Maritime Surveillance Aircraft Design Trades

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Overview

- Problem, Question
- Study Plan
- Models and Simulation overview
- Results
- Follow-on Analysis

Problem

- KJ&N Technologies is developing a maritime patrol aircraft (MPA) to meet specific customer needs

- An effective solution must balance endurance (driven by airframe, propulsion, and altitude/Mach regime), and sensor performance with Average Per Unit Cost (APUC).

- To meet customer requirements, KJ&N must deliver an aircraft that can effectively sanitize a maritime area of interest while remaining cost-competitive.

Question

What aircraft and sensor payload combination most effectively sanitizes a 100x100 km maritime Area of Interest (AOI)?

- Measures of Effectiveness:
  - Per-sortie effectiveness
    - Mission completion percentage $\mathrm{MC} = \min(1,\ \frac{sanitized_{km^2}}{AOI\ area_{km^2}})$
    - Surface area sanitized per average per-unit cost $(\mathrm{APUC})\left(\frac{sanitized_{km^2}}{APUC/\$1\mathrm{M}}\right)$
    - Surface area sanitized per sortie $\mathrm{A}_{sortie} = (km^2/sortie)$
  - Mission completion time (hrs)
    - Coverage Rate $(\frac{km^2}{hr})$
  - Total platform endurance
    - What residual capacity exists beyond the customer requirement (hrs)

Scenario, Assumptions

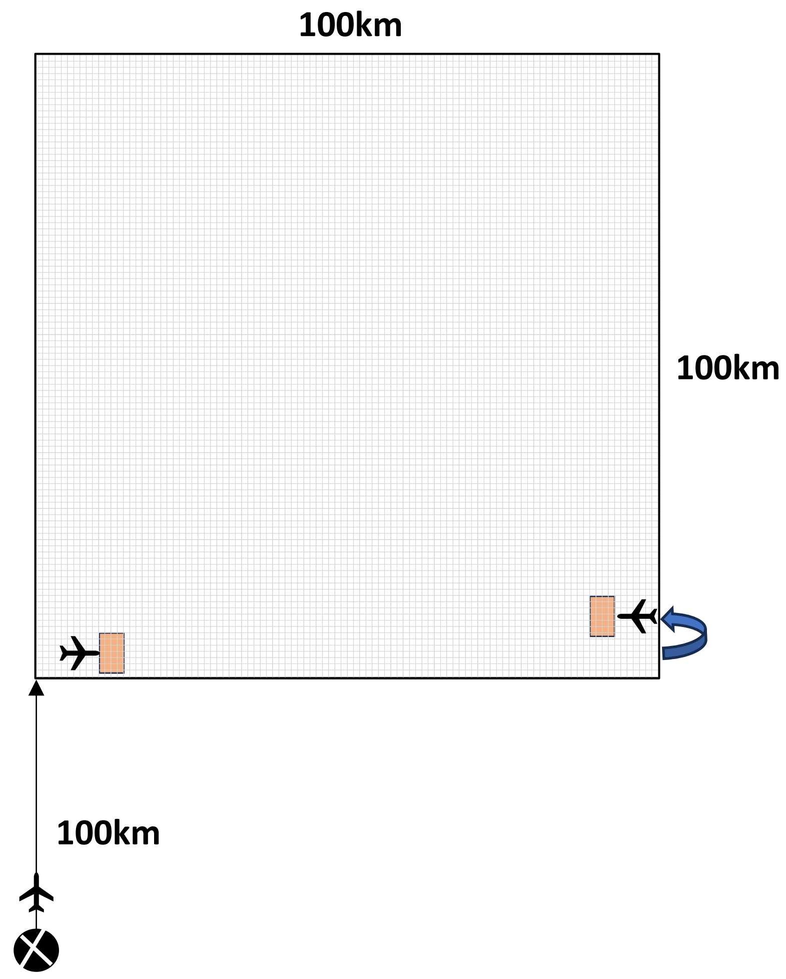
- 100km ingress/egress. 100x100km AOI
- Return to base with fuel for 1hr loiter
- MPA is fixed wing, capable of 45° angle of bank at all altitudes and airspeeds. Flies constant speed and altitude. No fuel adjustment for climbs or descents
- Flat earth, no terrain. Clear, standard day with clam sea state.
- Permissive environment
- "Lawnmower" search pattern
- Ignore start, taxi, and takeoff fuel requirements
- Staring IR mode detects targets. EO for recognition/identification. $n_{px\_IR} = 600$ $n_{px_{EO}} = 1920$
- 15m Target of Interest. $n_{px,det,} \geq 4px\ across\ target$. Limit effective FOV to account for ground sampling distance
- Polynomial surrogate functions for endurance and cost

