An Alternative Time Metric to Modified Tau for Unmanned Aircraft System Detect And Avoid

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Outline

- Background
- Modified Tau and Its Limitation
- Time to Protected Zone
- Surveillance Error Sensitivity
- Conclusion

Detect and Avoid

- Unmanned Aircraft Systems (UAS) will share airspace with manned aircraft
- Detect and Avoid (DAA) system for UAS replaces human "see and avoid"
- RTCA has completed Phase I Minimum Operational Performance Standards (MOPS) for DAA
- The MOPS targets UAS that can carry large and high-power sensor systems and operate in non-terminal areas
- Phase II work will extend to additional operations and UAS categories

NASA's Ikhana UAS

DAA Well Clear

- A DAA system keeps the UAS "Well Clear" of other aircraft
- UAS is assumed to be on instrument flight rules (IFR)

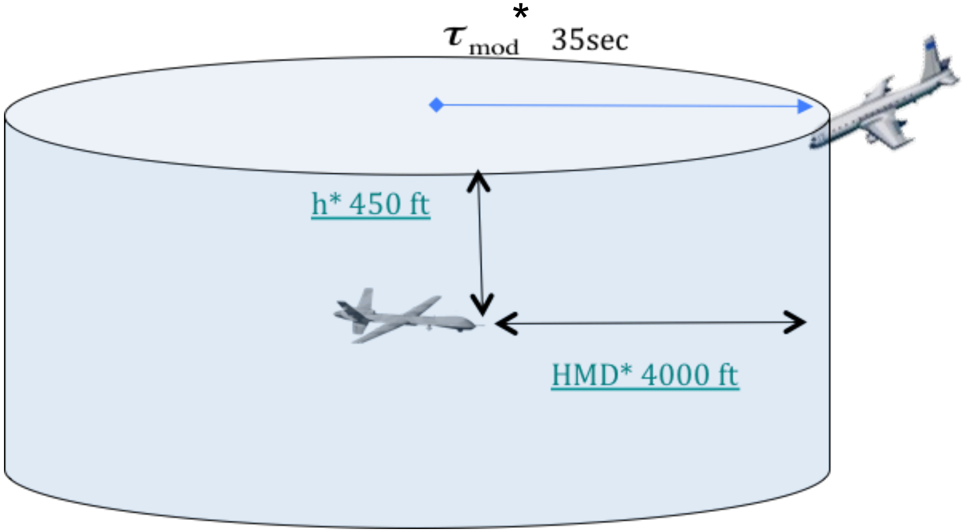
- A DAA Well Clear (DWC) zone must
    - be large enough to mitigate collision risks
    - be small enough to minimize operational impacts

- Traffic Collision Avoidance System II (TCAS II)
    - UAS can equip TCAS II as a safety net when DAA fails
    - DWC definition in Phase I MOPS driven largely by TCAS II interoperability
    - DWC should ideally enclose TCAS II's alerting zone

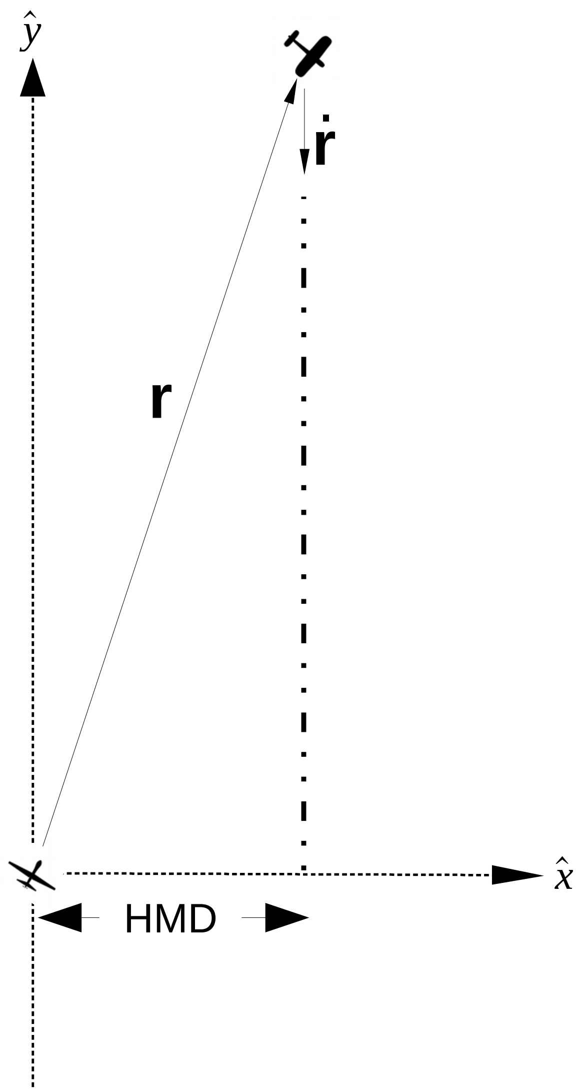
DWC Definition (Phase I)

- DWC
  - h: altitude difference
  - HMD: Horizontal miss distance (at closest point of approach)
  - τ_{mod}: modified tau, a horizontal time metric

- DWC is violated when all three variables fall below their respective thresholds (* represents threshold)



Horizontal Miss Distance



- **r**: relative position of intruder
- $\dot{\mathbf{r}}$: relative velocity of intruder

- HMD: predicted distance at horizontal closest point of approach (CPA)

- (predicted) Time to CPA

$$t_{\mathrm{cpa}} = -\frac{\boldsymbol{r}\cdot\dot{\boldsymbol{r}}}{\dot{\boldsymbol{r}}\cdot\dot{\boldsymbol{r}}}$$

Modified Tau

- Tau $\tau = -\frac{r}{\dot{r}}$ "estimates" t_{cpa}

  r is range

  $\dot{r}$ is range rate

  - Advantage: easy to compute, uses only range information
  - Limitation: shows no urgency for close, almost parallel flights
- Modified Tau: all intruders within a range of D_{mod} are treated with highest urgency

$$\tau_{\text{mod}} = \begin{cases} -\frac{r^2 - D_{\text{mod}}^2}{r\dot{r}}, \text{ if } r > D_{\text{mod}} \\ 0, \text{ if } r \le D_{\text{mod}} \end{cases}$$

