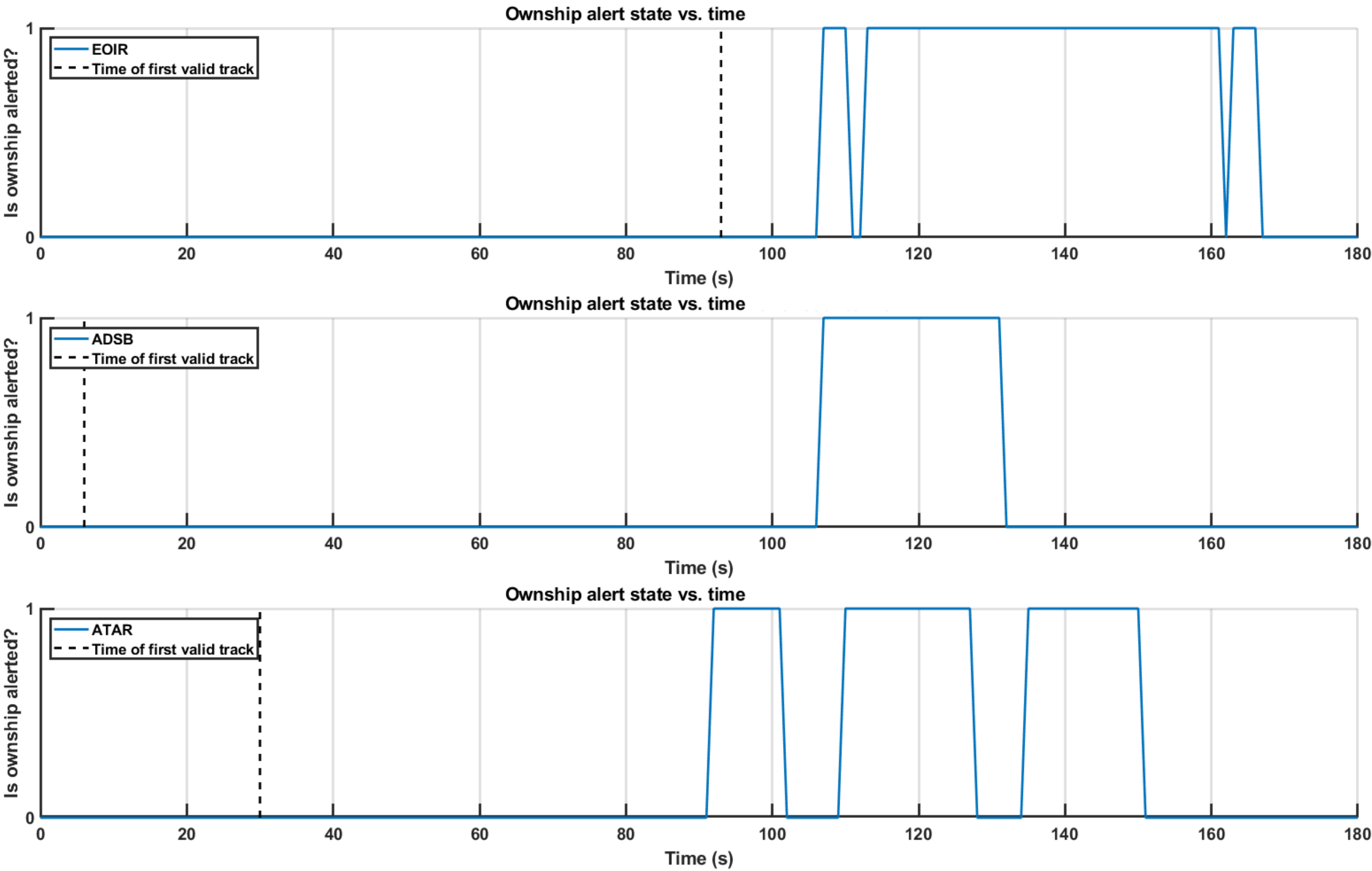


Track angle and vertical rate residual for example encounter 1



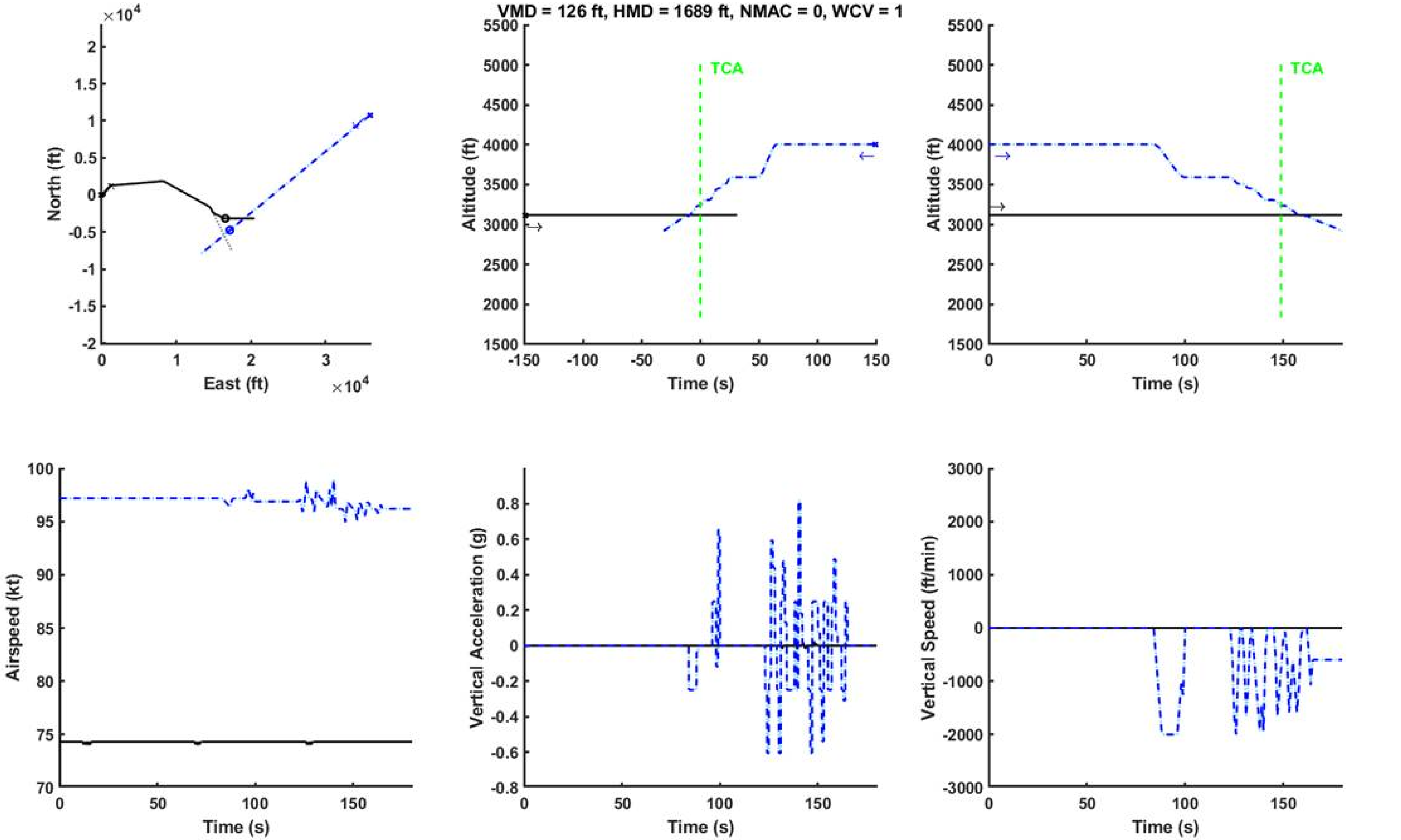


Ownship Alert state for example encounter 1

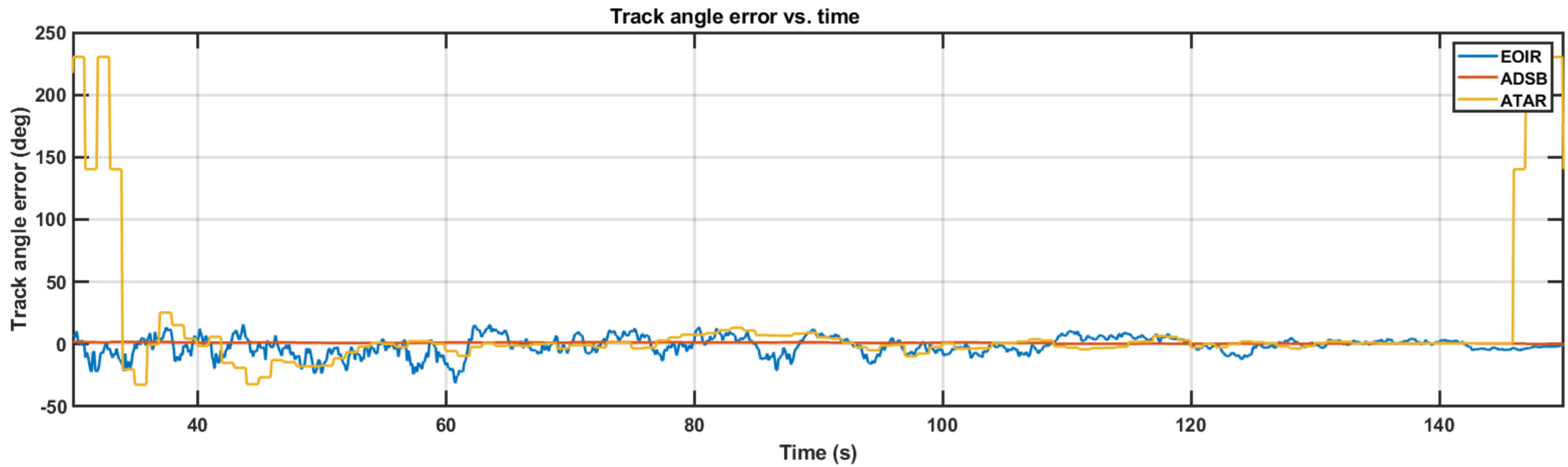


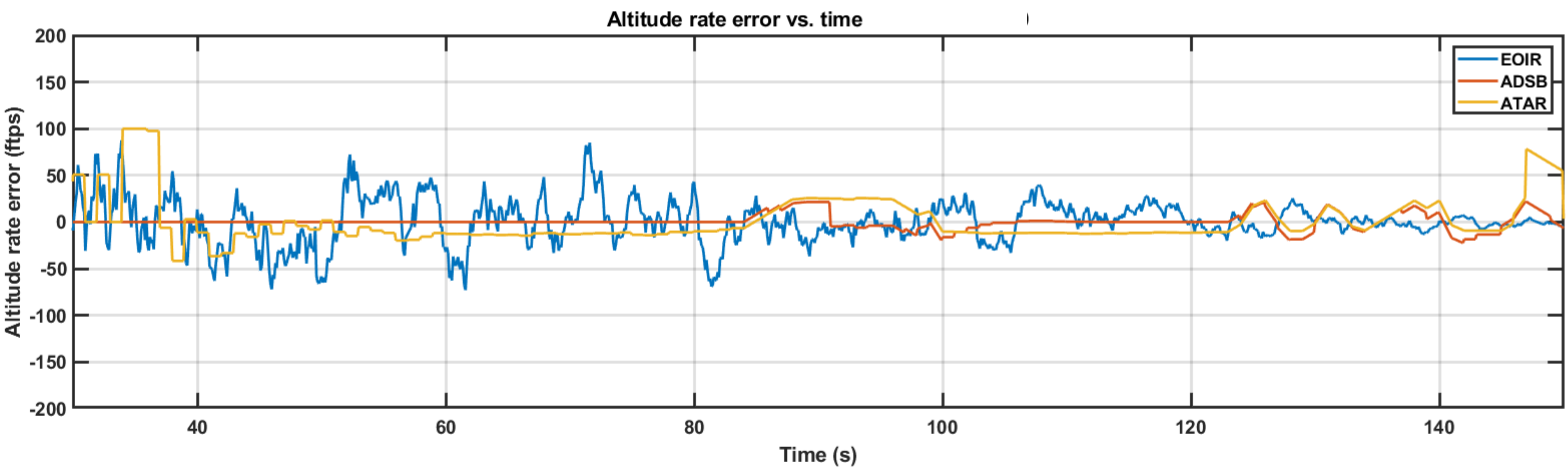
Example Encounter 2

Black line is ownship; Black dotted line is ownship nominal trajectory; Mitigated trajectory uses EOIR for DAA
Blue dashed line is intruder

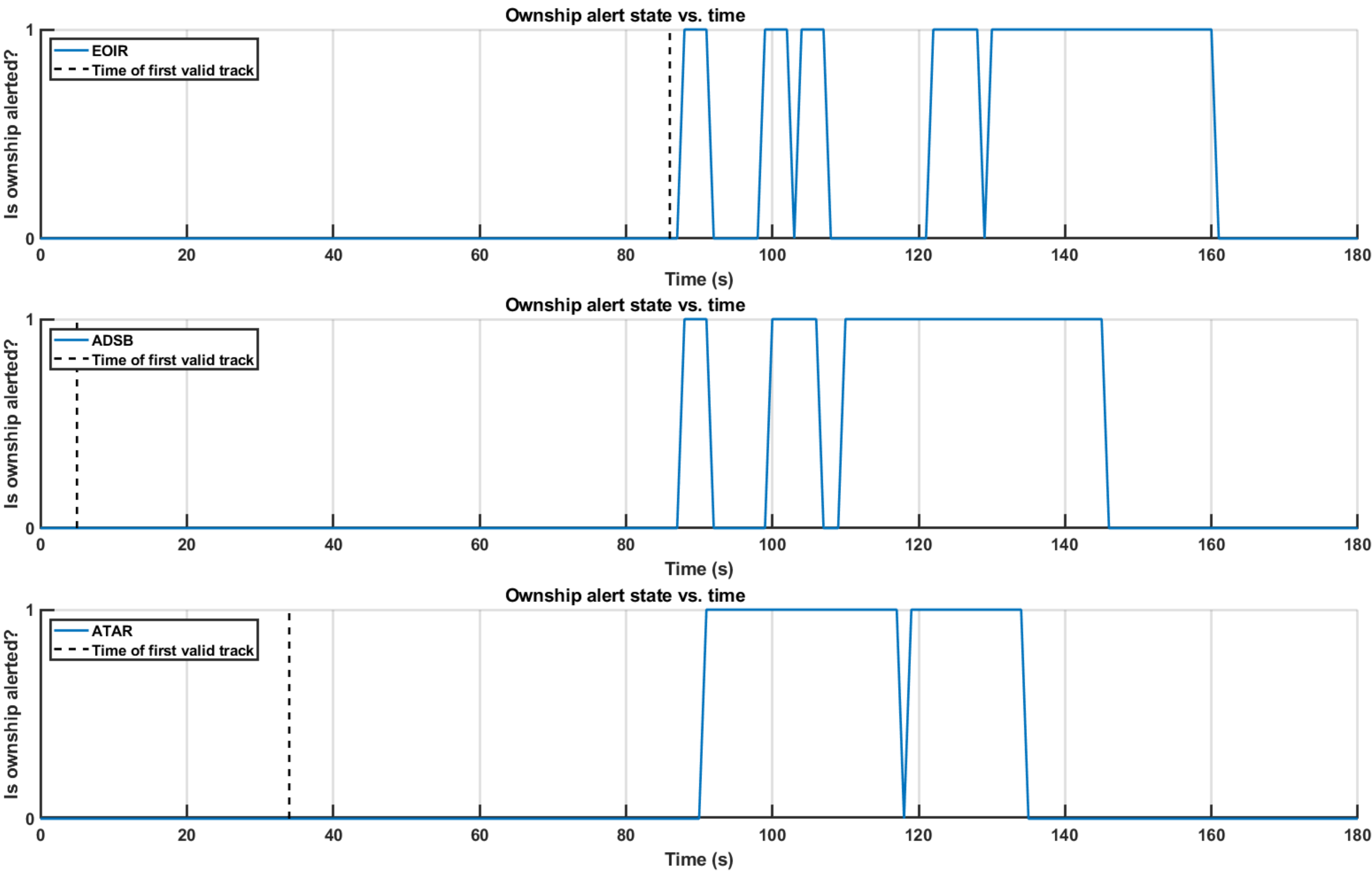


Track angle and vertical rate residual for example encounter 2





Ownship Alert state for example encounter 2



Example encounters

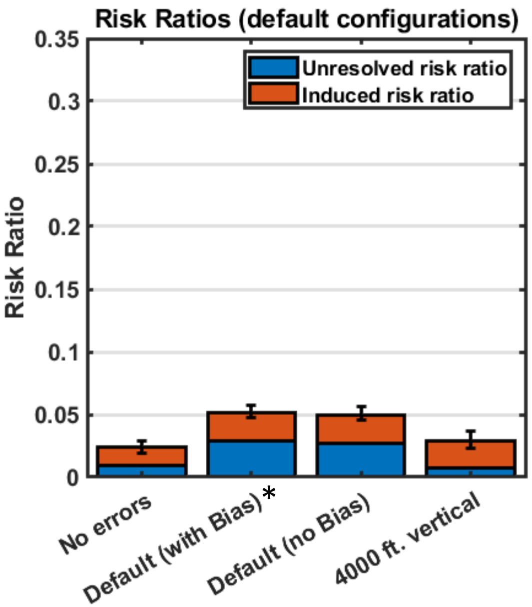
- The ADSB and ATAR sensors have their outputs put through the FAA Tech Center DAA Tracker, smoothing the tracks
- The EOIR sensor model output is not fed through a tracker, which causes noisy track angle and noisy vertical rate signals
- The ownship alert plots show that the EOIR sensor causes more splits when compared to using the ADSB or ATAR sensor