Trade Space

- Altitude [5 – 25kft]
- Speed [0.4 – 0.9 Mach]
- 3 Unique EO/IR Sensor payloads
  - 15x15 deg FOV ($50K)
  - 30x30 deg FOV ($1M)
  - 60x60 deg FOV ($10M)

Design of Experiment

- Full factorial. 5 altitude levels (every 5k feet), 6 speed levels (step 0.1 Mach)



Modeling Approach

- Physics-informed, deterministic mission-level simulation
- Combines aerodynamic and geometric relationships (turn-radius, sensor footprint) with polynomial surrogate functions to approximate platform endurance and cost
- Pros: Fast, scalable, transparent
- Cons: Simplified aero, engine, and sensor representation.

Inputs:

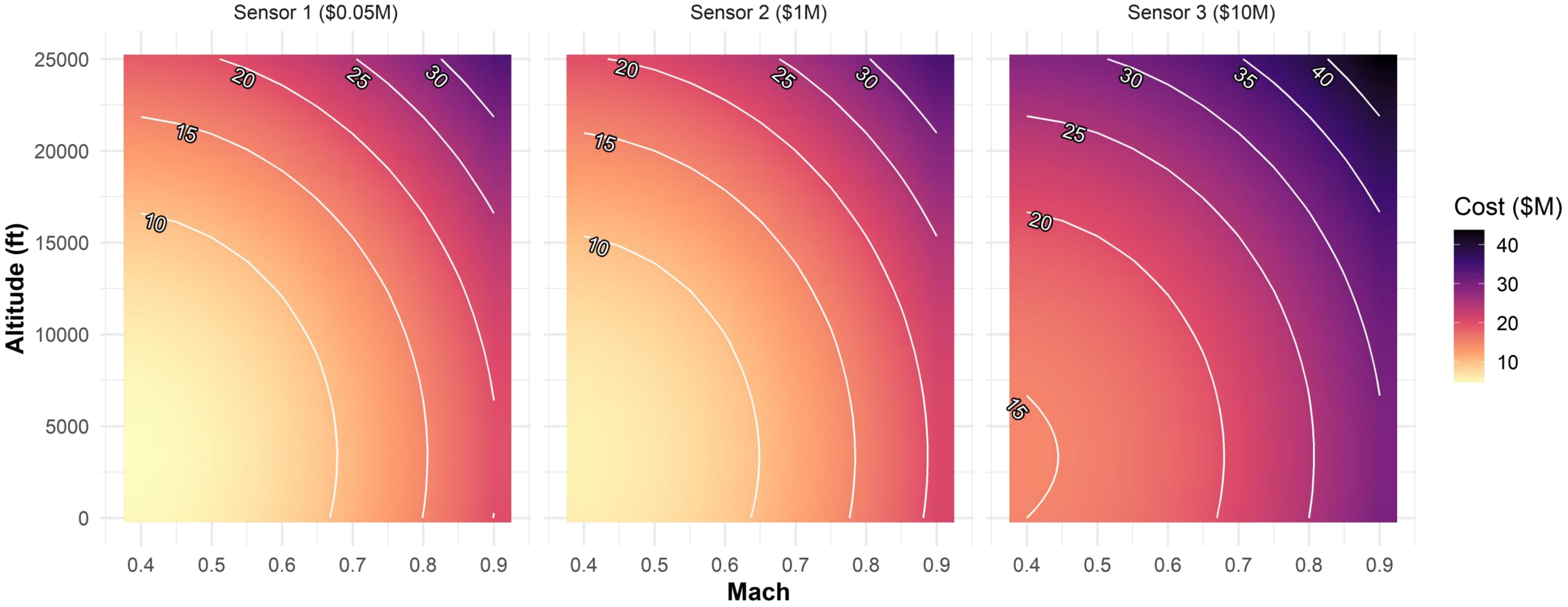
1. Mach number
2. Altitude
3. Bank angle
4. Sensor field of view/cost
5. AOI Size
6. Ingress distance
7. Endurance, Cost surrogates

Outputs:

1. Area sanitized/sorties (km^2)
2. Mission time
3. Endurance, cost

Cost Model

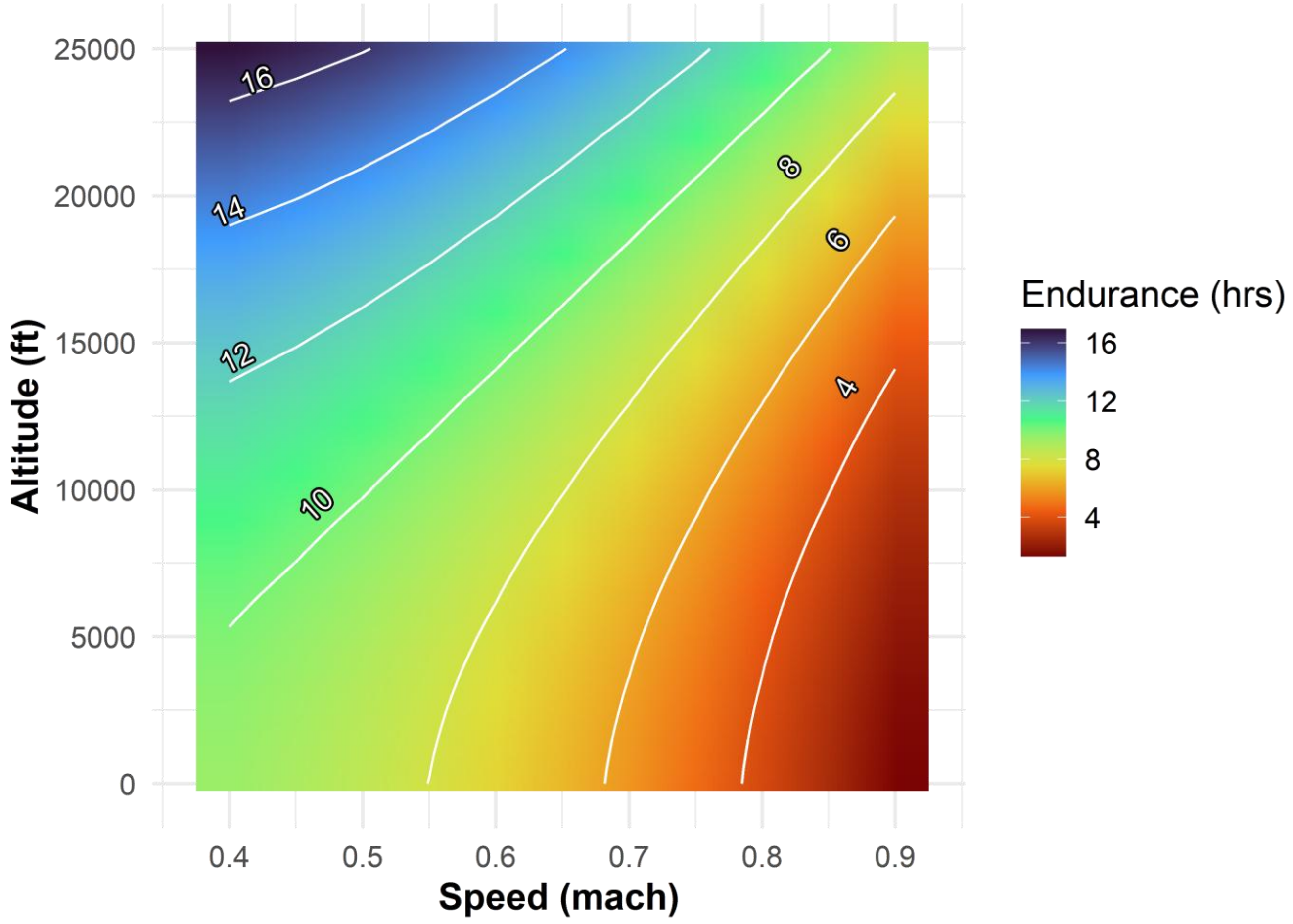
Altitude, Mach, Sensor vs Cost



$$Cost_{\$M} = 50 * Mach^2 - 35 * Mach + 0.03 * Alt_{kft}{}^2 - 0.2Alt_{kft} + 11$$