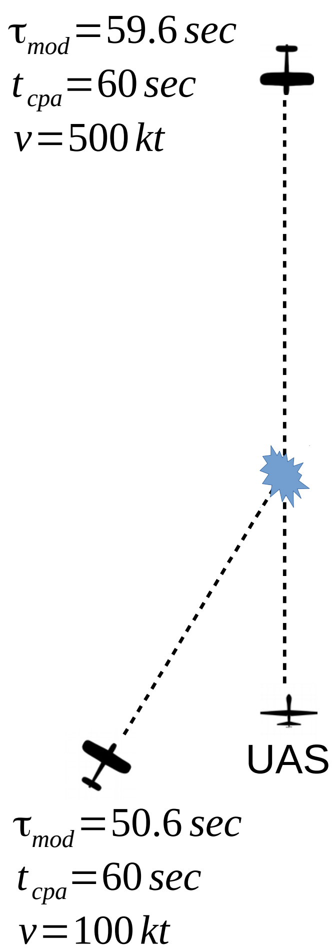
For DWC, $D_{\text{mod}} = \text{HMD}^* = 4000$ ft

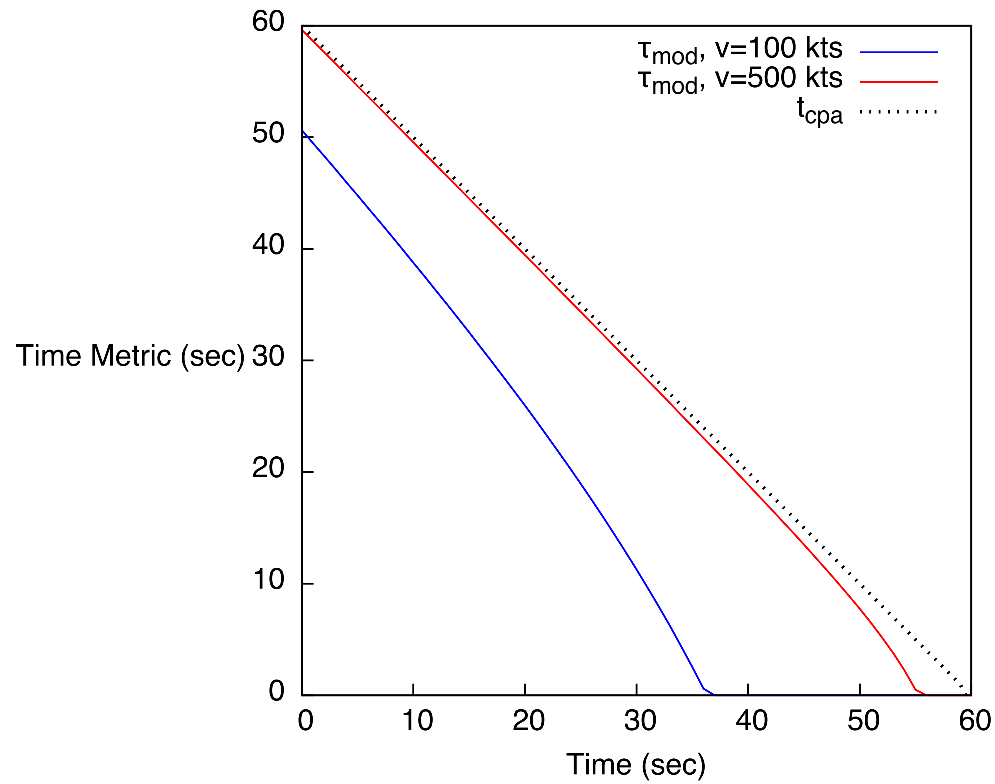
$\tau_{\text{mod}} \; -> \; \tau$ when $D_{\text{mod}} \; -> 0$

- DWC uses τ_{mod} because TCAS II also uses τ_{mod}
- DAA alerting requirements use τ_{mod} too

Example of Modified Tau

Non-accelerating intruders
v is relative to the UAS
HMD = 0





- τ_{mod} approaches t_{cpa} when $v \to \infty$

Limitations of Modified Tau

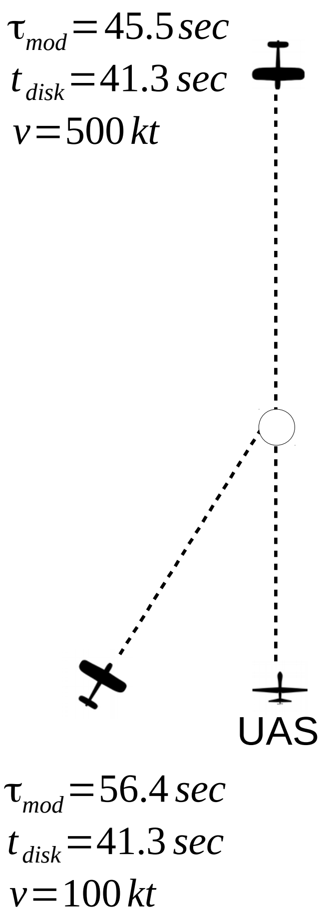
- τ_{mod}
  - does not correspond to a physical event
  - does not change linearly with time