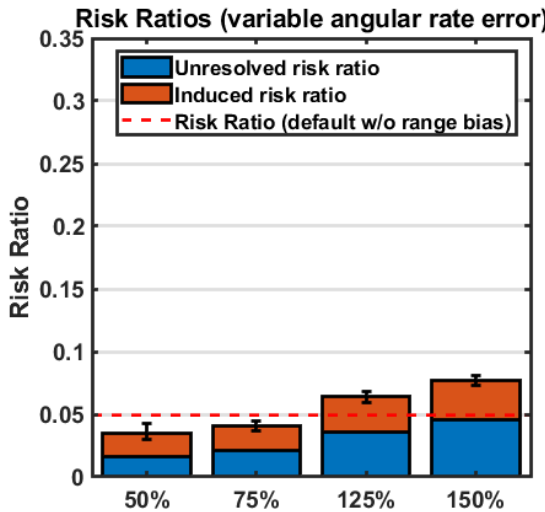
- Note:
  - Range time correlation = 5 sec for EOIR, 8 sec for ATAR (from Tech Center tracker)
  - Range rate time correlation = 2 sec for EOIR, 1.7 sec for ATAR (from Tech Center tracker)

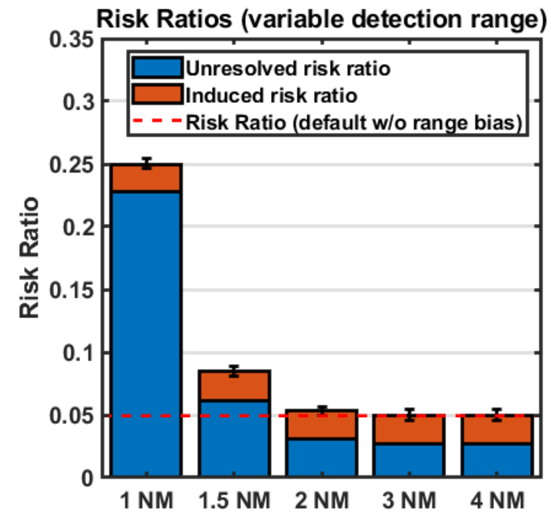
Approach

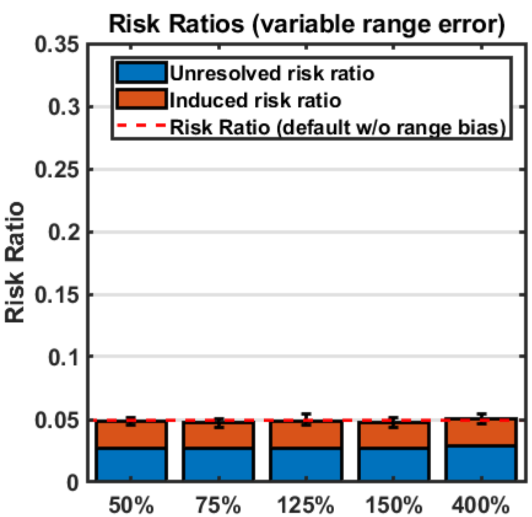
- General approach is to vary individual sensor parameters from the default parameters to evaluate sensitivity
  - Additional scenarios evaluated to contextualize the results:
    - No error: no measurement error or detection range limits
    - No bias: the default model parameters with the exception of the range bias
    - 4000 ft vertical: vertical alerting threshold of DAIDALUS set to 4000 ft (similar to the MOPS recommendation for encounters with noncooperative aircraft)
- It is assumed that there is not an additional filter after the EO/IR model, so the EO/IR outputs are used directly by the alerting and guidance
  - Therefore, the EO/IR output characteristics can form the basis for Table 2-20 in DO-365 (Single-Source Integrated Track Performance)
- Key safety metrics are risk ratio (based on NMAC) and LoWC ratio: measures the fraction of the events remaining after the DAA system is employed (desire much less than 1)

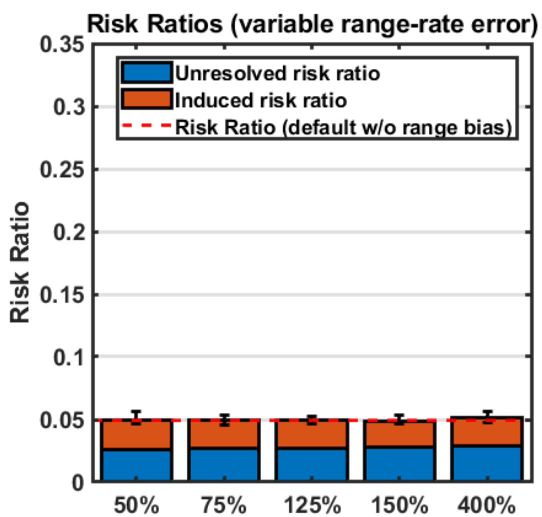
Risk Ratio for all configurations

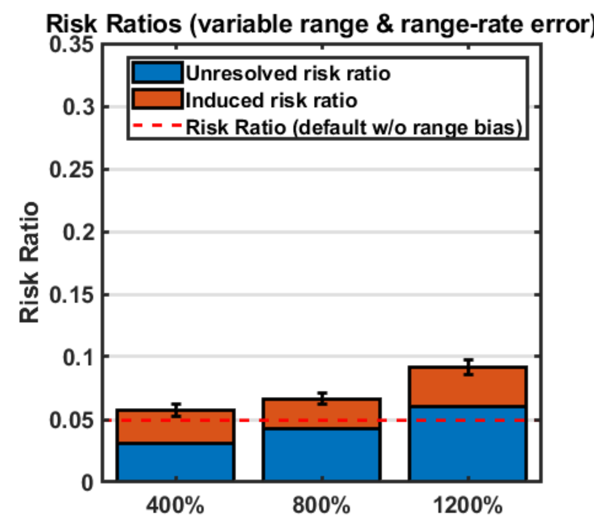










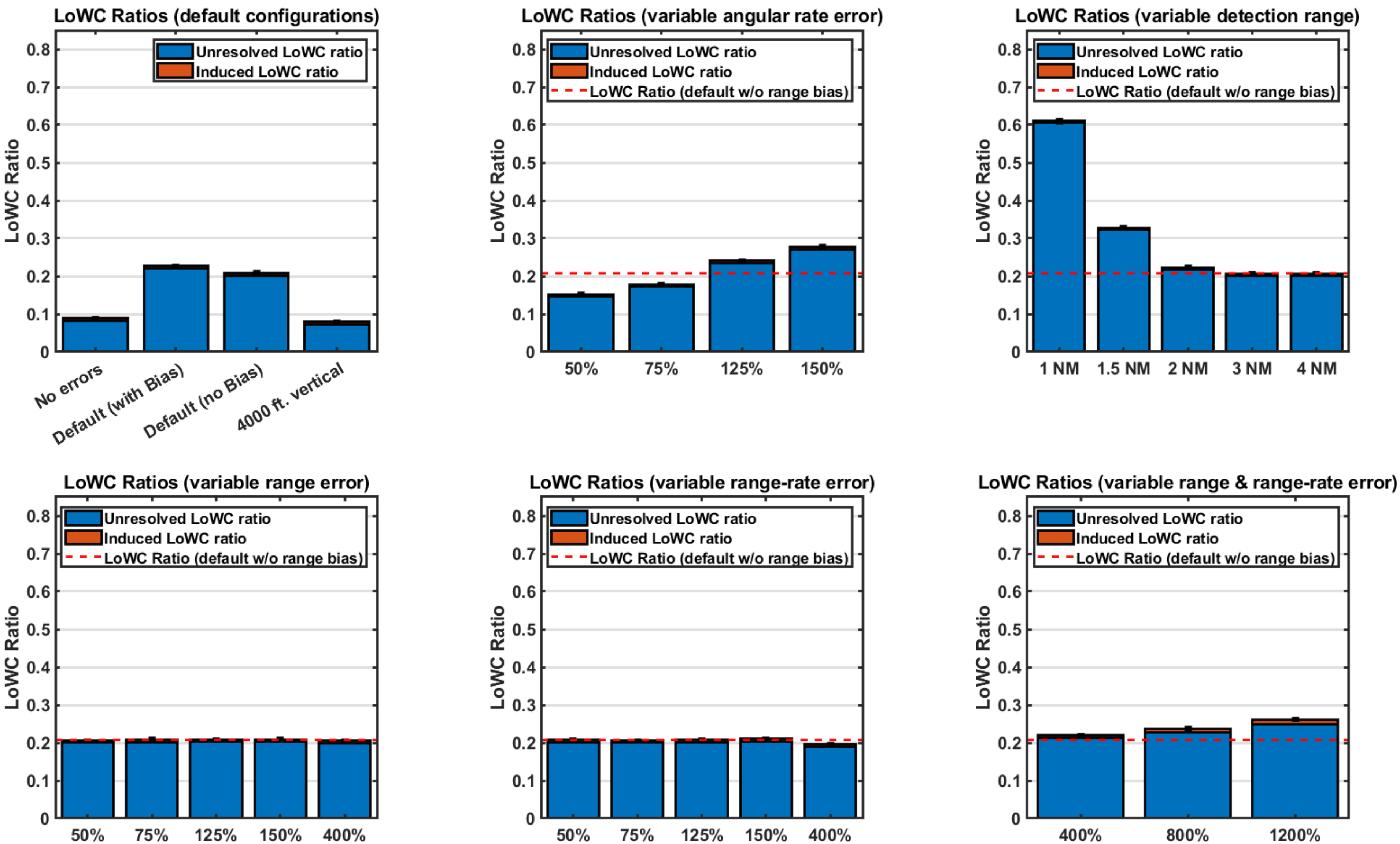


*Note: all other configurations do not include range bias component

Risk Ratio for all configurations

- The largest risk ratio belongs to the 1 NM detection range configuration
- The risk ratio is most sensitive to increasing the angular rate error and decreasing the detection range
- The risk ratio is insensitive to the range and range rate error, but does show some sensitivity when they are both increased together (when increased to more than 400% of their default values)

LoWC Ratio for all configurations



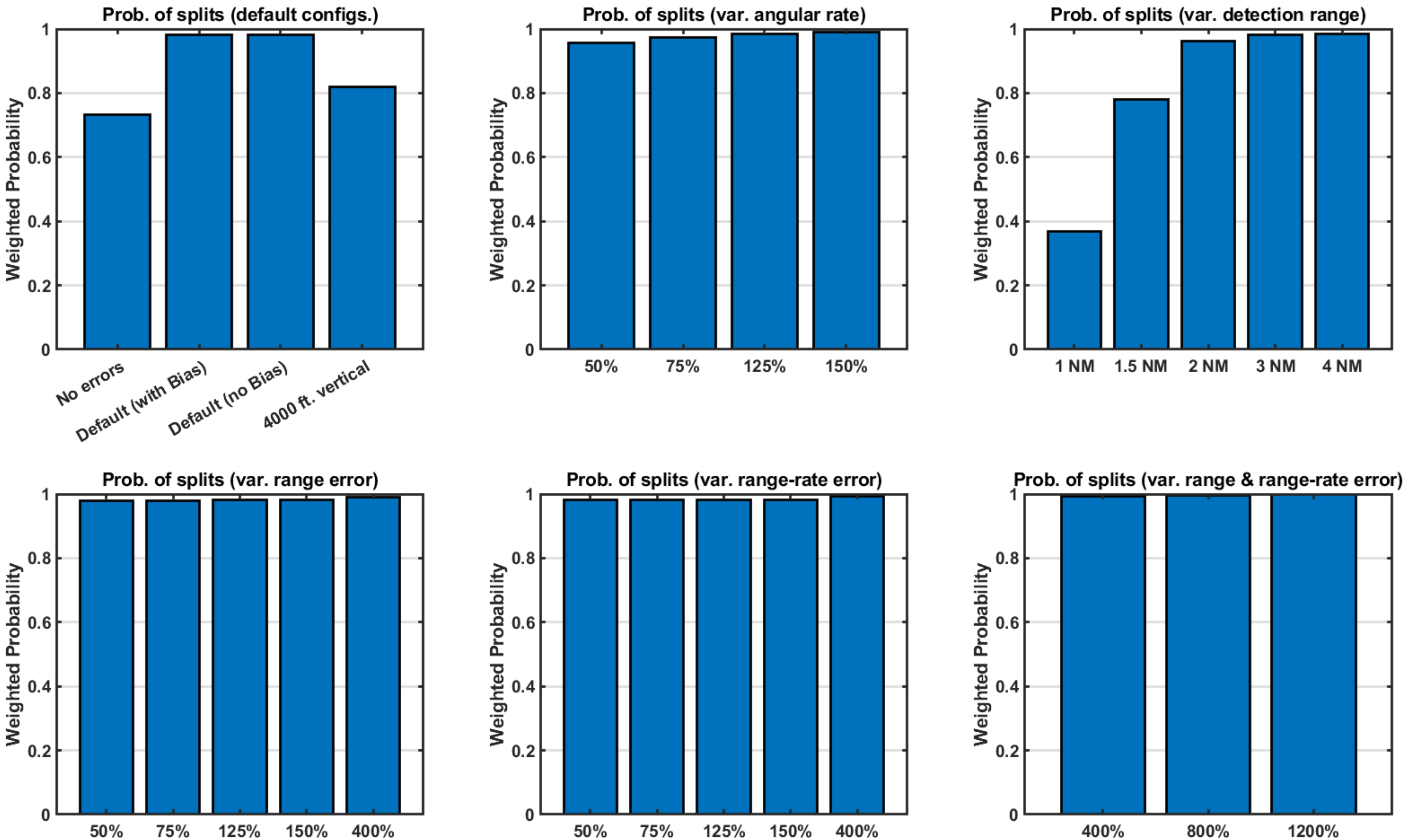
LoWC for all configurations

- Generally, the trend for each configuration sweep is the same as the risk ratio trends
- The largest LoWC ratio belongs to the 1 NM detection range configuration
- The LoWC ratio is most sensitive to increasing the angular rate error and decreasing the detection range
- The LoWC ratio is insensitive to the range and range rate error, but does show some sensitivity when they are both increased together (when increased to more than 400% of their default values)
- The LoWC ratio for the default without range bias configuration is slightly lower than the default with range bias configuration