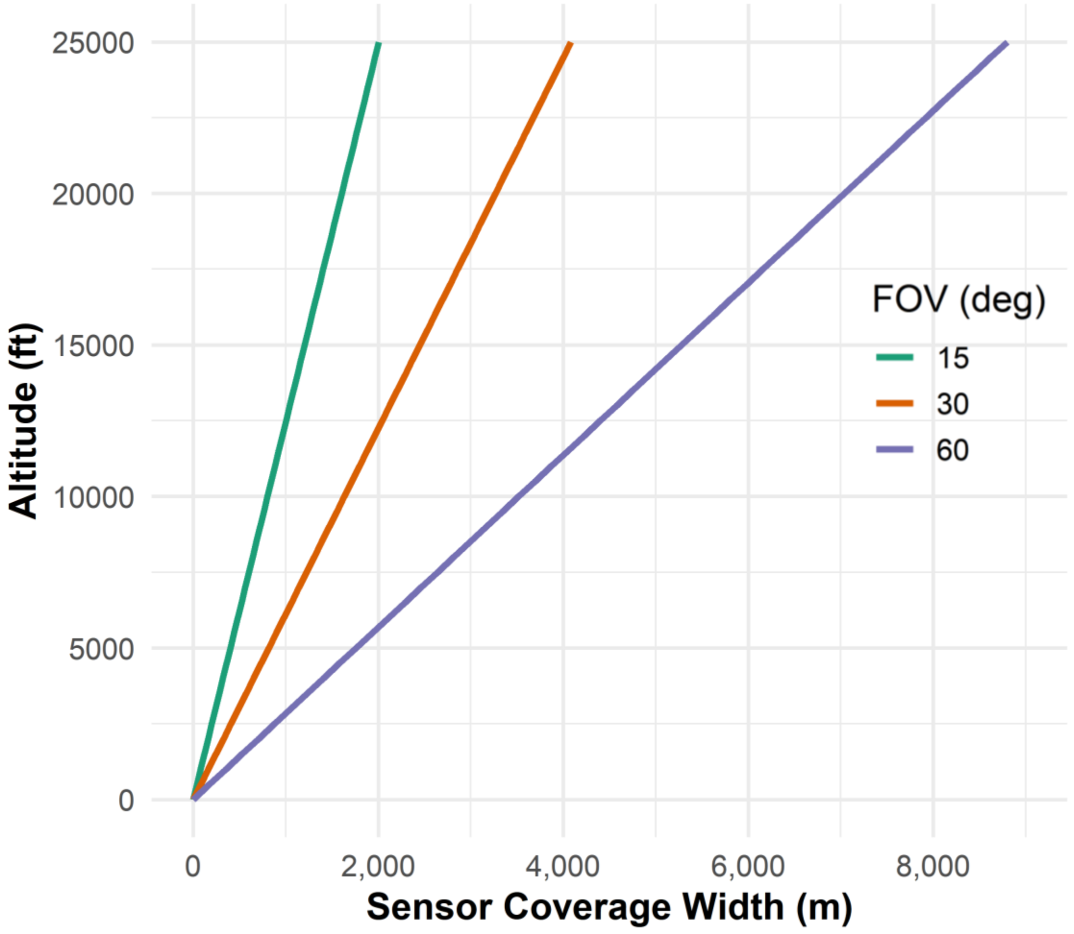
Endurance, Sensor Models

Altitude, Speed vs Endurance



$$Endurance_{hrs} = 18.75 * Mach^2 + 8.0893 * Mach + 0.01 * Alt_{kft}^2 + 0.05 * Alt_{kft} + 9.2105$$

Sensor Footprint (width) vs Altitude



$$Sensor\ Footprint\ (width) = 2h * \tan\frac{\theta}{2}$$

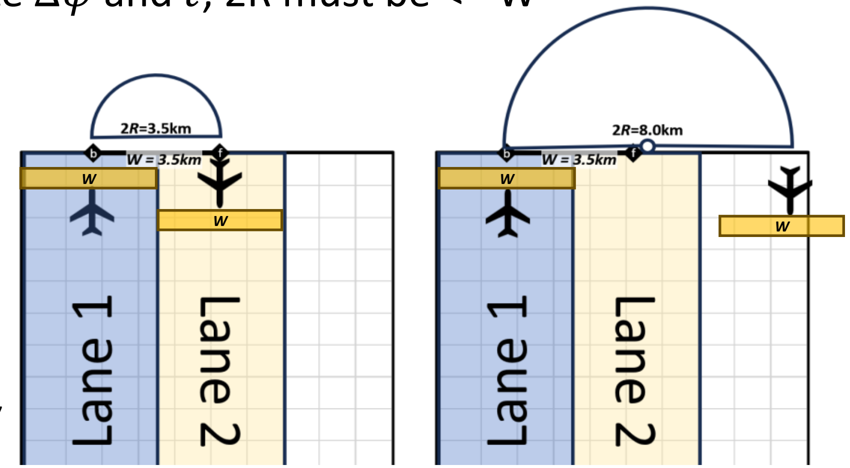
Turn Radius and Sensor Alignment

- Assuming no overlap, the optimal lateral separation between patrol lanes equals sensor footprint width W
- Time to turn t, turn radius R, and turn rate $\dot{\psi}$, depend on bank angle ϕ and velocity V

$$R = \frac{V_{m/s}^2}{g\tan(\phi)} \qquad \dot{\psi} = \frac{g\tan(\phi)}{V_{m/s}} \qquad t_{sec} = \frac{\Delta\psi}{\dot{\psi}}$$