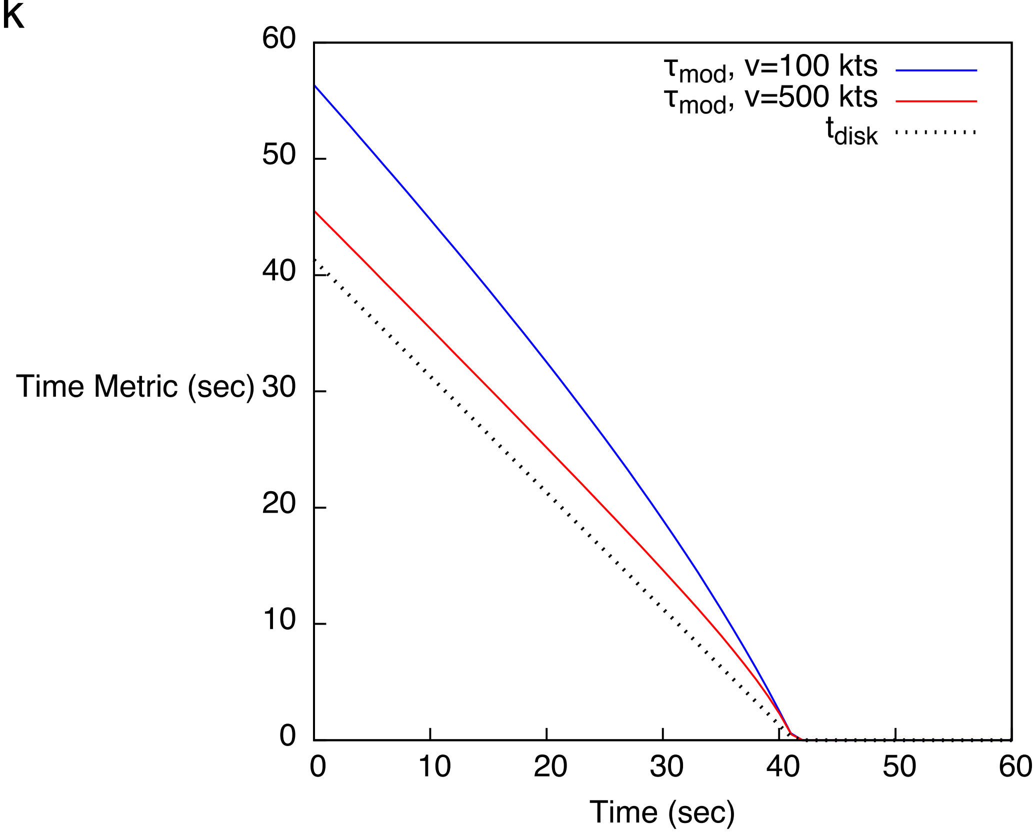
- Example: For a co-altitude, head-on encounter, τ_{mod} = 75 sec now.
  - How long until the ownship loses Well Clear ($\tau_{\mathrm{mod}}{}^{*}$= 35 sec) ?
  - Answer is NOT 40 sec

- For alerting, prioritization of intruders using τ_{mod} lacks physical basis
  - τ_{mod} is neither the time to CPA nor the time to the D_{mod} disk
  - Dependency on relative speed

Another Example of Modified Tau

Non-accelerating intruders
v is relative to the UAS
HMD = 0
t_{disk}: time to the D_{mod} disk





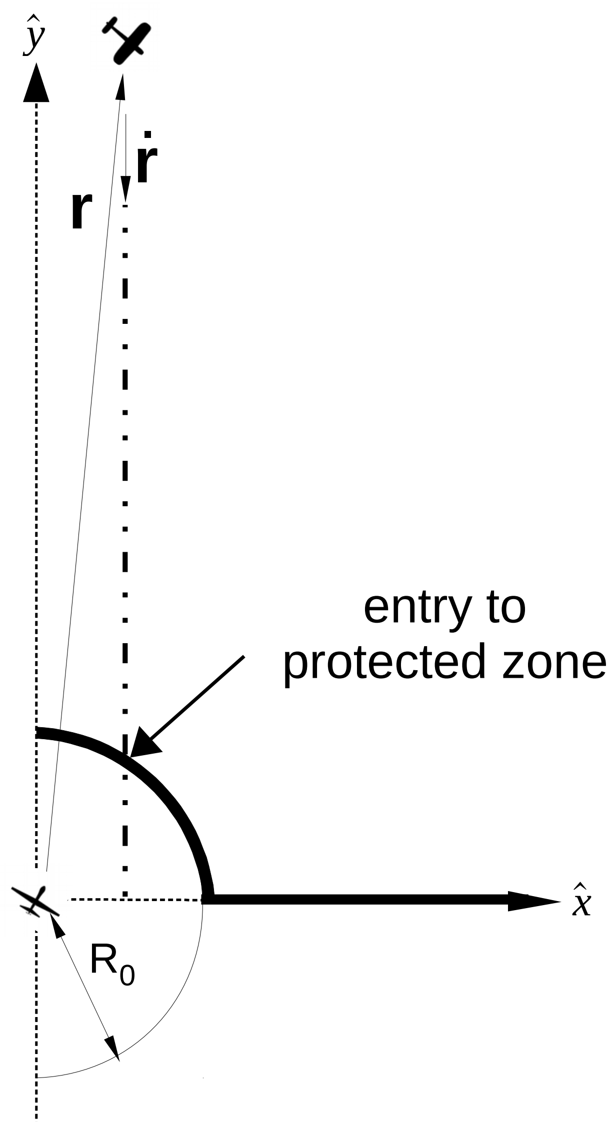
Time to Protected Zone

- This work proposes the Time to Protected Zone, t_{pz}
- t_{pz} has advantages over τ_{mod}
  - Corresponds to a physical event
  - Is linear with time
  - Intruder prioritization by an alerting algorithm using t_{pz} has a physical basis

- t_{pz} is also suitable for DAA interoperability with TCAS II

- Same framework for both DWC and alerting algorithm

Time to Protected Zone for DWC



- t_{pz}: time to Protected Zone
  - is the time to the disk (t_{disk})
  - or t_{cpa} if not entering disk
  - or 0 if already inside disk

- t_{cpa} a special case in which $R_0 = 0$

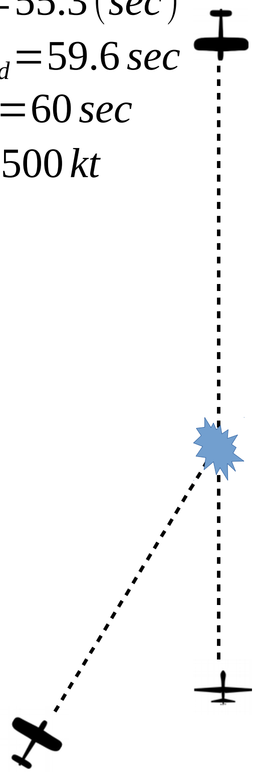
- Interoperability with TCAS II
  - $t_{pz} \leq \tau_{\text{mod}}$ if $R_0 = D_{mod}$
  - DWC with t_{pz} instead of τ_{mod} using the same threshold (35 sec) is larger
  - Maintains DWC/TCAS boundary