Operational Suitability Metrics

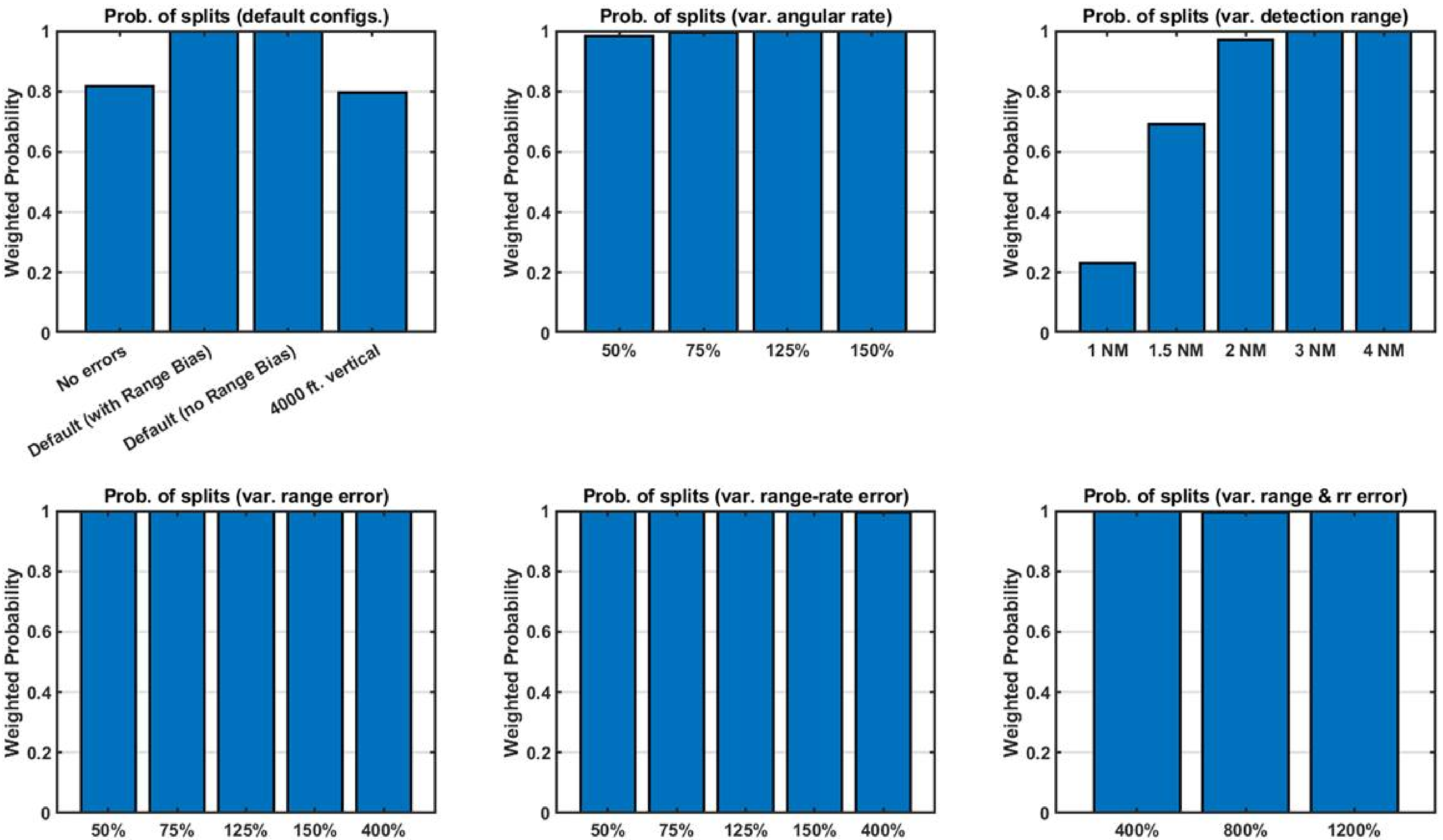
- Reversals:
  - Reversals are based off of commanded headings from the pilot model
    - An encounter has a reversal if the commanded heading changes sign (e.g., from turn left to turn right)
- Splits
  - Splits are based off of the alert level from DAIDALUS
    - An encounter has a split if DAIDALUS 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 for encounters where there was a nominal LoWC



Note: *weighted probability* simply indicates that the encounter likelihood was considered when computing the probability

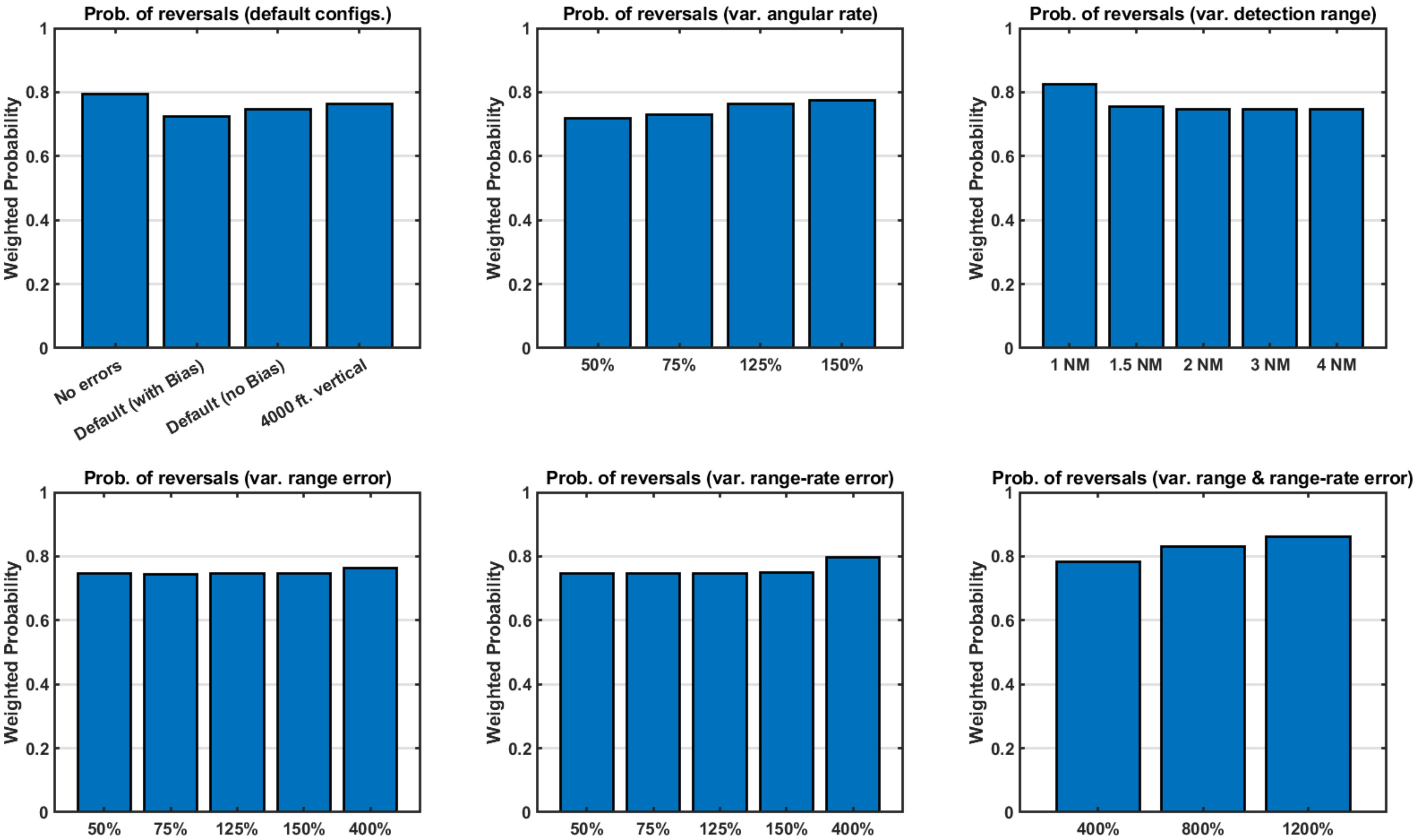
Operational Suitability Metrics: Splits for non-maneuvering encounters with a nominal LoWC



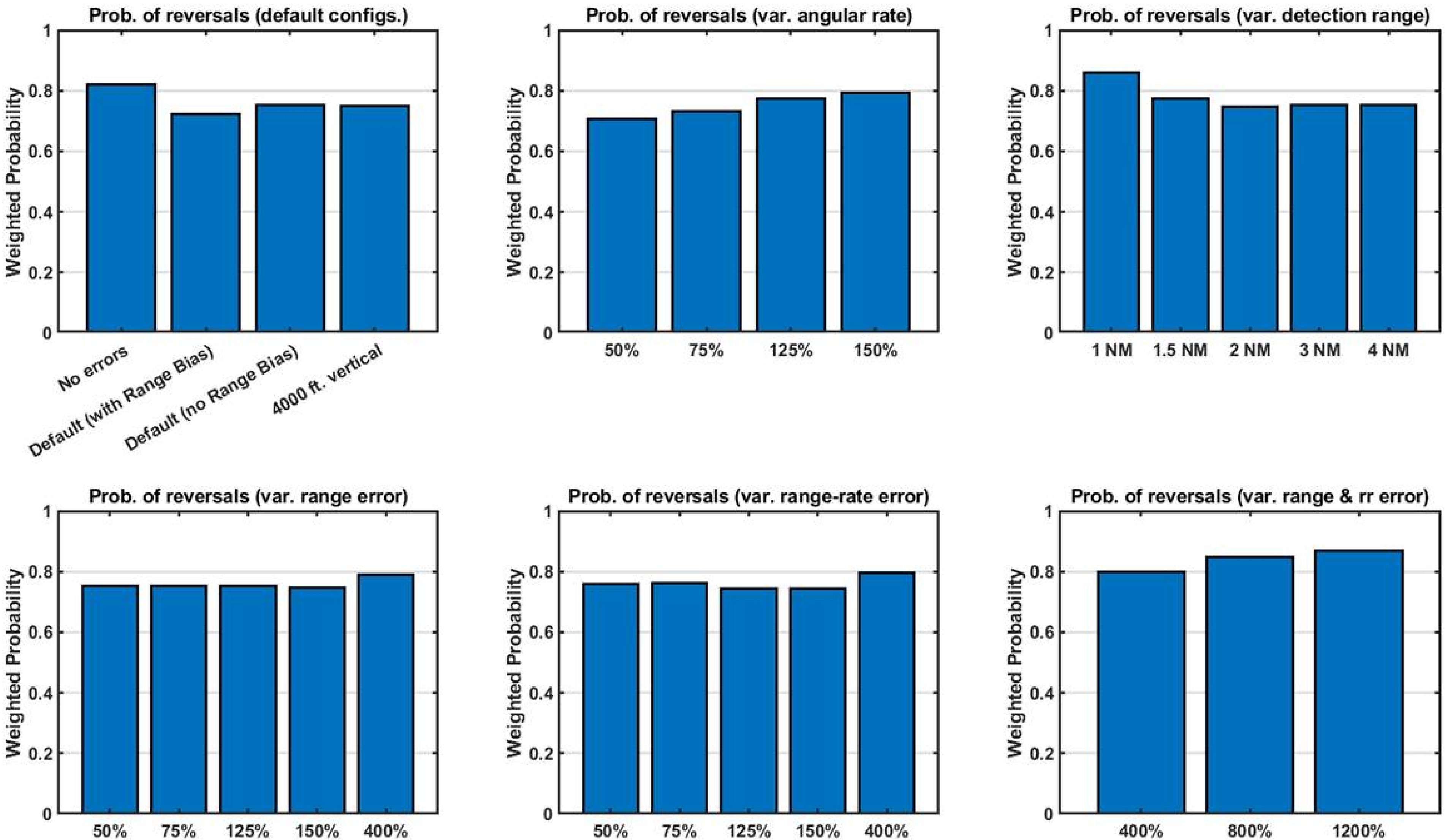
Operational Suitability Metrics (Splits)

- Consistent with the safety results, the parameters that have the largest effect on splits are variable angular rate and variable detection range
- For non-maneuvering encounters with nominal LoWC, the split probability is similar, if not higher, to the split probability for all encounters with nominal LoWC
- One possible reason for the large split probability is the ownship maneuvering to the edge of the band resolves the alert only momentarily
  - Large probability of split for the no errors case implies that split alerts are not heavily influenced by sensor error
  - Investigation of encounters has shown that the ownship overshoots the commanded heading and oscillates around it before settling
  - One solution is to add a 5-10° buffer to the commanded heading, as to prevent the ownship from reentering the alerted guidance bands

Operational Suitability Metrics: Reversals only for encounters where there was a nominal LoWC



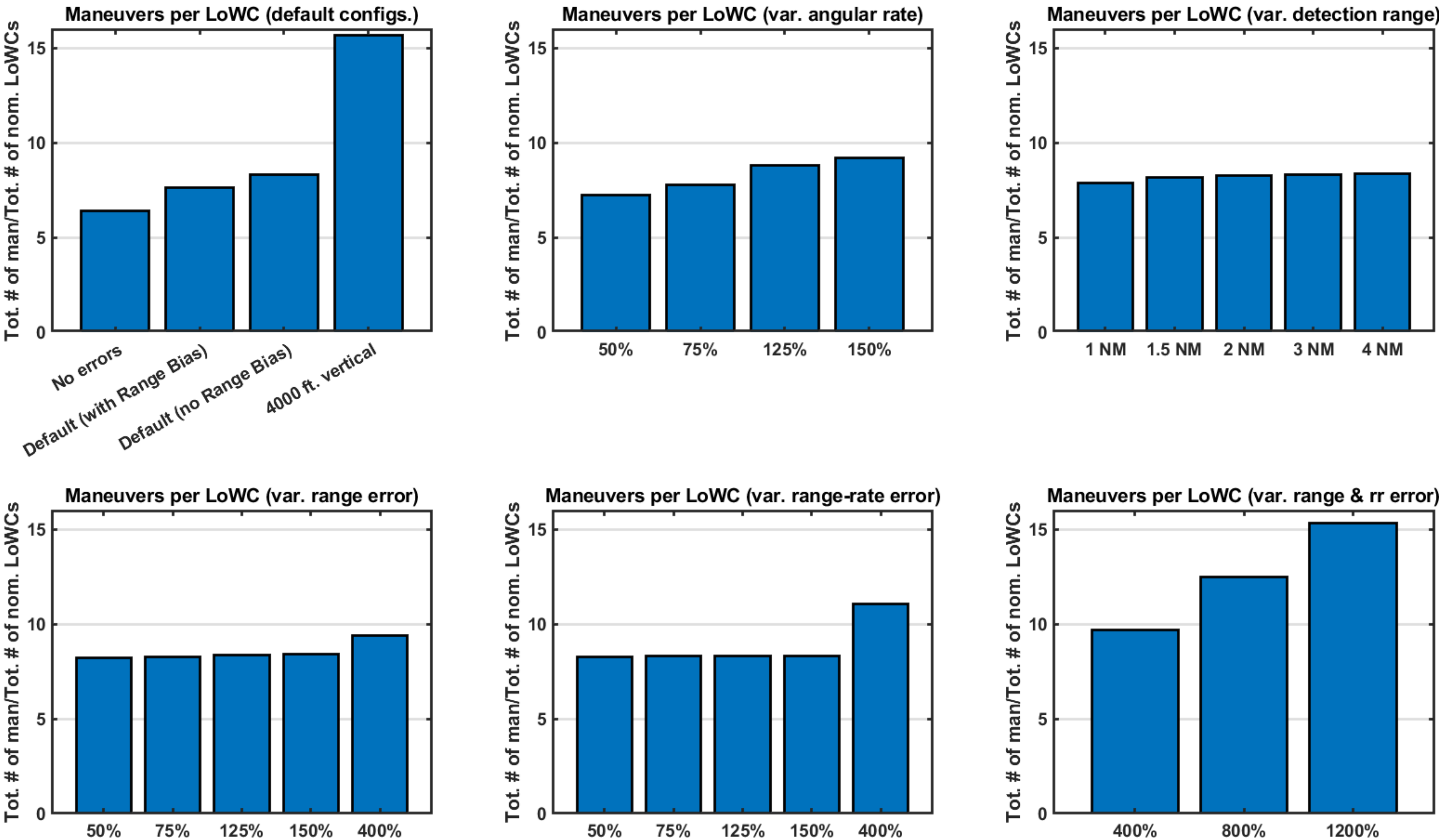
Operational Suitability Metrics: Reversals for non-maneuvering encounters with a nominal LoWC