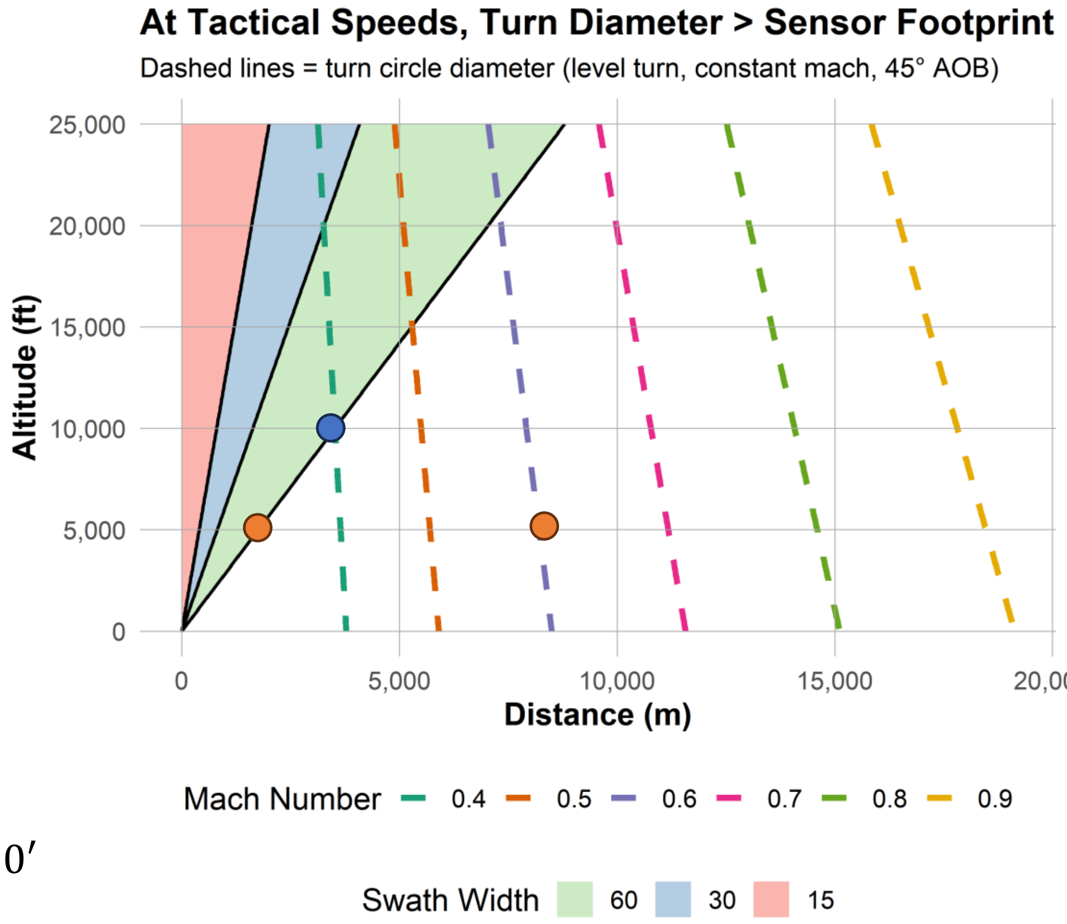
- If an aircraft's turn circle diameter ($2R$) exceeds sensor footprint width W, the additional maneuvering required
- To minimize $\Delta\psi$ and t, 2R must be <= W