- Example: set $R_0 = \text{HMD}^* = 4000$ ft

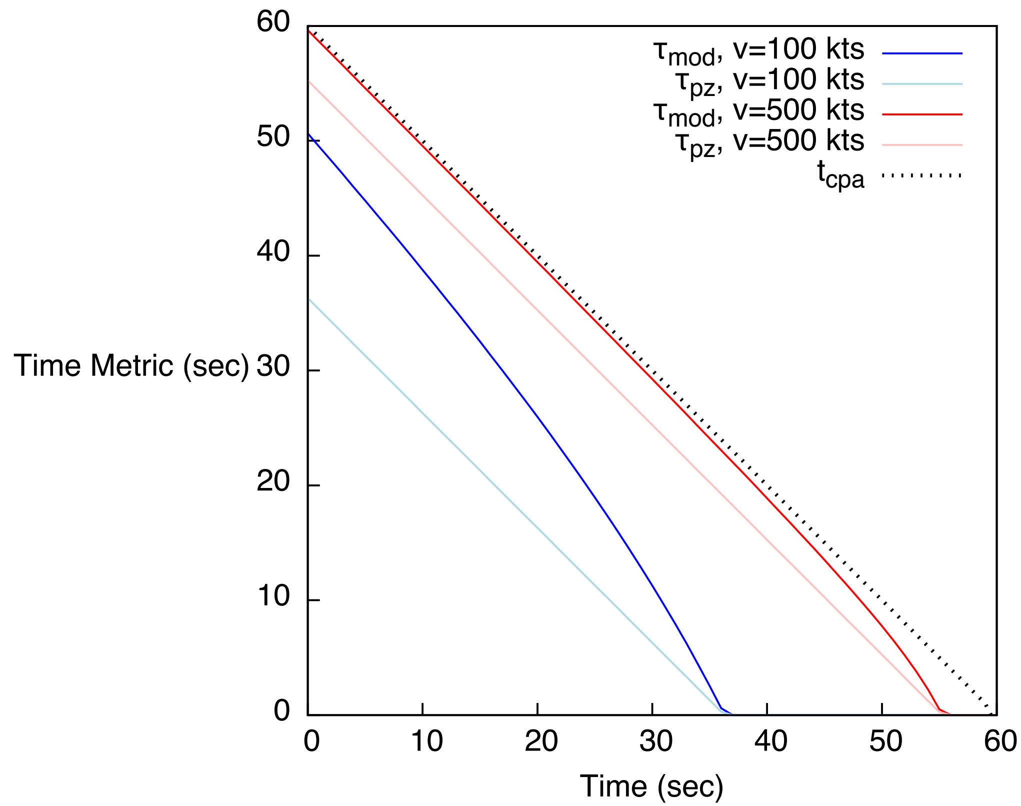
Example of Time to Protected Zone

Non-accelerating intruders
v is relative to the ownship

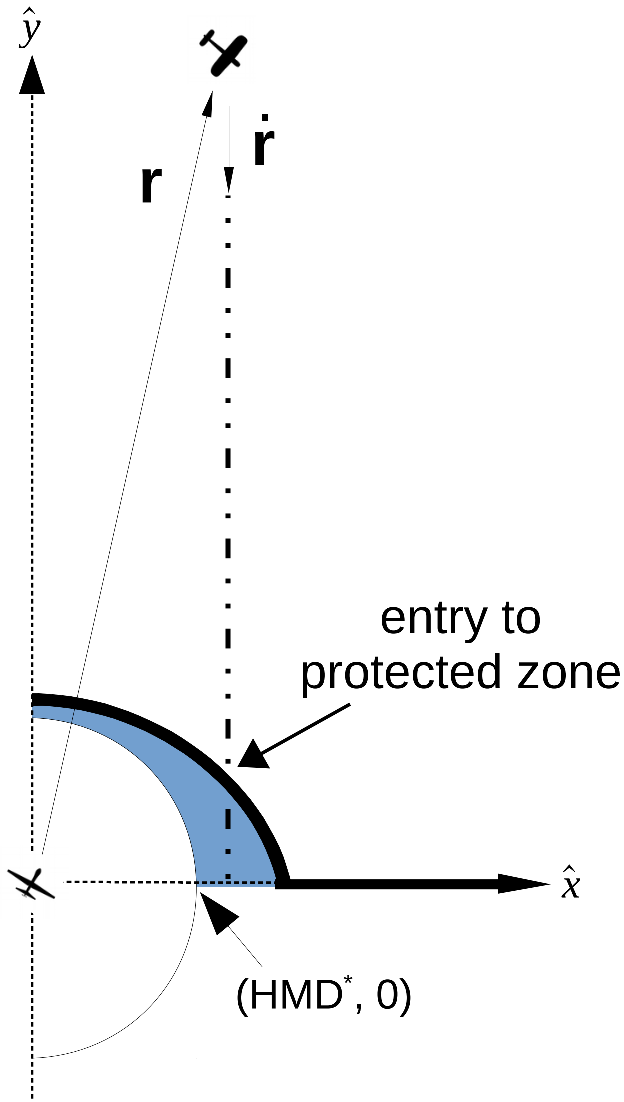
$t_{pz} = 55.3\,(sec)$
$\tau_{mod} = 59.6\,sec$
$t_{cpa} = 60\,sec$
$v = 500\,kt$



$t_{pz} = 36.3\,(sec)$
$\tau_{mod} = 50.6\,sec$
$t_{cpa} = 60\,sec$
$v = 100\,kt$