Operational Suitability Metrics (Reversals)

- For the no sensor error configuration, the probability of a reversal occurring given a nominal LoWC is approximately 79%
  - This is the highest reversal probability for the default configurations
- The probability of a reversal occurring is sensitive to increasing the angular rate and both the range and range-rate
  - The default configurations (with and without range bias) have a lower probability of reversal than the no sensor error configuration
  - The probability of reversal also increases once the range-rate error reaches a certain threshold, in this case 400%, as seen in the variable range-rate error plot
  - The reversal probability also increases for smaller detection ranges
- For non-maneuvering encounters with a nominal LoWC, the reversal probability is similar to the reversal probability for all encounters with a nominal LoWC
- Large probability of reversals for the no errors case implies that guidance reversals are not heavily influenced by sensor error
  - Ownship heading oscillations in conjunction with the pilot maneuver update can trigger the reversal metric

Operational Suitability Metrics: Pilot Workload for All Encounters*

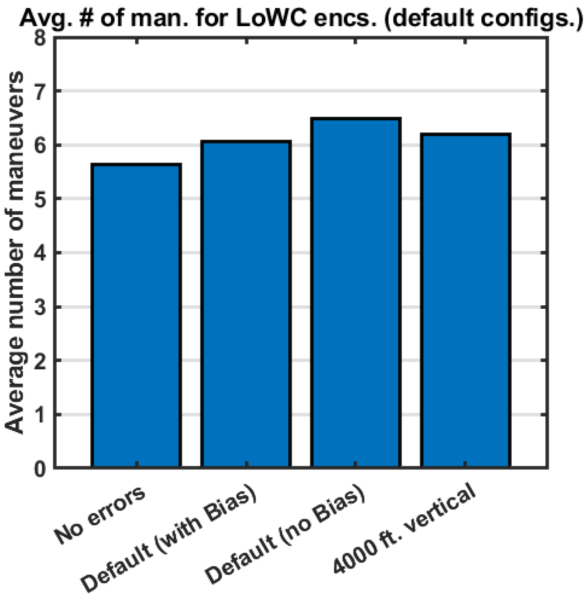


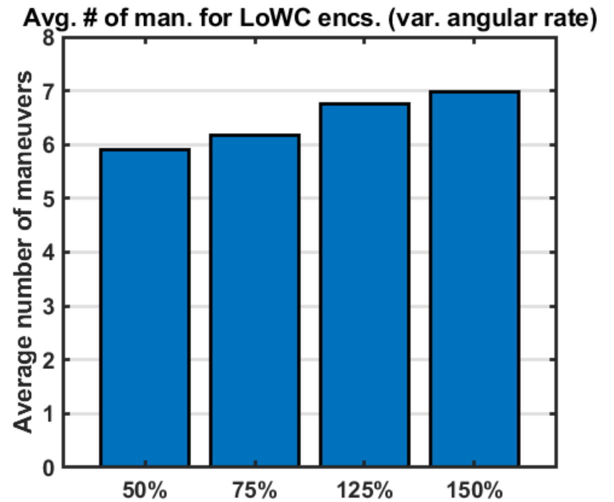
*A maneuver is defined as any update to the pilot heading, no matter the magnitude of the maneuver

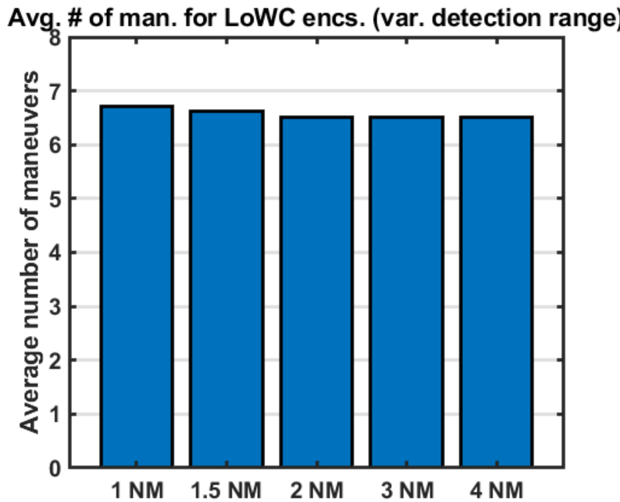
Operational Suitability Metrics (Pilot Workload)

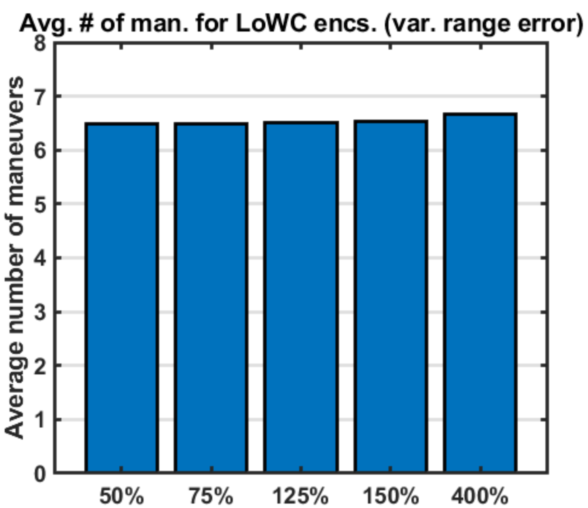
- A maneuver is defined as any update to the pilot heading, no matter the magnitude of the maneuver
- The pilot workload metric for all encounters calculates the average number of maneuvers per nominal LoWC
  - Can be understood as the maneuver rate
- The general trend is that more sensor noise leads to more maneuvers
- The 4000 ft vertical configuration had the most pilot maneuvers, due to the large vertical alerting threshold
- The pilot workload is sensitive to angular rate error, and sensitive to range and range-rate error once it is above a certain threshold
  - Increasing the range and range-rate error at the same time increases the pilot workload at a greater rate than increasing either one individually

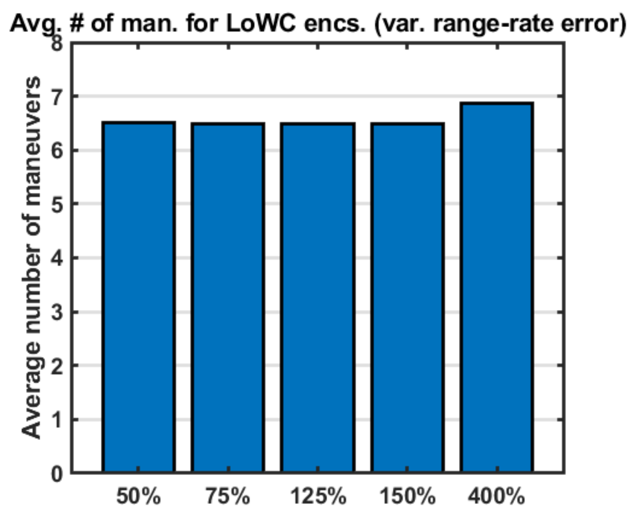
Operational Suitability Metrics: Average number of maneuvers per encounter for encounters w/ a nominal LoWC

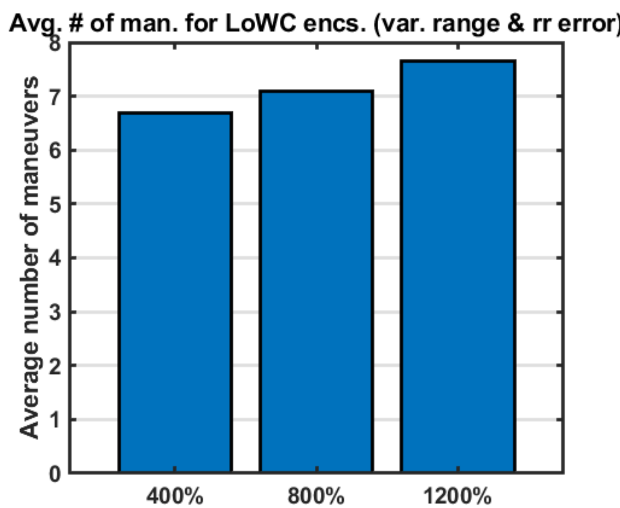








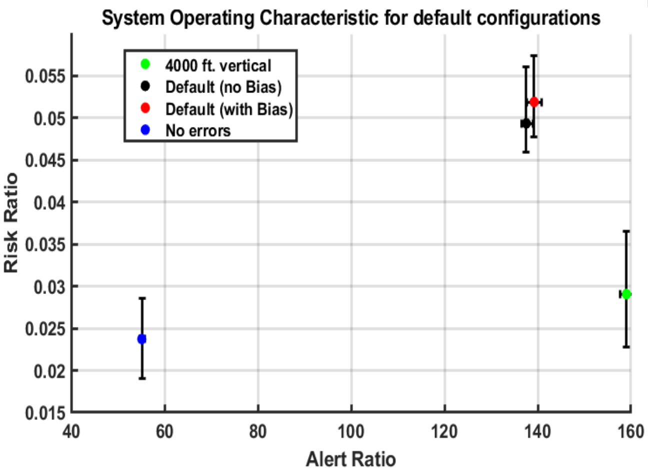


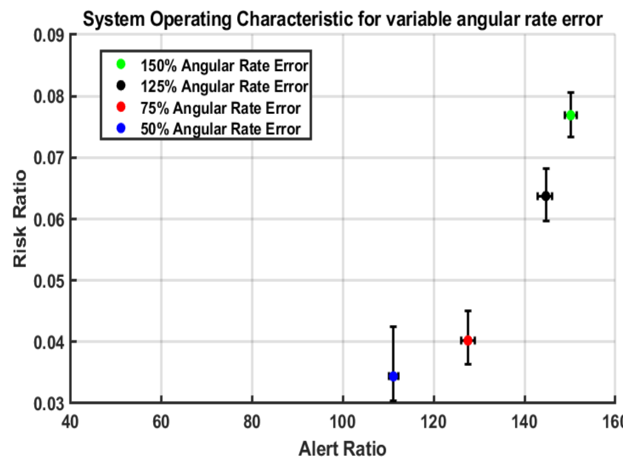


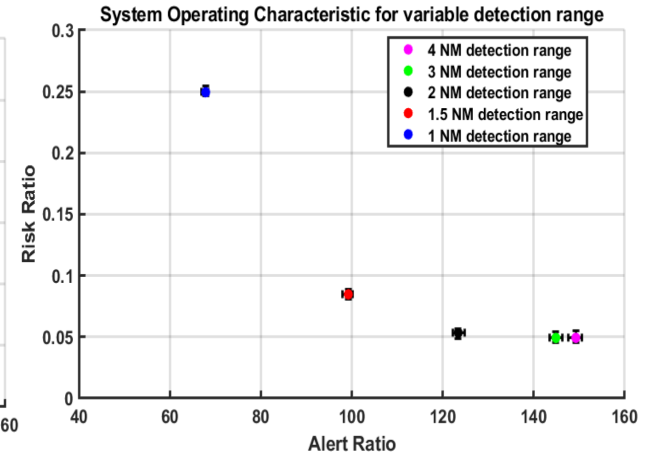
Operational Suitability Metrics: Average number of maneuvers per encounter

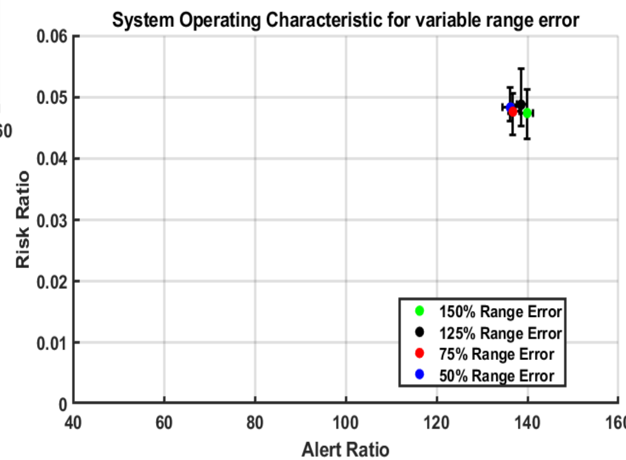
- The no sensor error configuration had the lowest average number of maneuvers with approximately 5.6 maneuvers per encounter
- The average number of maneuvers per encounter is most sensitive to increasing angular rate error
  - Increasing the range and range-rate errors above a certain threshold also has an effect
  - The range bias does have a small effect on the average number of ownship maneuvers

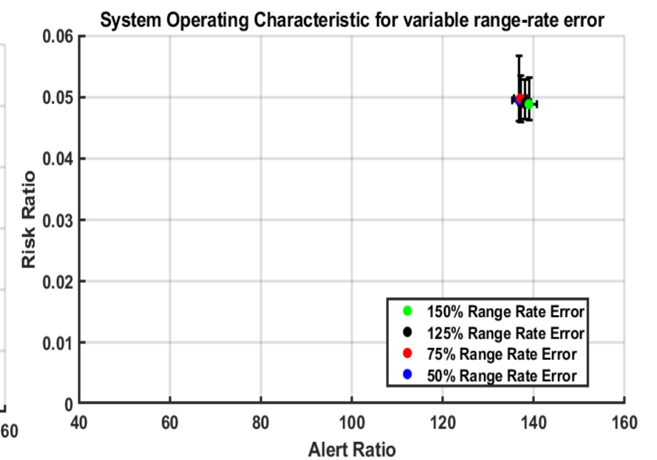
System Operating Characteristic: Risk Ratio vs. Alert Ratio











- Alert ratio is defined as the ratio of all ownship alerts to nominal NMACs
- 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
  - Alert ratio is least sensitive to range and range-rate error
- A smaller alert ratio and risk ratio implies more effective DAA maneuvers

Conclusion

- Variable angular rate error and variable detection range have the greatest effect on safety and 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 is additional data required?