10k', 0.4 Mach
$2R = {\sim}3500m$
$W_{60} = 3500m$
$2R - W = 4500'$



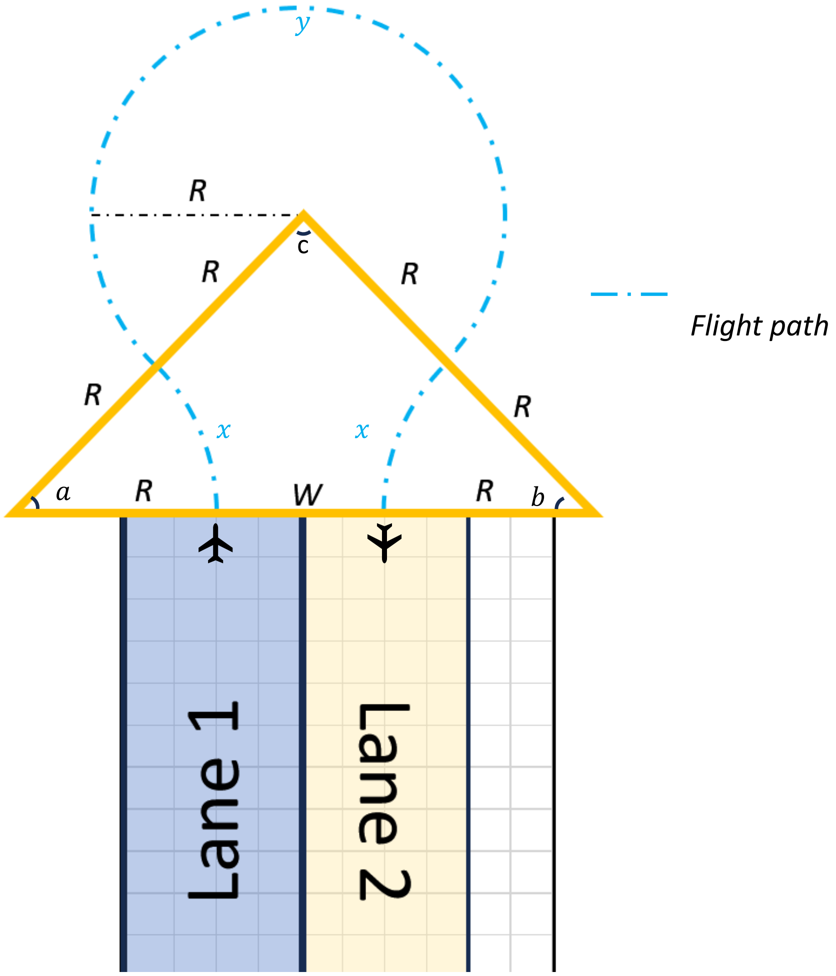
Optimal flight path ($2R <= W$) *$2R > W$)*

0.6 Mach, 10k'
$2R = {\sim}8000'$
$W = 3500m$
$2R - W = 4500'$



Turn Radius and Sensor Alignment

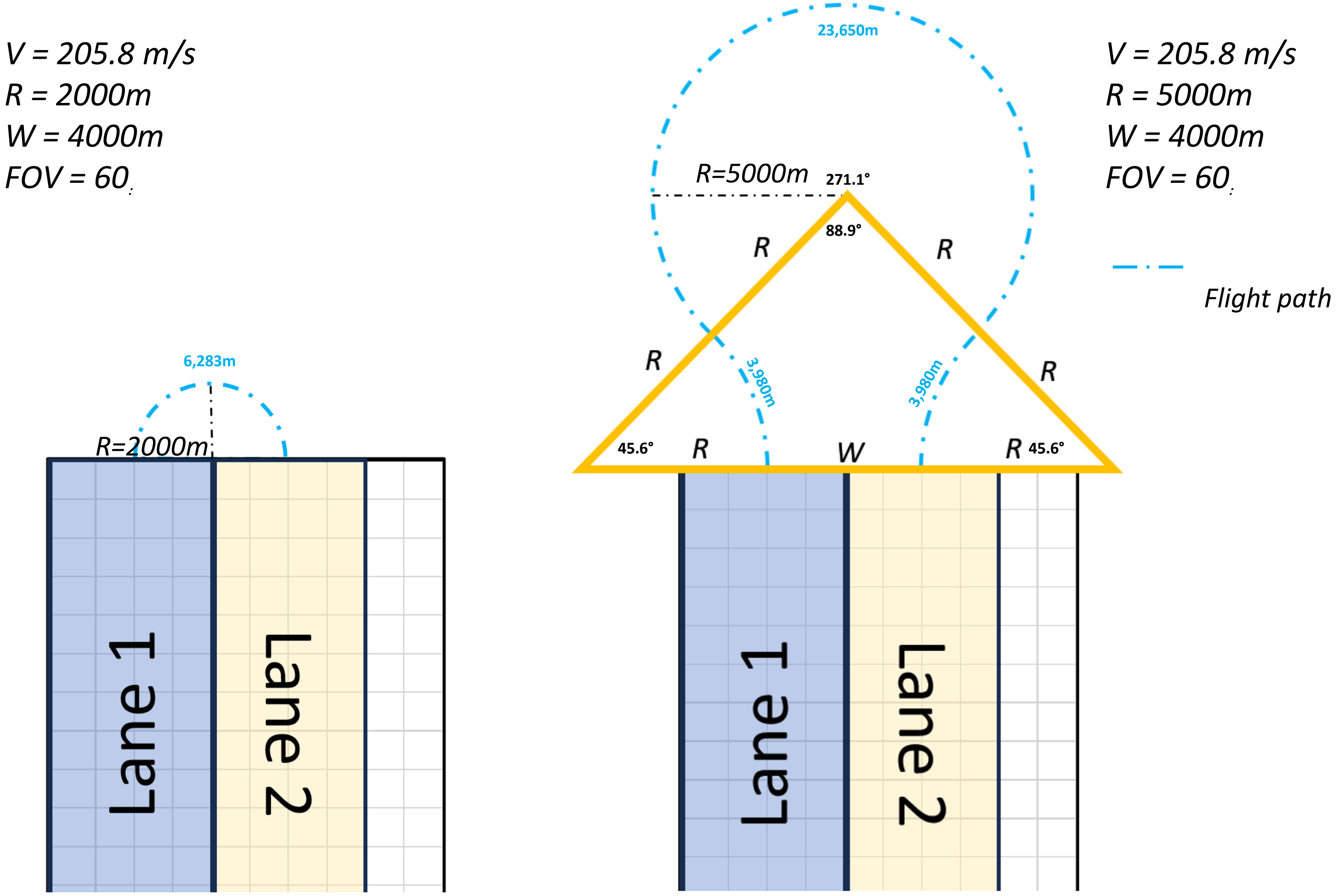
- To accurately model endurance when flying a lawn-mower search pattern, the overshoot distance from one lane to the next must be accounted for
- When $2R \leq W$, turn duration is the time to fly half of a turn circle (πR)
- When $2R > W$, turn duration can be calculated by solving for angles a, b, and c ($\angle a = \angle b$), then summing the arcs $2x + y$