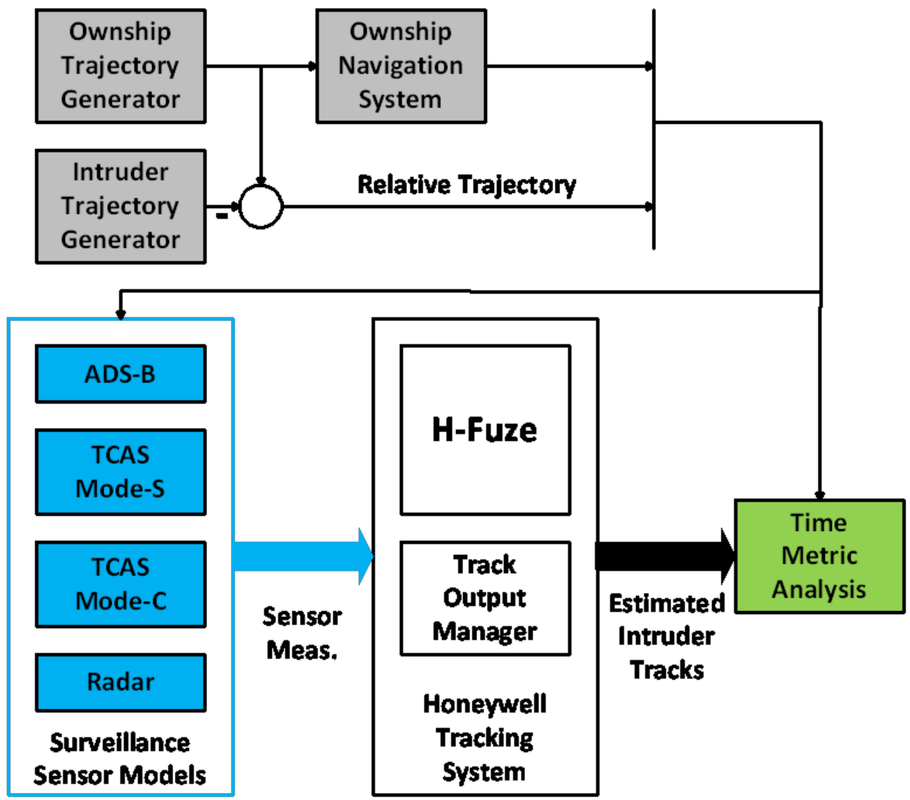
DAA Alerting



- The Protected zone can have an additional buffer to account for surveillance noise and reduce missed alerts
- Alert is issued if intruder is predicted to enter the protected zone
- Buffer size can be a function of individual intruders' equipage
  - ADS-B out
  - Mode S/C
  - Unequipped

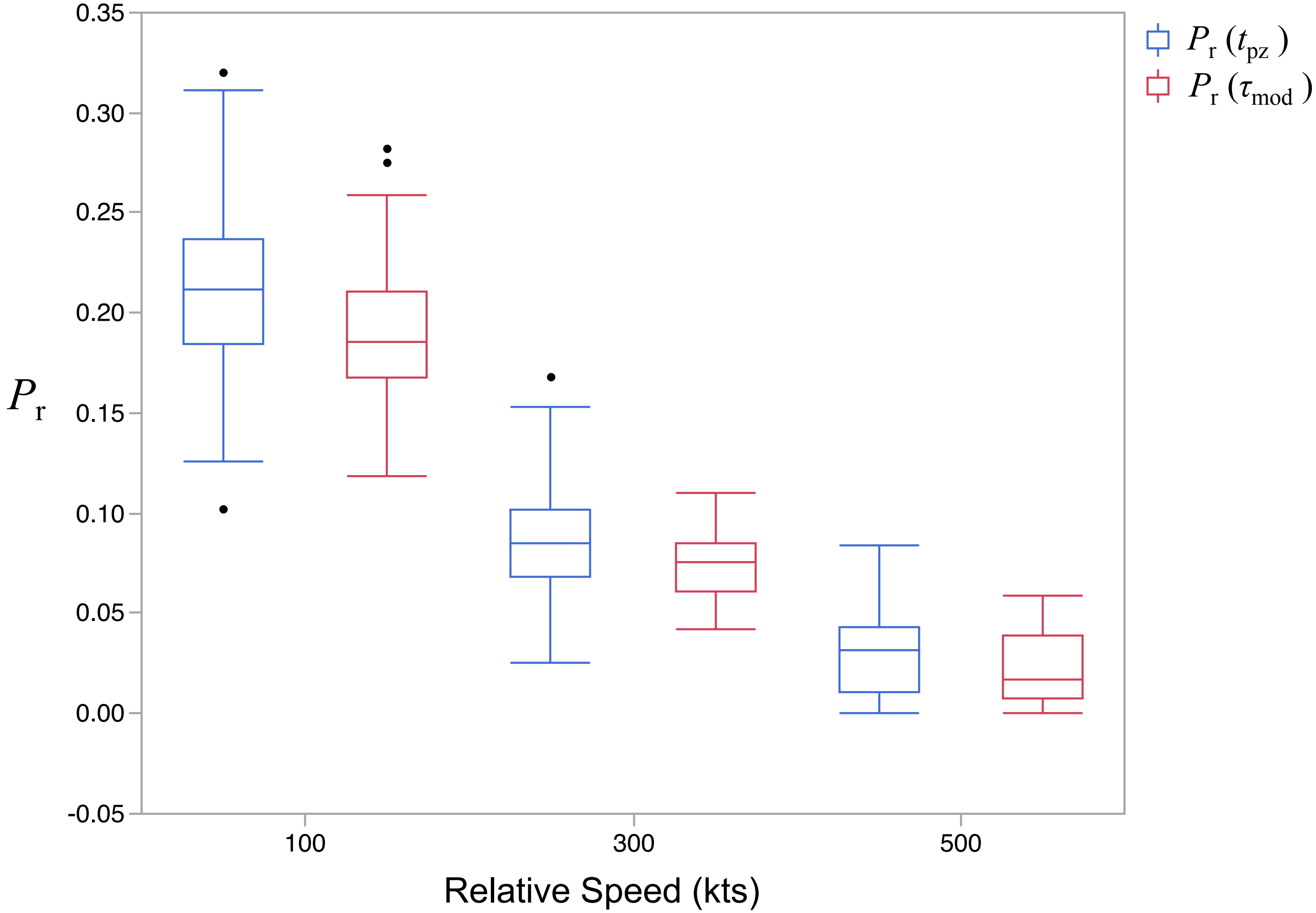
Sensitivity of t_{pz} to Sensor Errors

- Compared to τ_{mod}, t_{pz} is potentially more sensitive to surveillance sensor errors, because it depends on heading measurements.
- Analysis of simulated encounters with realistic sensor errors



- Results show sensitivity of t_{pz} is comparable to that of τ_{mod}

Relative Speed



P_r - probability of reversal of a time metric during the progression of an non-accelerating encounter