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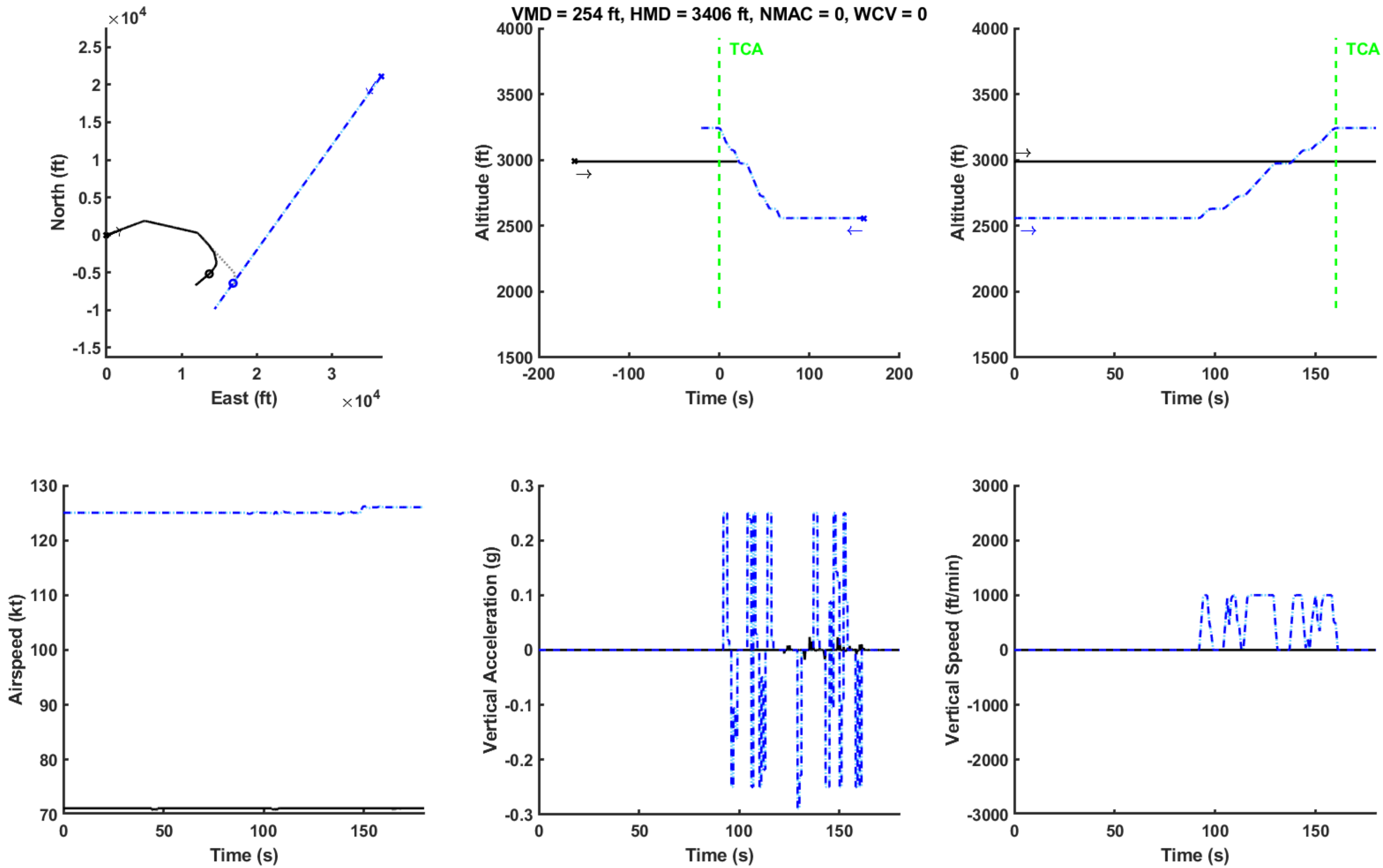
Next Steps

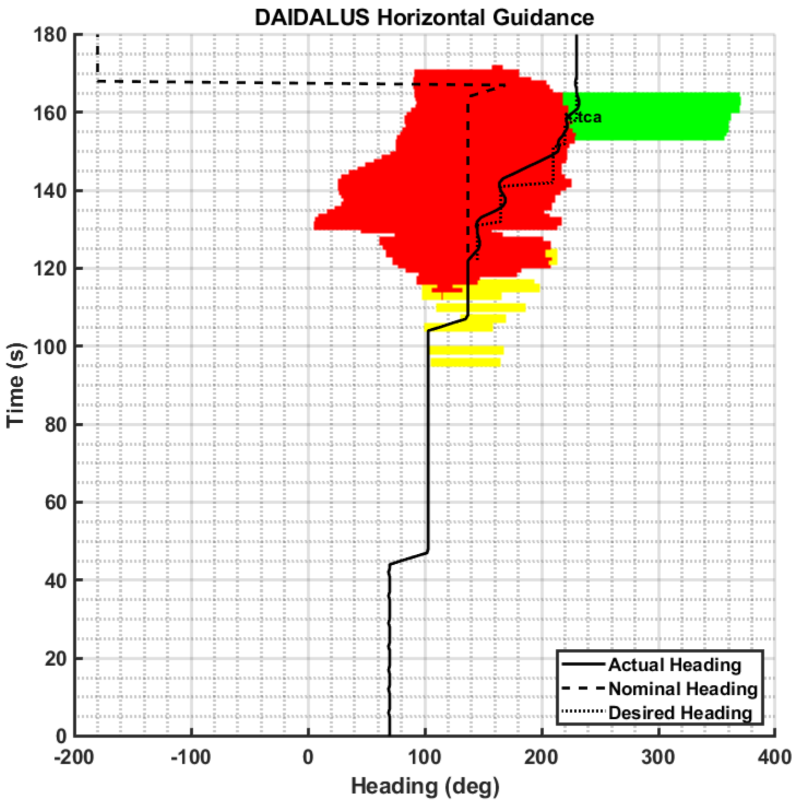
- Run simulations with buffer on minimum suggestive guidance (e.g., 15°)
  - Splits may be caused by following guidance too closely and overshooting desired heading
- Add expected # of split/reversals to the metrics
  - Currently only capture whether an encounter had any split/reversal
- Investigate effect of EOIR error time correlation

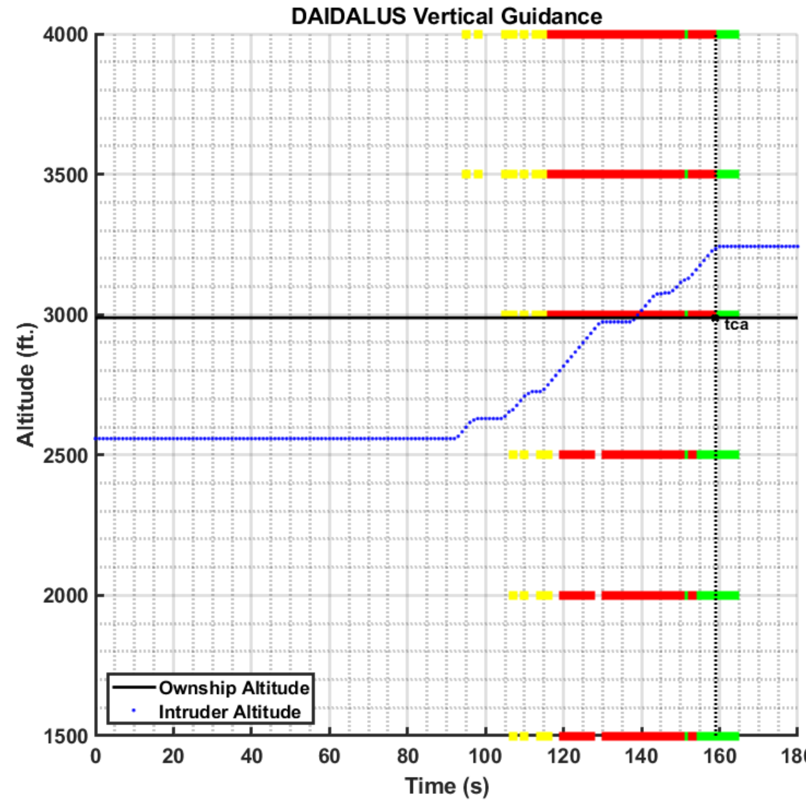
Backup

Example 1 guidance - EOIR

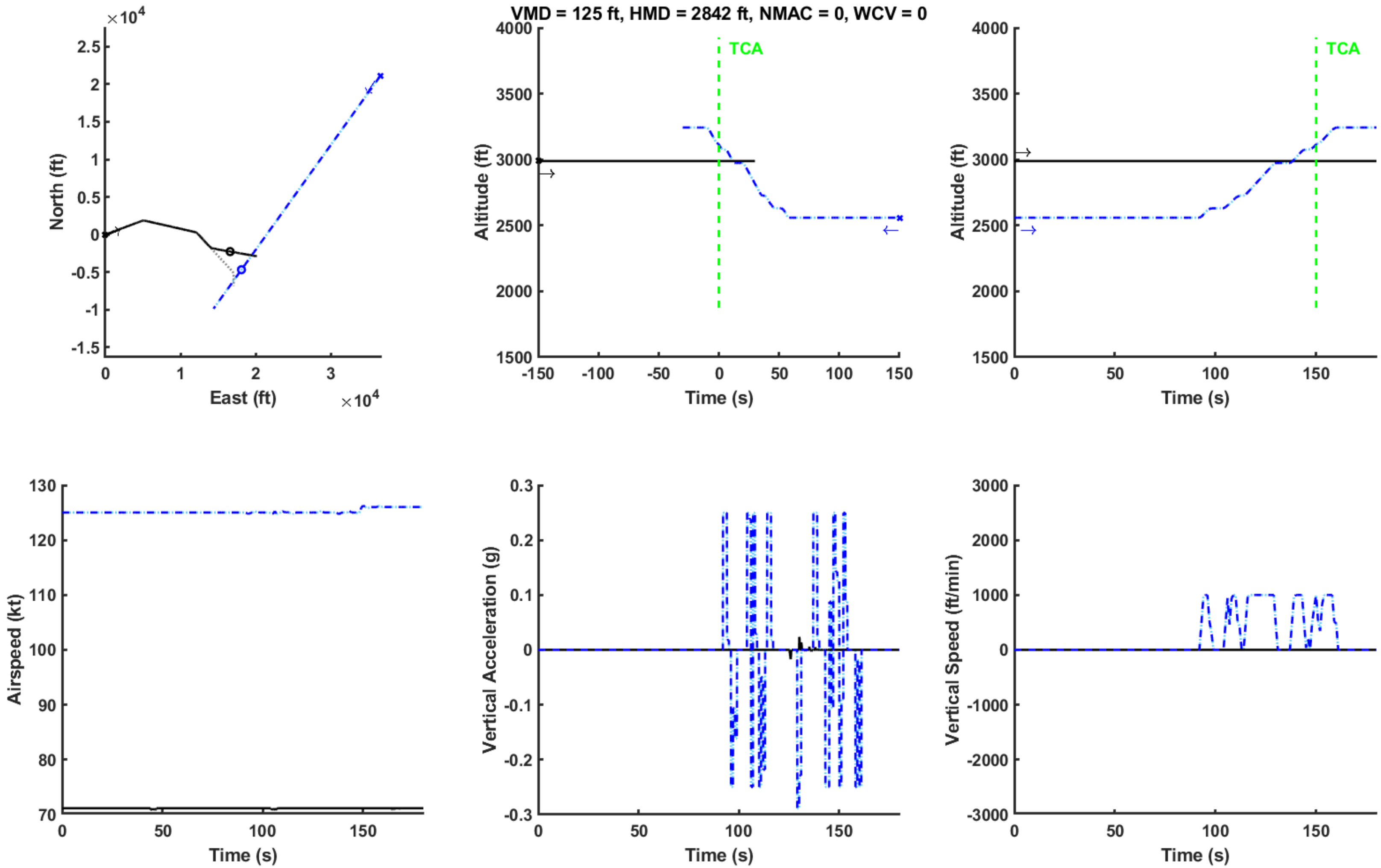


Example 1 guidance - EOIR





Example 1 guidance - ADSB



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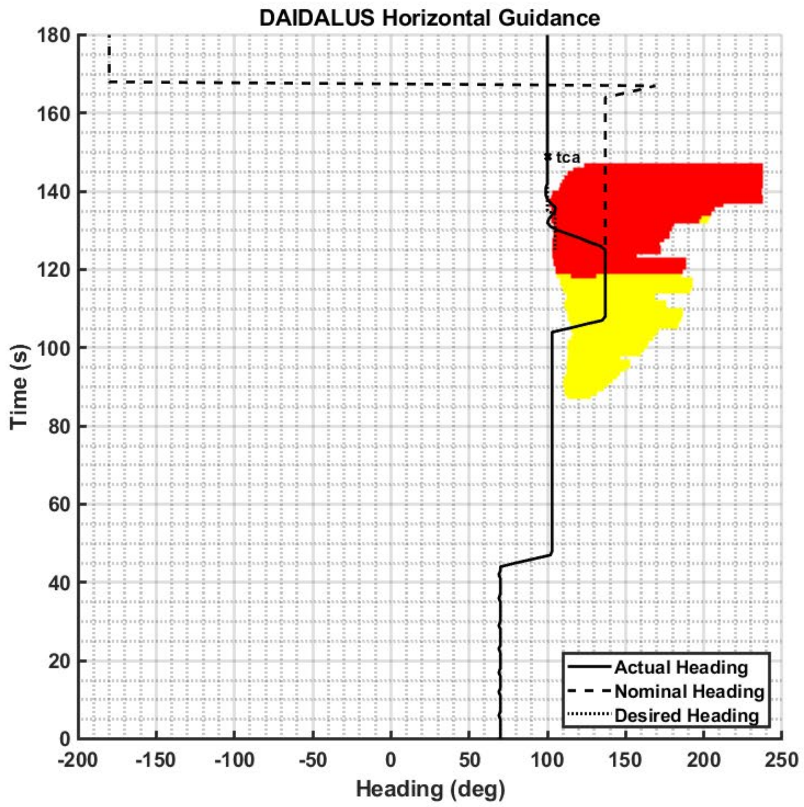
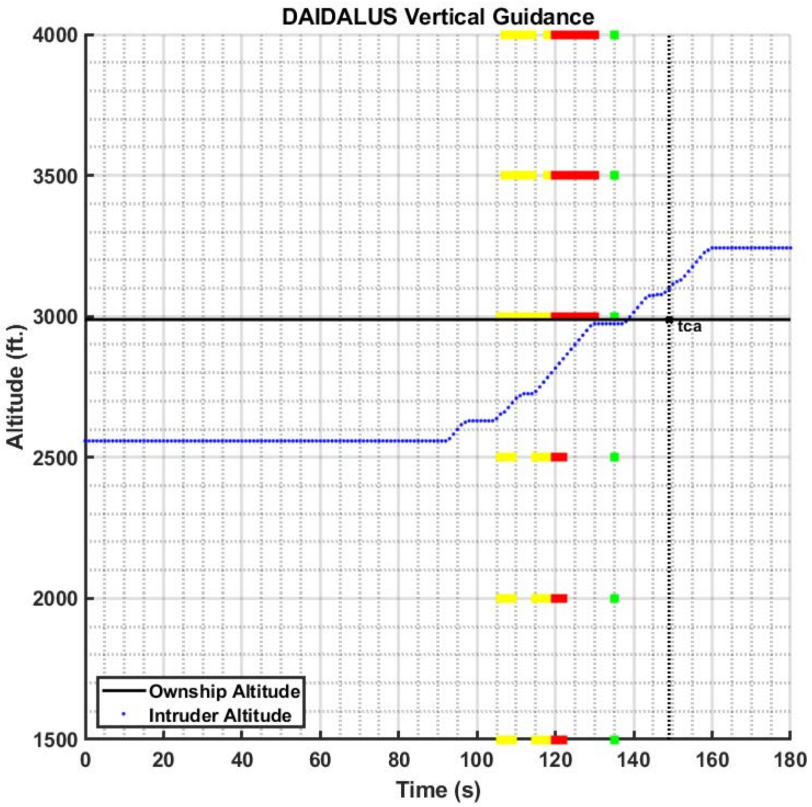
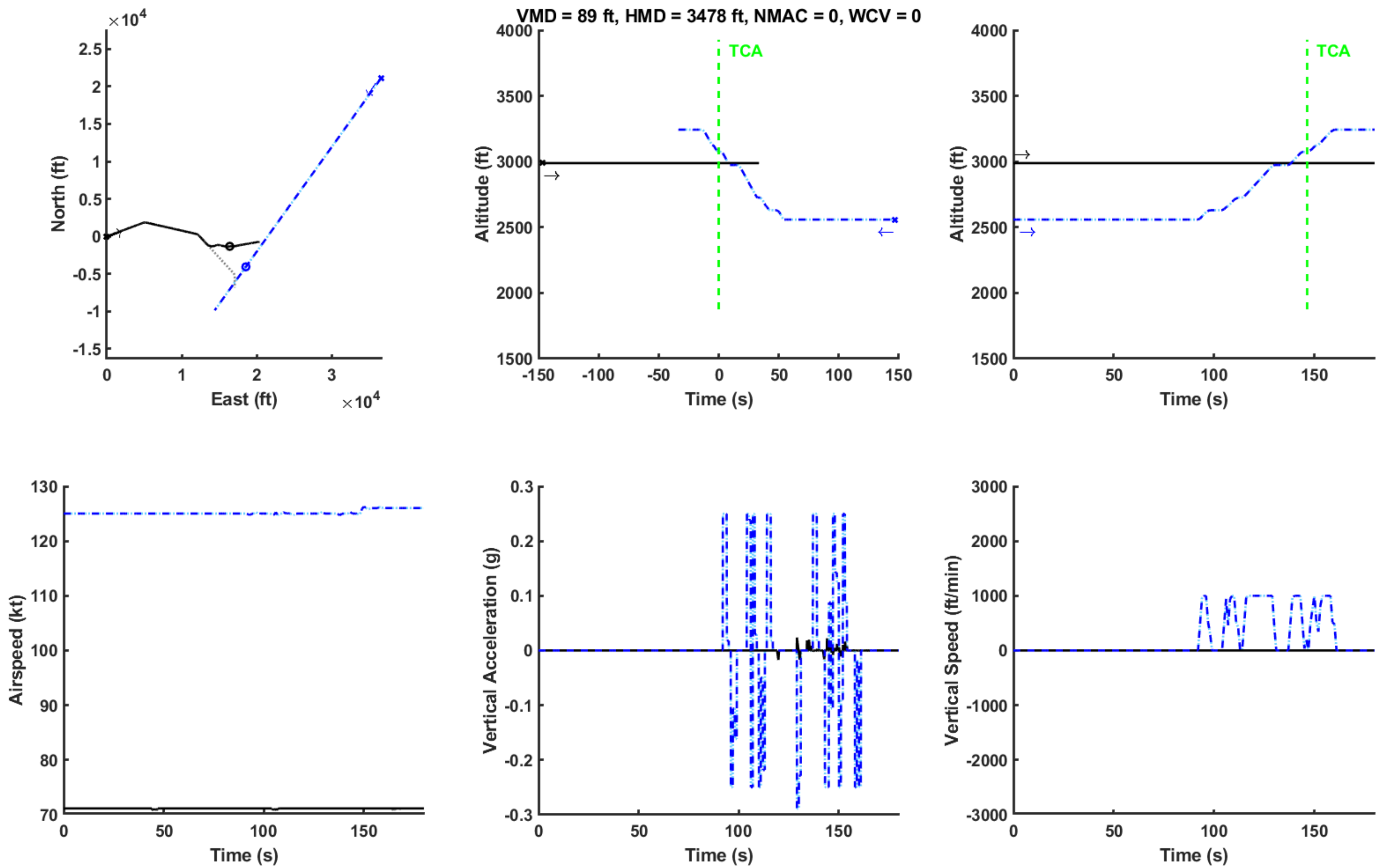