Turn Radius and Sensor Alignment

- **Aircraft A** with $R = 2000m$ and $W = 4000m$ limits $\Delta\psi$ to $\pi_{radians} = 180_{degrees}$
  - Completes maneuver in 31 seconds, begins patrolling lane 2 nearly two minutes sooner than an **aircraft B**

- If a patrol requires 25 180° direction changes, **aircraft B** spends *62 minutes* maneuvering outside the AOI, compared to *12* for aircraft B



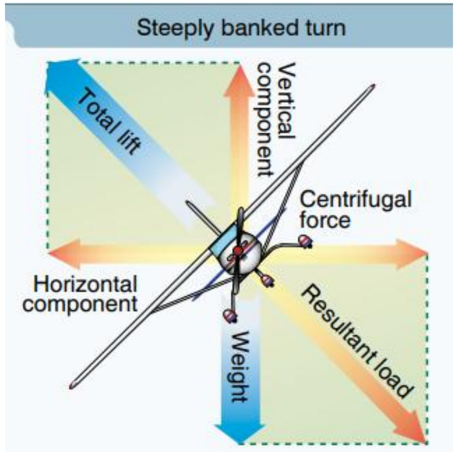
Aircraft A
31 seconds begin lane 2 (6.3km turn maneuver)

Aircraft B
154 seconds to begin lane 2 (31.6km maneuver)

Load Factor and Thrust Required

- During a level turn, the load factor n increase according to $n = \dfrac{1}{\cos(\phi)}$
- Increase in load factor requires a proportional increase in lift which in turn increases induced drag
- Additional thrust is required to overcome the induced drag experience during a level turn
- If our endurance model is based on straight-and-level flight, we must account for the additional thrust required during maneuvers, which increases fuel burn and reduces endurance.

1) Estimate k, the fraction of total drag at cruise caused by induced drag (0.2) $k = \dfrac{1}{\pi e AR}$
2) Because $C_{D_i} \propto C_L^2$ and $C_L \propto n \Rightarrow C_{D_i} \propto n^2$ $\quad C_{\{D_i\}} = \dfrac{C_L^2}{\pi e AR} \quad C_{\{L\}} = \dfrac{L}{qS} = \dfrac{nW}{qS}$
3) When $n > 1$, $D = D_p + D_i n^2$ $\quad \dfrac{D_{turn}}{D_{level}} = \dfrac{D_p + D_i n^2}{D_p + D_i} = \dfrac{D_p}{D_p + D_i} + \dfrac{D_i n^2}{D_p + D_i} = 1 - k + kn^2$
4) Assume thrust $\propto$ fuel flow
5) Derived $Fuel\ Burn\ Multiplier\ =\ 1\ + k(n^2 - 1)$



EG: For a 45° turn: $n = 1.414$, assume $k = 0.2,\ 1 + 0.2(1.414^2 - 1) = 1.2$

Account for $n > 1$ with $Endurance\ = Endurance\ - (turn\ duration * 1.2)$

https://www.faa.gov/sites/faa.gov/files/07_phak_ch5_0.pdf

Sensor Resolution v Slant Range

- Instantaneous FOV (IFOV) is angular per pixel (the angular size each pixel subtends)

$$IFOV_{px} = \frac{FOV_{axis}}{N_{px,axis}} \text{ [rad/px]}$$

- Ground sampling distance (GSD), the linear ground distance each pixel represents, increases with altitude H and slant range R

$$GSD_{m/pixel} = IFOV_{px} * H_{nadir} \text{ (best case)}$$

- For pixels near the edge of the FOV, $R > H$. Each pixel covers more ground by a factor of $\sec^2 \alpha$ where α= angle off boresight (nadir)

$$GSD_{edge} = H * sec^2\left(\frac{FOV_{rad}}{2}\right) * IFOV_{px} \text{ (worst case)}$$