Conclusions

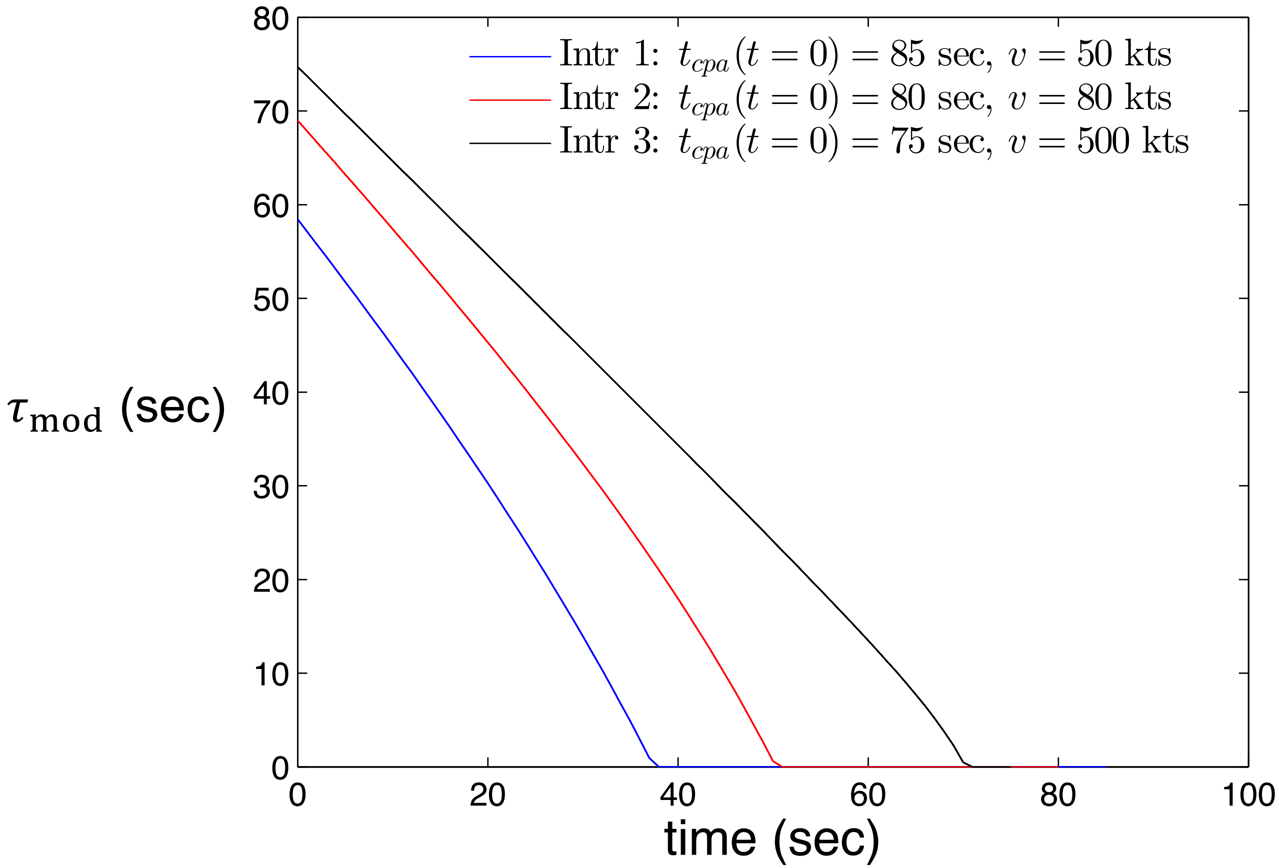
- A new time metric called Time to Protected Zone, t_{pz} is proposed for use in UAS's Detect and Avoid (DAA) systems.
- Three advantages over modified tau, τ_{mod}
  - It corresponds to a physical event
  - It is linear with real time during progression of an encounter
  - Prioritization of intruders by t_{pz} has a physical basis
- For alerting, the protected zone can be defined to be a function of surveillance errors to provide potentially better alerting performance.
- Sensitivities of τ_{mod} and t_{pz} to surveillance noises are comparable.

Future Work

- RTCA Phase II MOPS
- Alerting performance

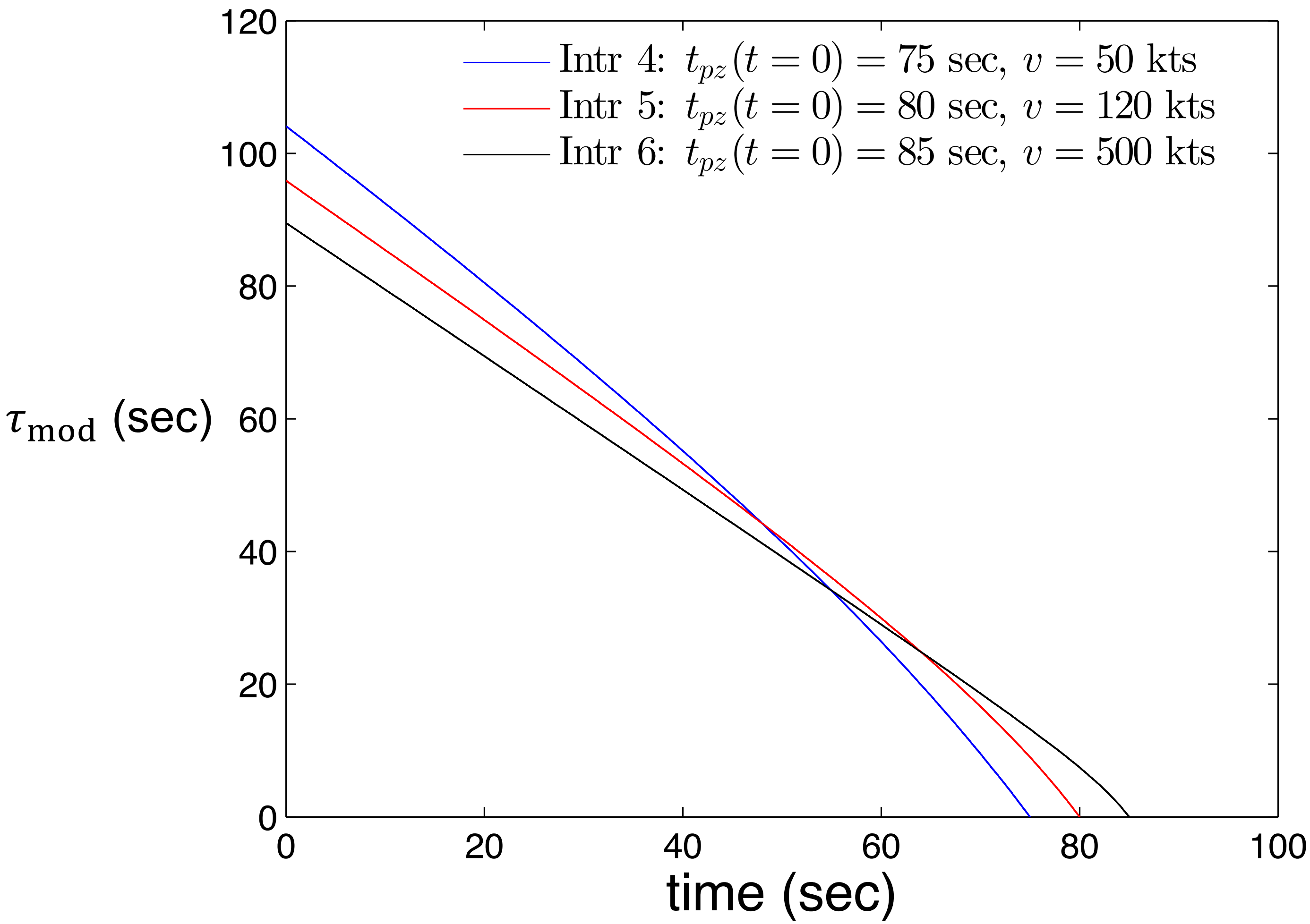
Backup Slides

Intruder Prioritization



- t_{cpa} predicts intruder 3 as the highest threat
- τ_{mod} predicts intruder 1 as the highest threat