Example 1 guidance - ATAR



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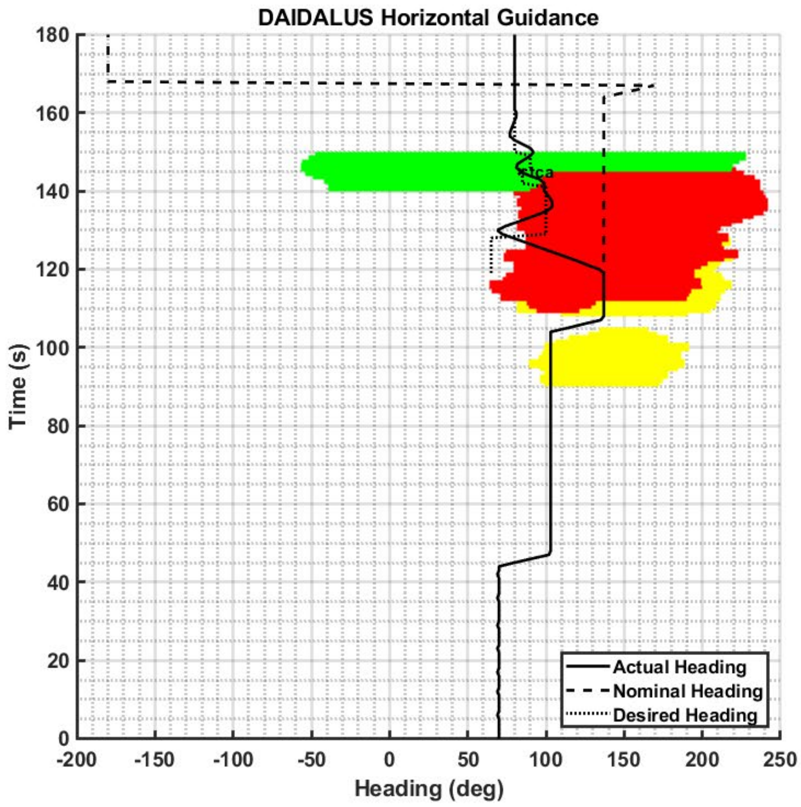
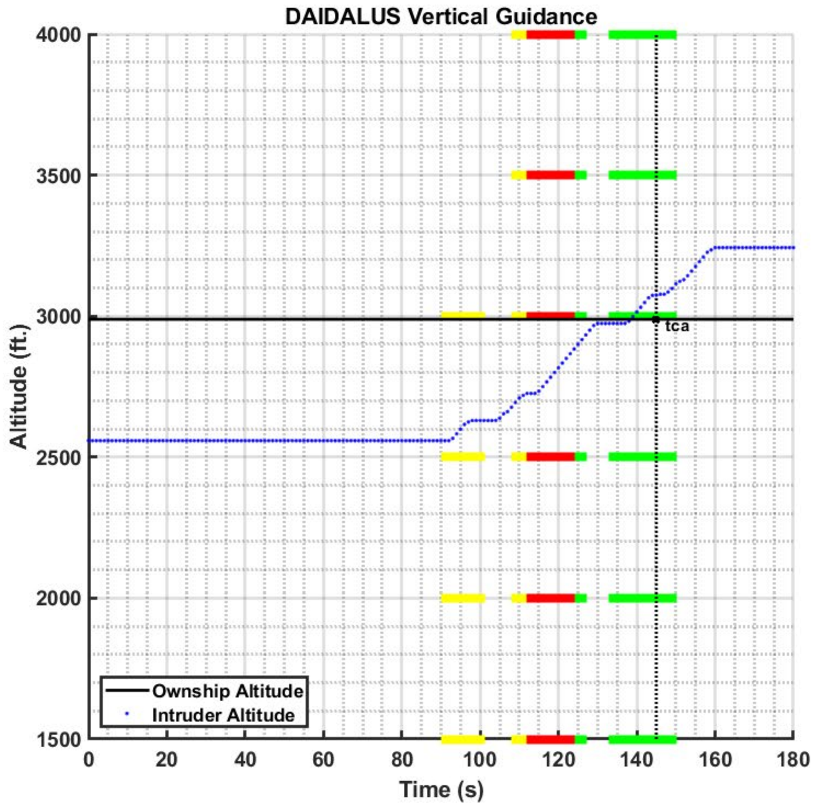
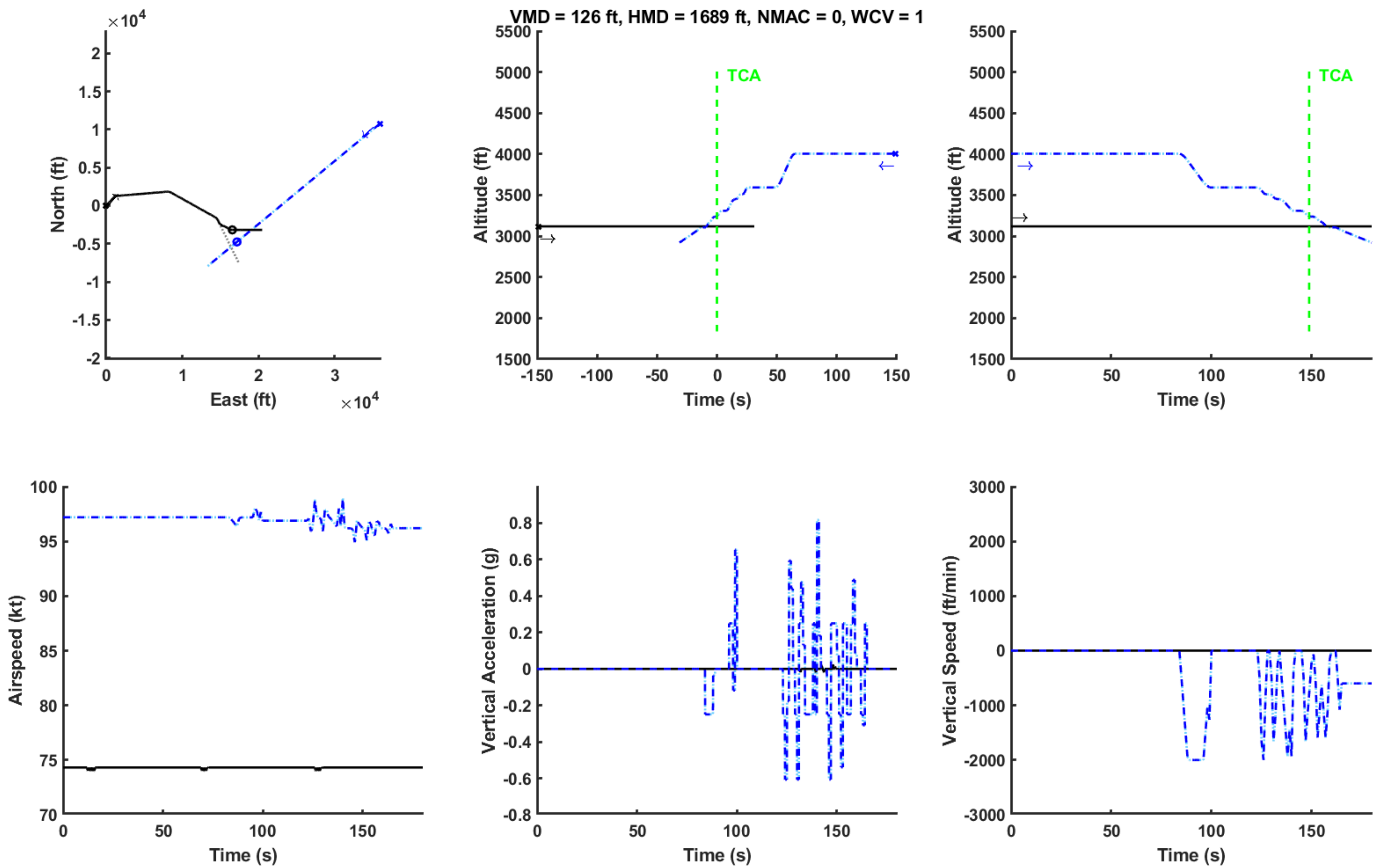




Example 2 guidance - EOIR



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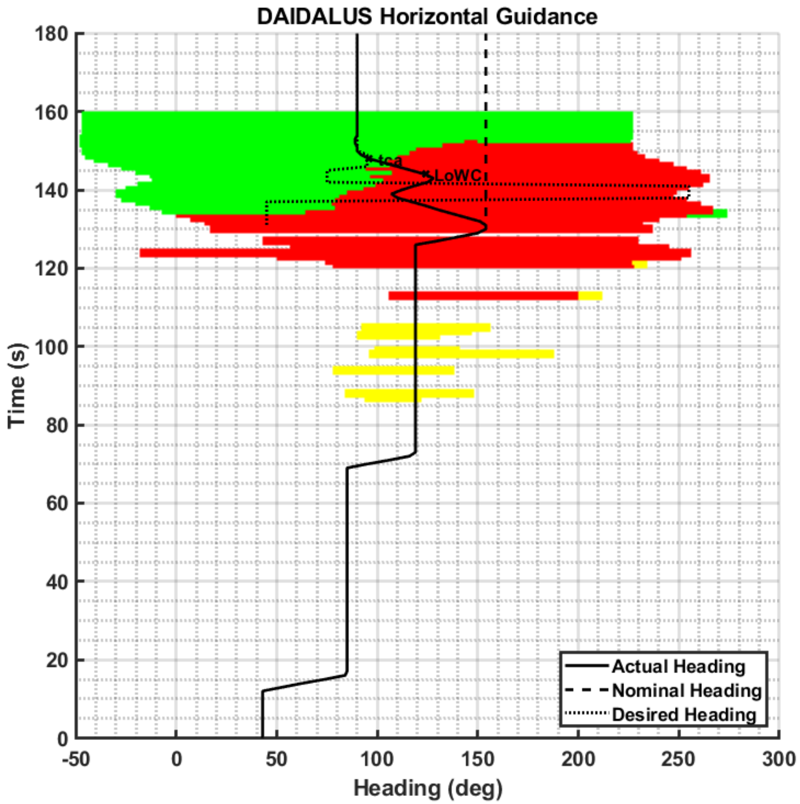

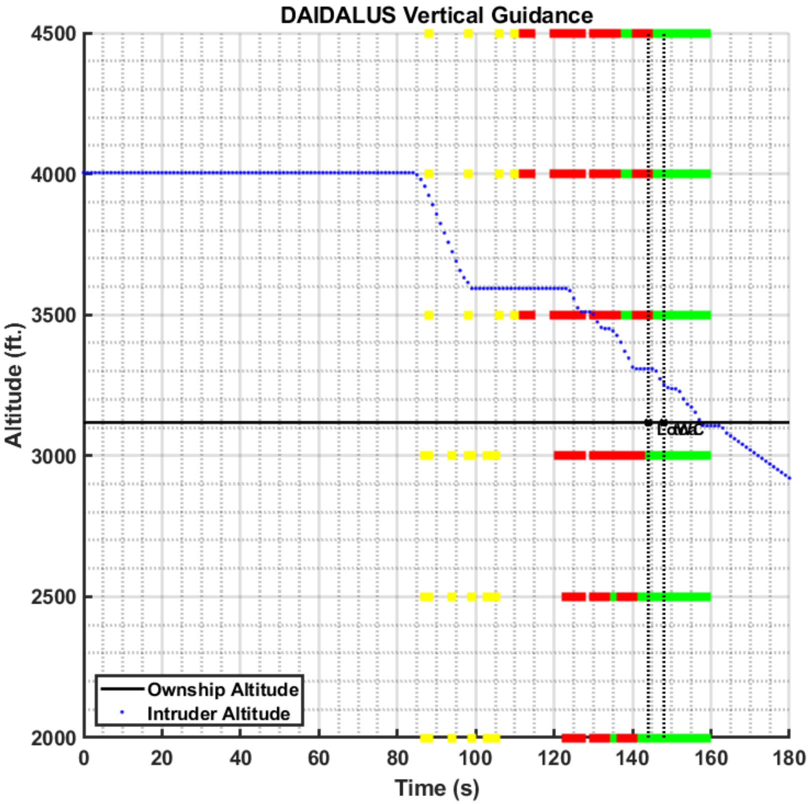

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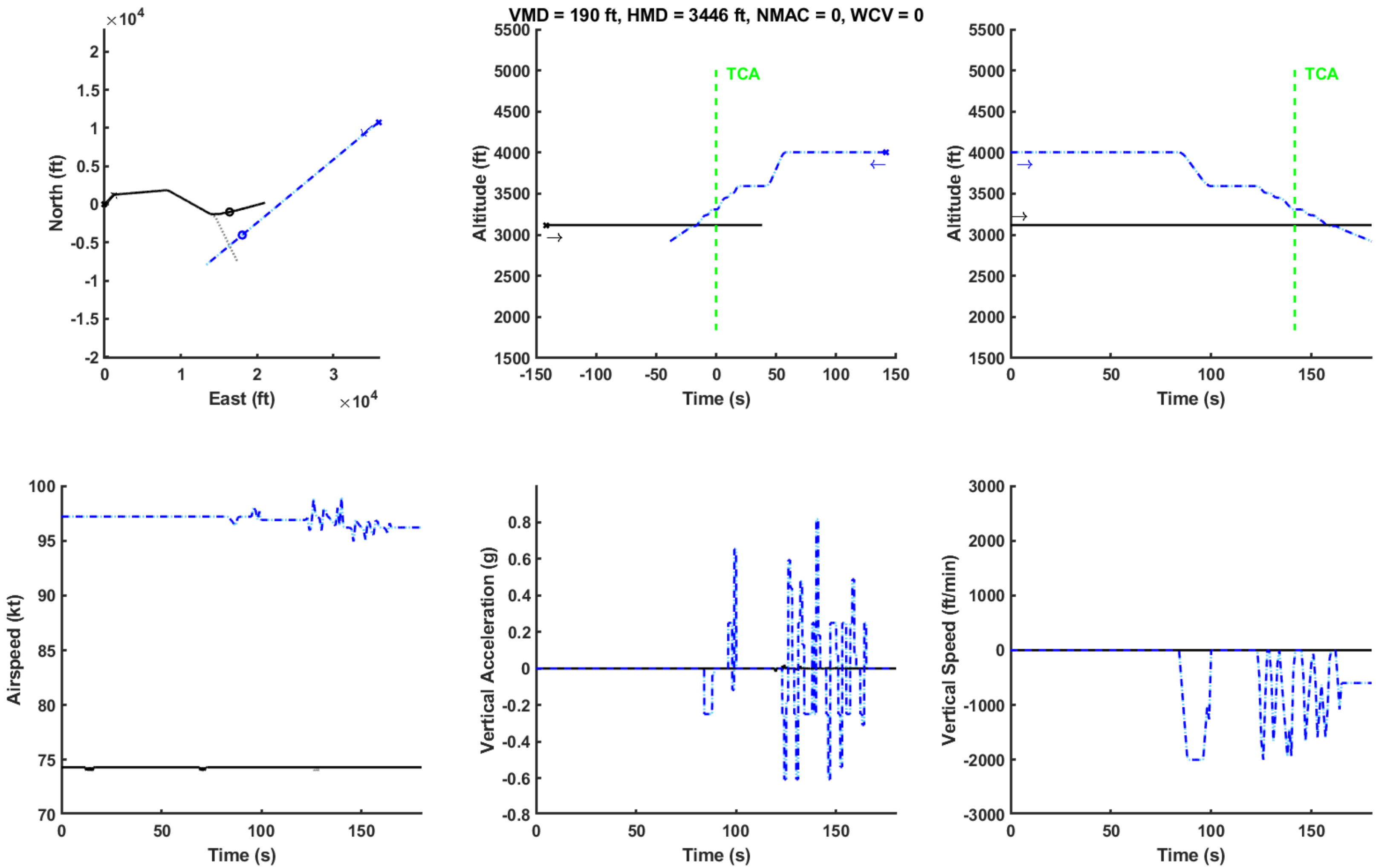

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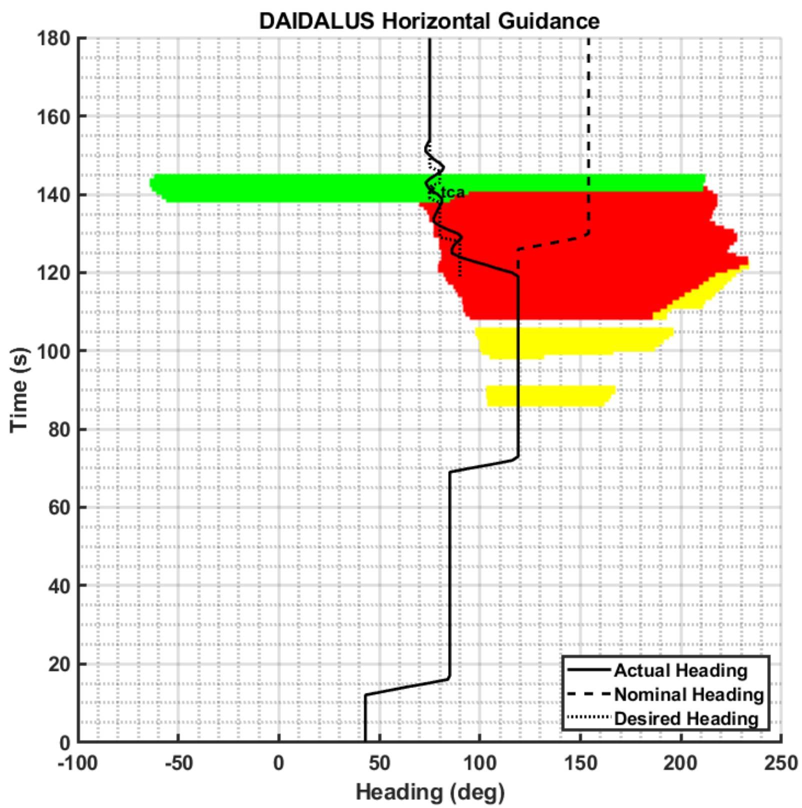

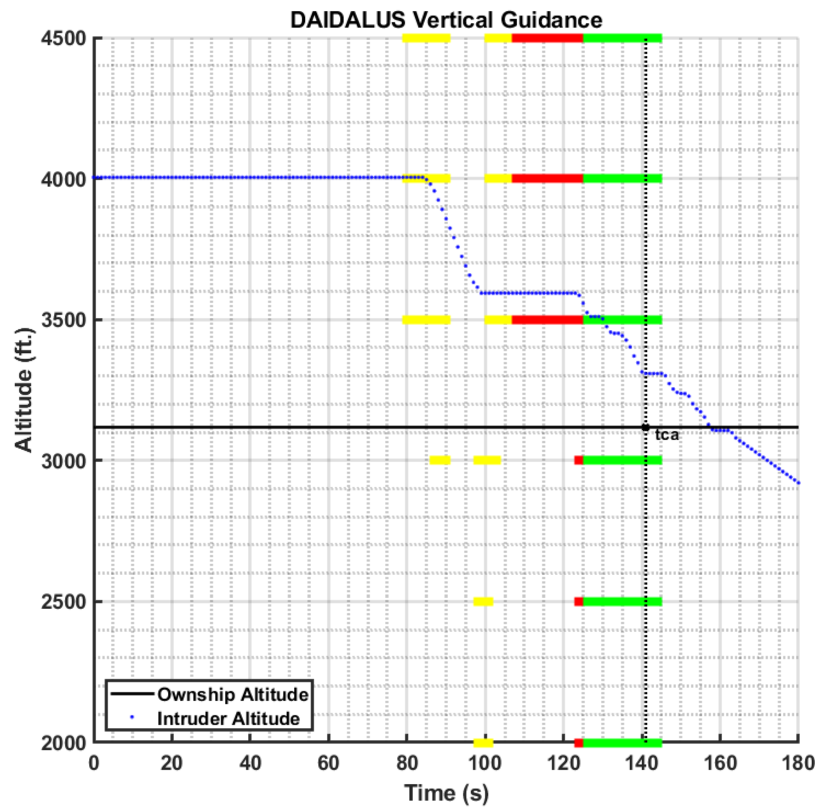

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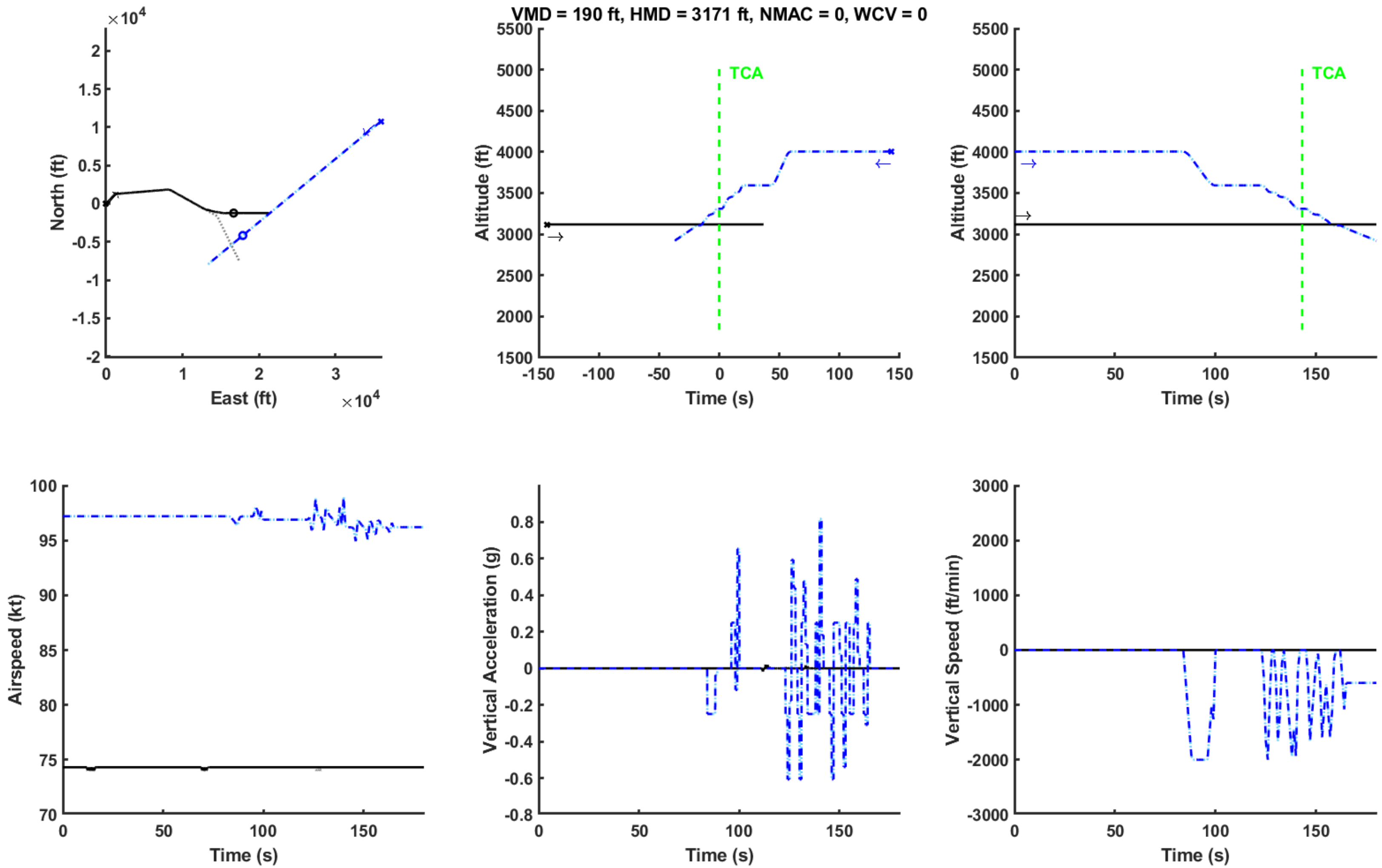
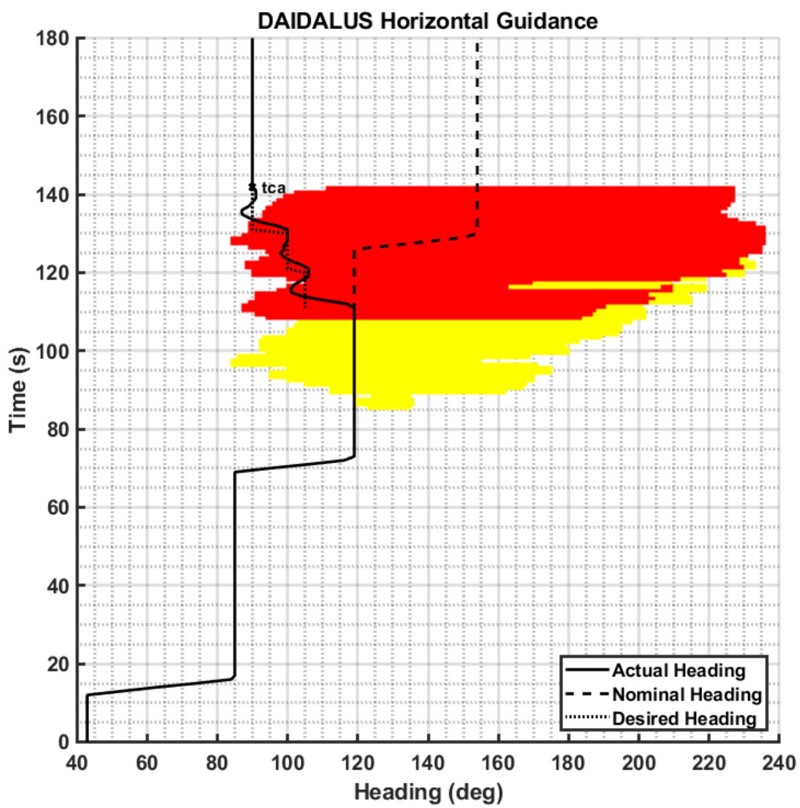
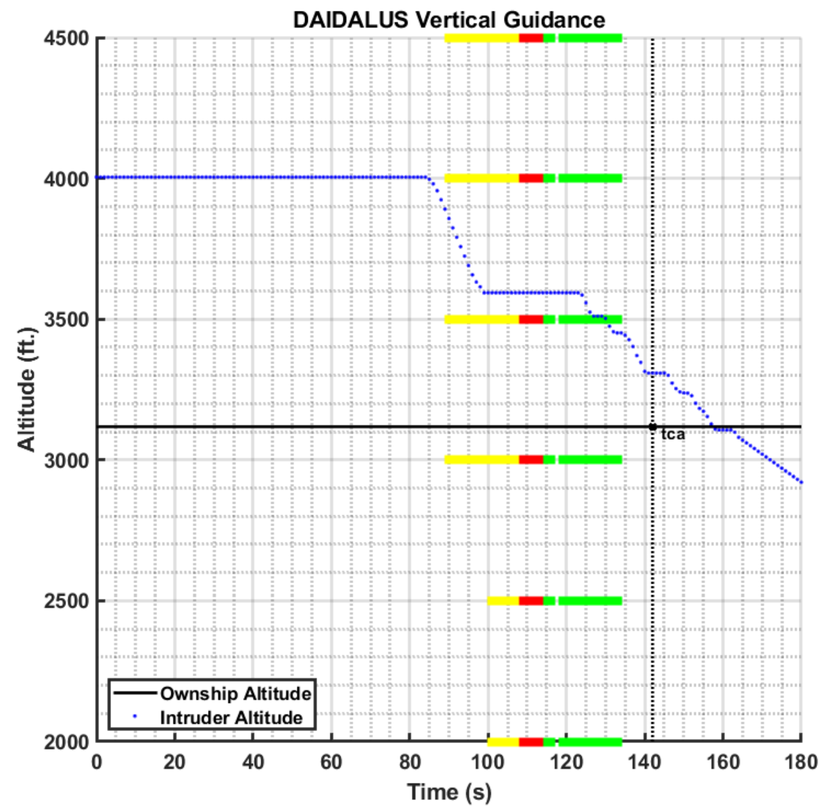
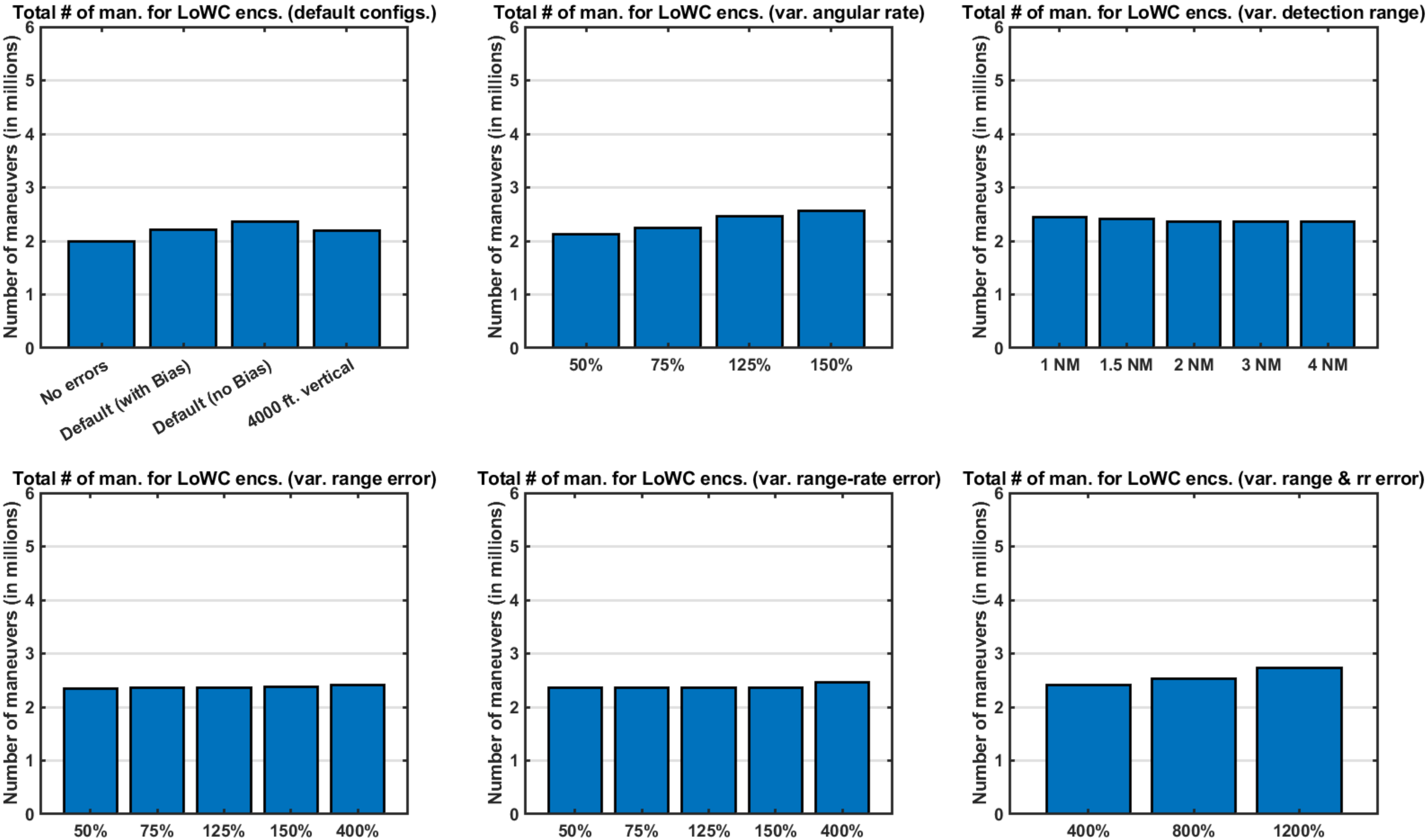