Intruder Prioritization



- t_{pz} predicts intruder 4 as the highest threat
- τ_{mod} predicts intruder 6 as the highest threat

Modified Tau for DWC

- DWC uses τ_{mod} because TCAS II also uses τ_{mod}
- τ_{mod} is range-based and therefore not sensitive to TCAS's poor bearing sensor measurements
- Even with the use of τ_{mod}, DWC cannot completely enclose TCAS II resolution advisory zone due to complicated alerting logic in TCAS that
  - does not use HMD consistently
  - has altitude-dependent thresholds
  - uses slant range τ_{mod} (DWC uses horizontal τ_{mod})

Sensitivity of t_{pz} to Sensor Errors

- Compared to τ_{mod}, t_{pz} is potentially more sensitive to surveillance sensor errors, because it depends on heading measurements.
  - Fluctuating values may cause the alert type to vary back and forth
  - Inaccurate values may advance or delay the onset of an alert
- Analysis of simulated encounters with modeled realistic surveillance errors to quantify the sensitivity
- Sensitivity metrics - lower is better
  - P_r - probability of reversal of a time metric during the progression of an non-accelerating encounter
  - $|\Delta|_{avg}$ - average absolute error of a time metric as a result of surveillance errors
  - Both metrics are zero in the absence of surveillance errors

Test Matrix

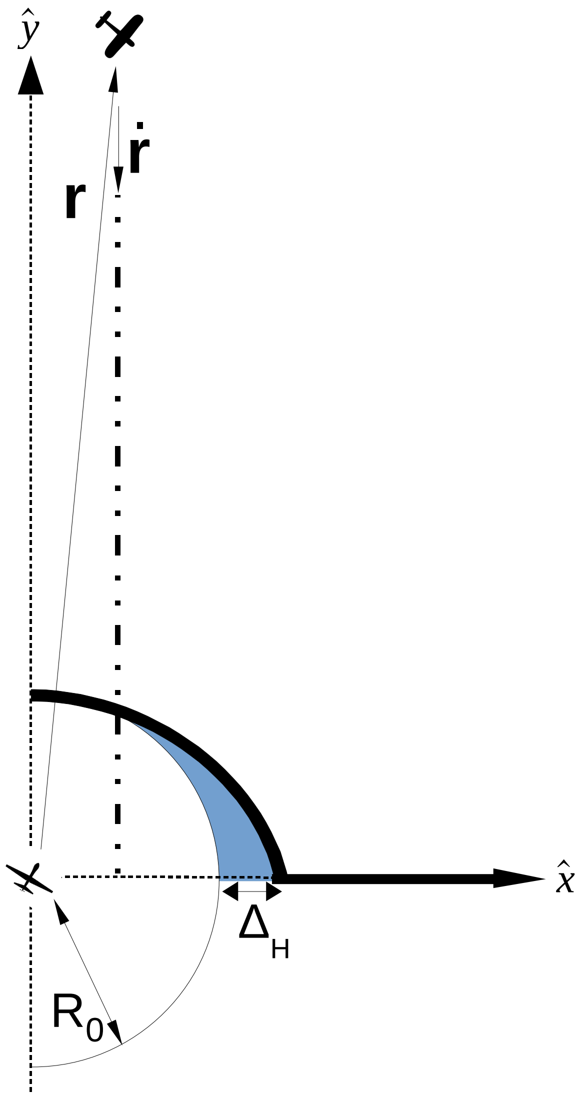
Parameter	Value
Intruder Equipage	ADS-B, Mode-S, Mode-C, None
Relative Speed (kts)	100, 300, 500
HMD (ft)	0, 1000, 2000, 3000, 4000
Relative Altitude (ft)	-500, 0, 500
Relative Heading (deg)	0, 45, 90
Passing	in front, behind (if HMD > 0)

- 972 encounters in total
- Intruder has a constant velocity
- Relative heading of 0 deg means a head-on

Surveillance Sensor Errors

- Sensor models are validated by flight test data
  - ADS-B: accurate position and velocity
  - Active surveillance for Mode S and Mode C: accurate range and altitude, noisy bearing
  - Air-to-air radar: accurate range and bearing
- Tracker (Honeywell Tracking System): a multi-intruder, multi-sensor fusion system
  - Data association
  - Track management
  - Track estimation

Equipage-Specific Protected Zone



For this work, the buffer zone width (blue) increases linearly from 0 at y = R_0 to Δ_H at y = 0

Δ_H : intruder equipage dependent

Benchmark values

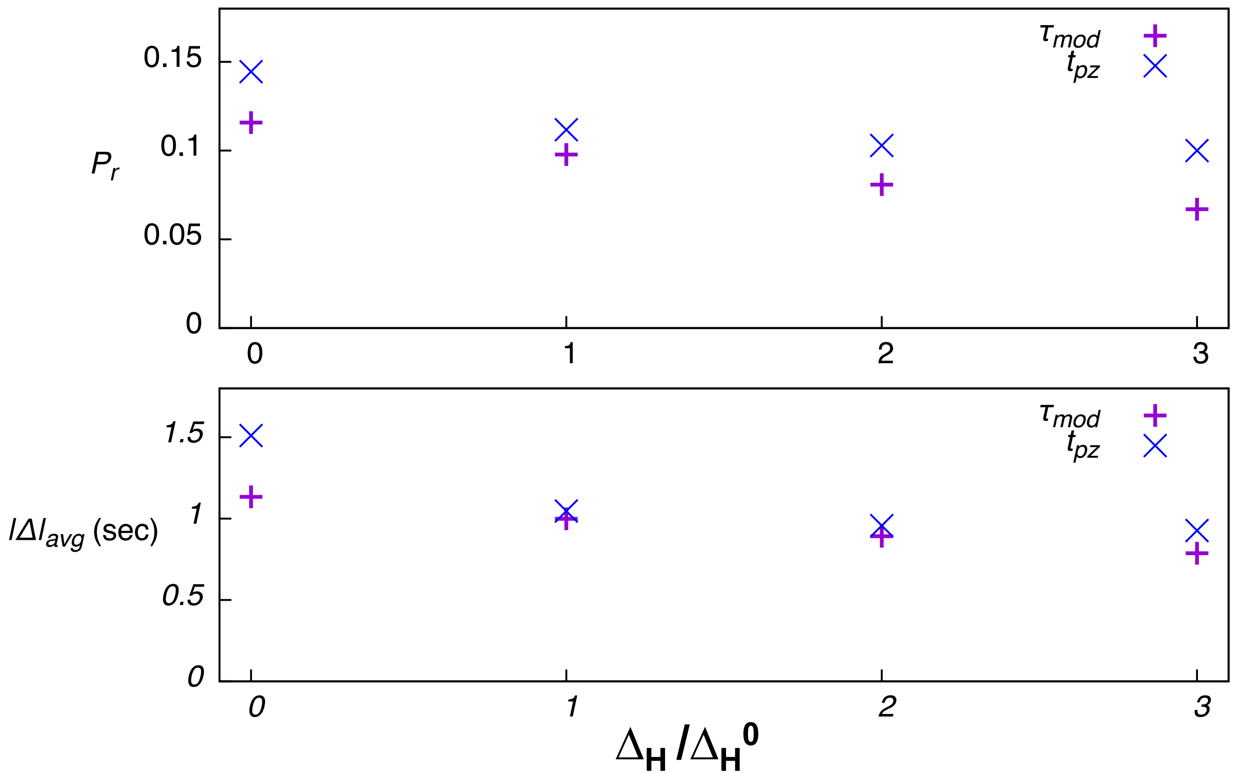
Δ_H^0 = 900 ft for ADS-B intruders

1700 ft for mode-S and mode-C

1900 ft for unequipped intruder

Simulations use 0, 1, 2, and 3 times of Δ_H^0

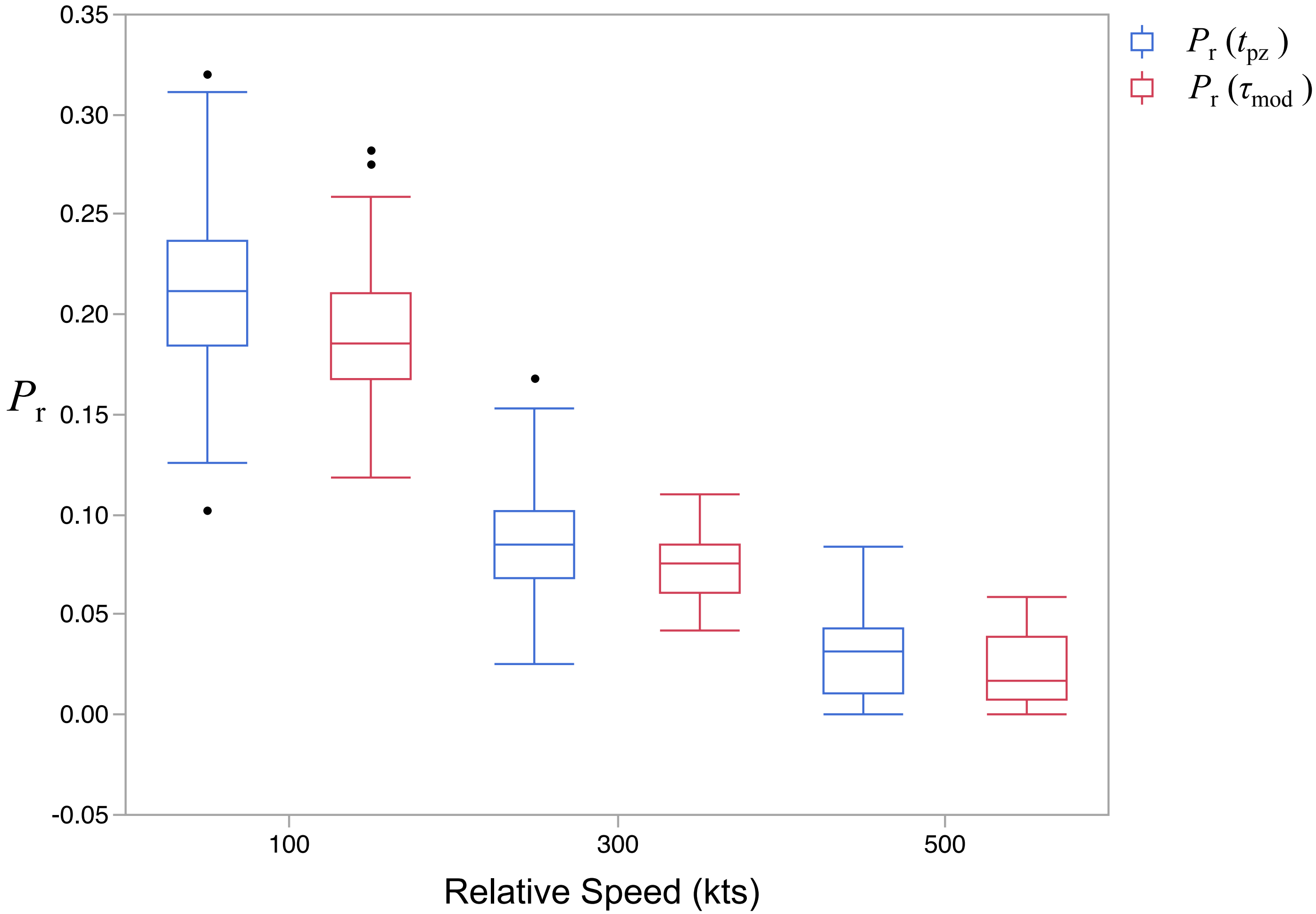
Aggregate Results



When Δ_H / Δ_H^0=1, τ_{mod} and t_{pz} have small differences in sensitivity (14% Pr, 5% $|\Delta|_{avg}$). Likely not significant enough to impact alerting performance

- P_r - probability of reversal of a time metric during the progression of an non-accelerating encounter
- $|\Delta|_{avg}$ - average absolute error of a time metric as a result of surveillance errors

Relative Speed



$$\delta t \approx t\left(\frac{\sigma_r}{r} + \frac{\sigma_{\dot r}}{\dot r}\right) \propto \frac{1}{\dot r}$$

Since the 2nd term dominates and $\sigma_{\dot r}$ is constant for ADS-B and radar

Intruder Equipage