Example 2 guidance - ATAR





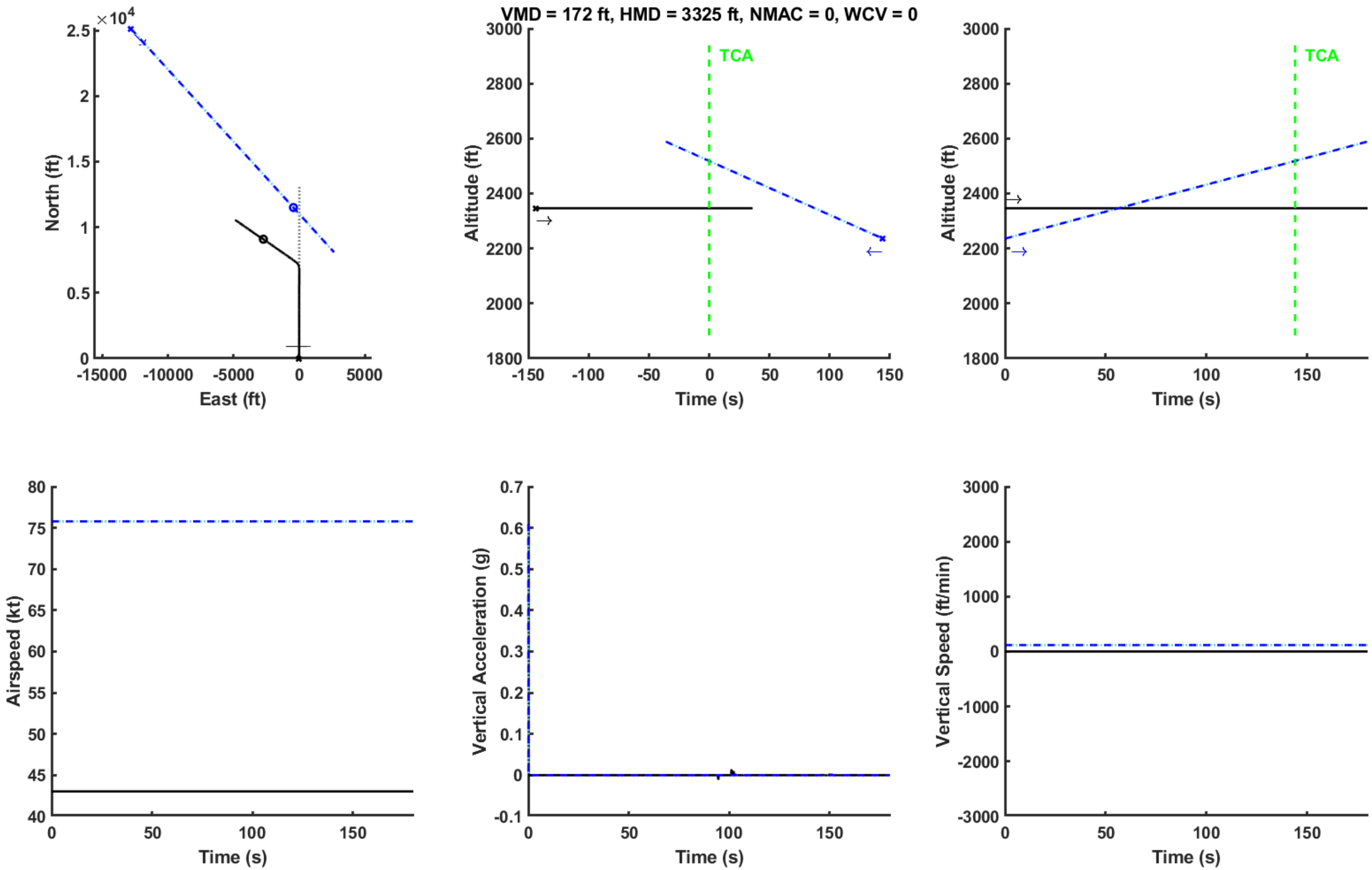
Operational Suitability Metrics: Pilot Workload only for encounters where there was a nominal LoWC



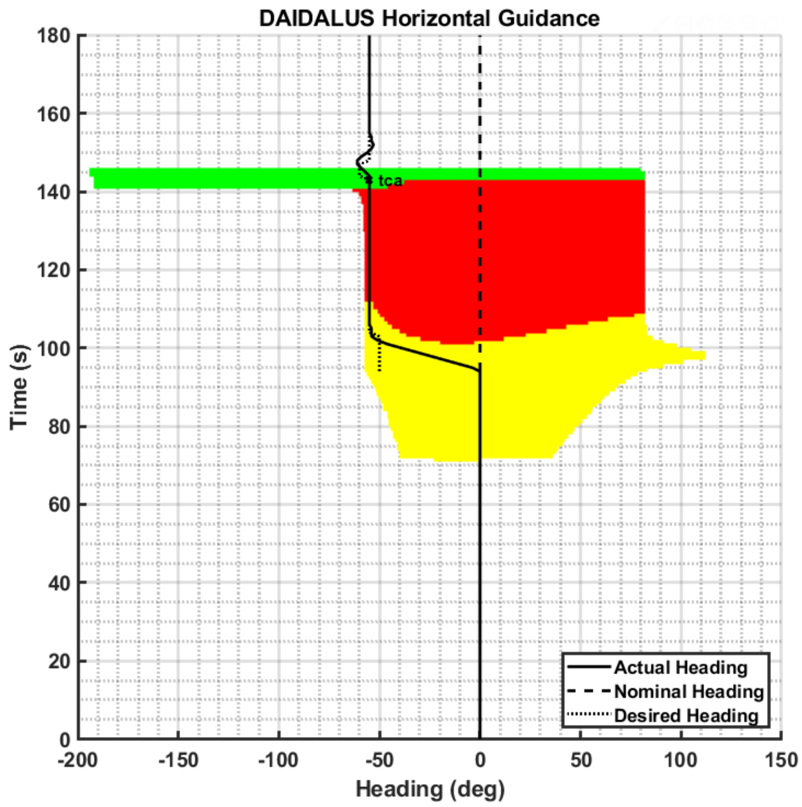
Operational Suitability Metrics: Pilot Workload for Nominal LoWC Encounters

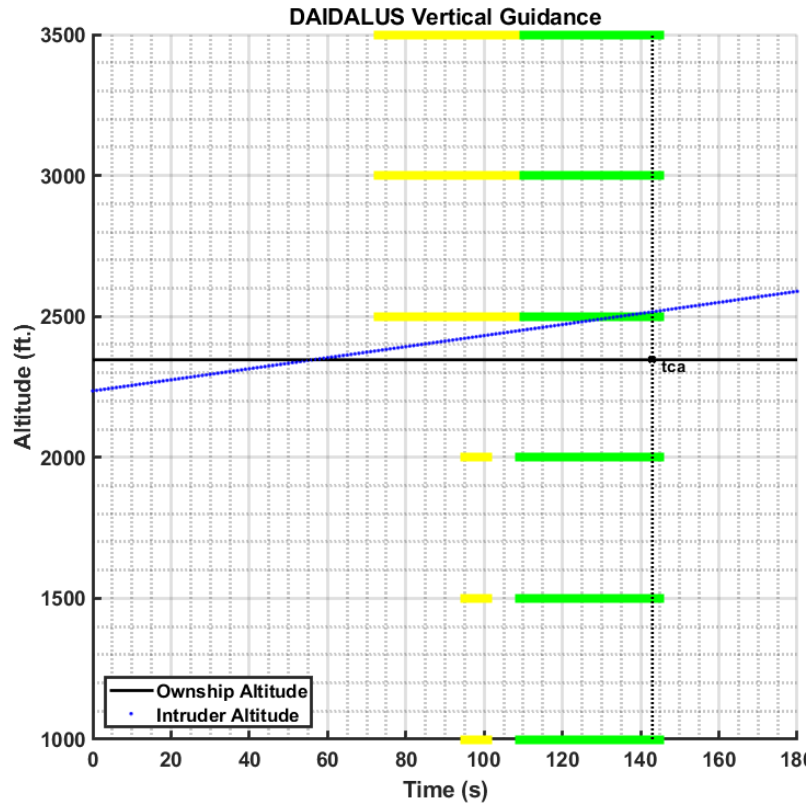
- The trend of increasing the sensor noise leading to more pilot maneuvers remains the same
- There is a drop-off in the number of pilot maneuvers for encounters where there was a nominal LoWC when compared to all encounters
  - The difference in pilot workload from encounters with a nominal LoWC to all encounters can be interpreted as the number of unnecessary maneuvers

Reversal example - no sensor error

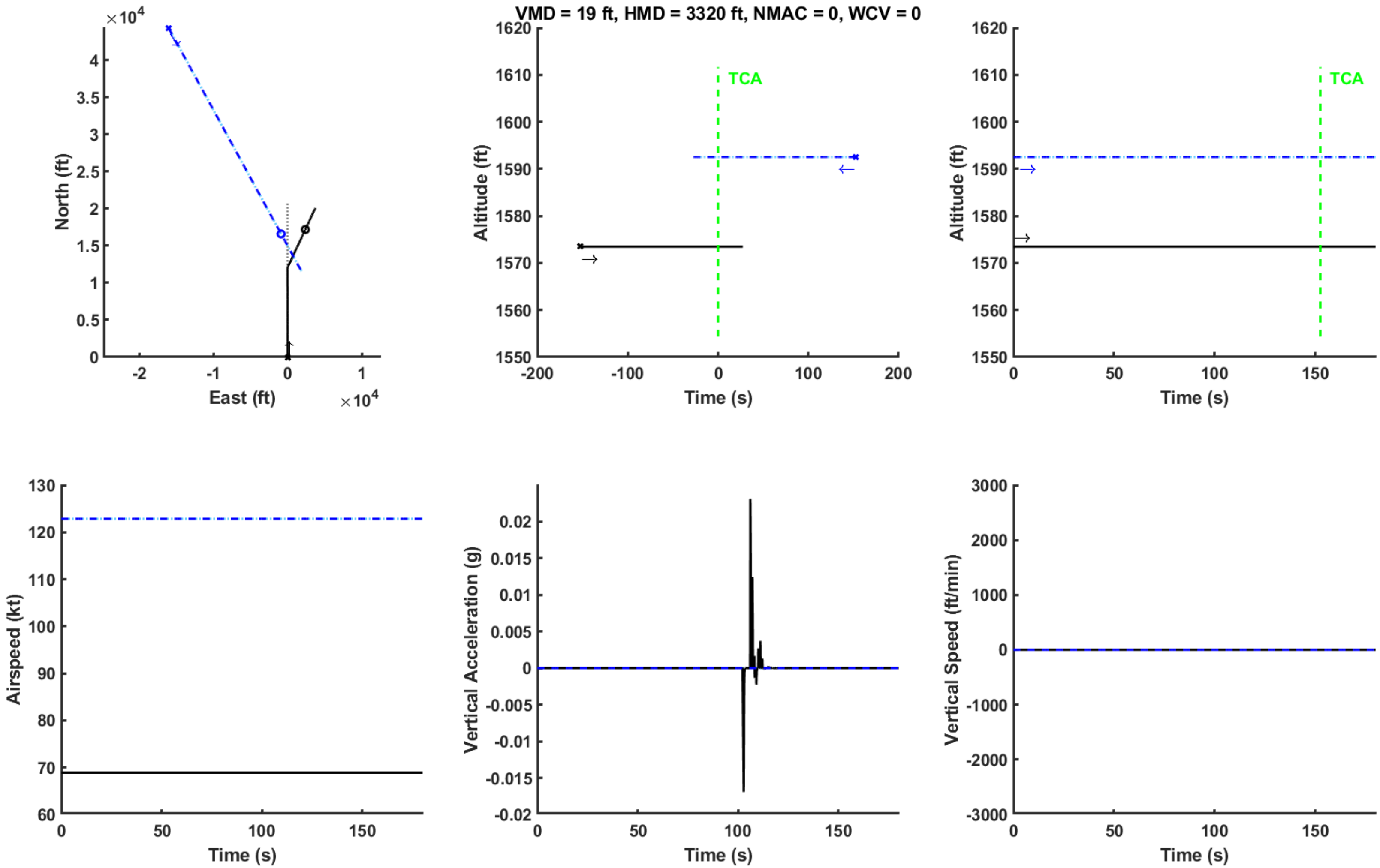


Reversal example - no sensor error





Split example – no sensor error



Split example - no sensor error