- Account for sensor resolution by requiring $n_{px} \geq 4$ for detection of a target with length L. Use expected target size to cap GSD and constrain FOV. For this analysis assume $L = 15m$ (FFG beam)

$$n_{px} = \frac{L_{target}}{GSD} \quad \Rightarrow \quad GSD_{max,IR} = \frac{L}{n_{px,det}} = 5\text{m/pixel}$$

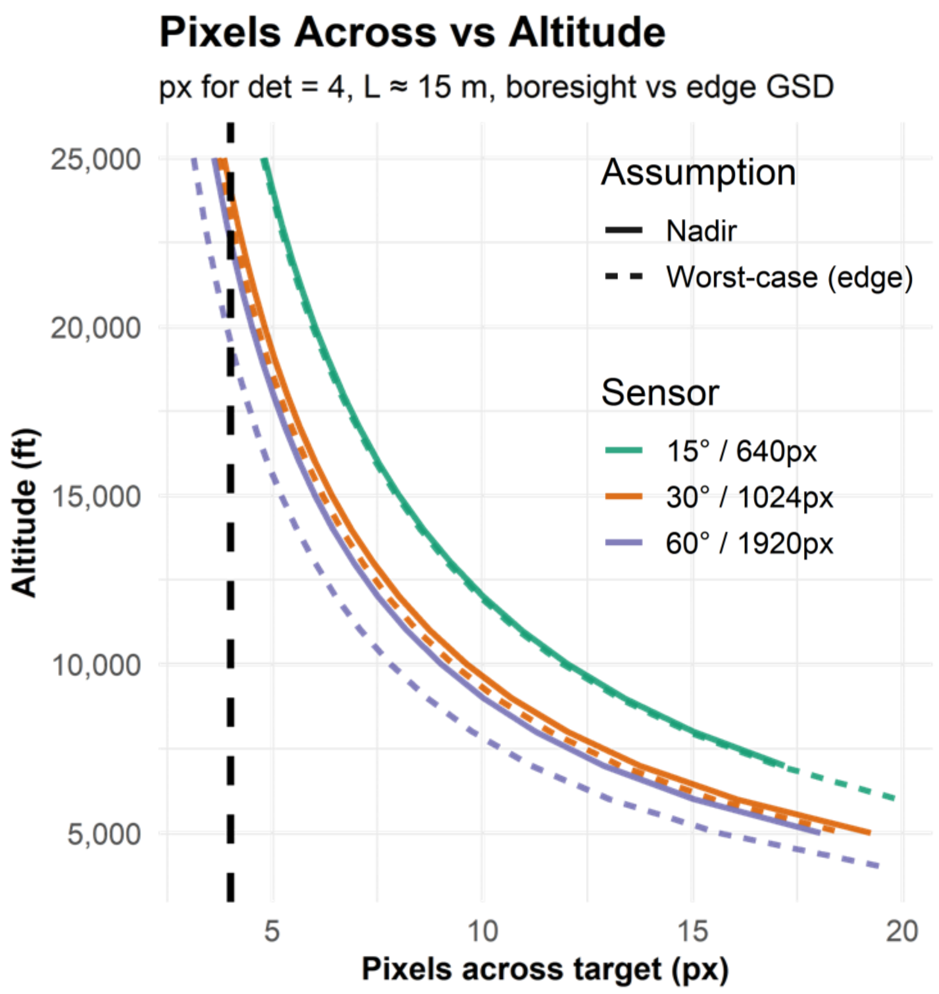
- Account for sensor resolution by using GSD_{max} to constrain sensor FOV based on altitude

$$FOV_{cap,IR}(H) = \frac{n_{px\_IR} * L}{n_{px,det} * H}$$

$$FOV_{eff,IR}(H) = \min(FOV_{lens,IR}, FOV_{cap,IR}(H))$$

α

$$W_{eff,IR}(H) = 2\text{H} \tan\left(\frac{\text{FOV}_{\text{eff,IR}}(\text{H})}{2}\right)$$



Sensor Package Options

Sensor 1

- \$0.05 Million
- 15x15° FOV
- $640x640_{px}FPA$
- IFOV: $0.409_{mrad/px}$
- $GSD(20{,}000') = 2.5m/px$

Sensor 2

- \$1.0 Million
- 30x30° FOV
- $1024{,}1024_{px}FPA$
- IFOV: $0.511_{mrad/px}$
- $GSD(20{,}000') = 3.1m/px$

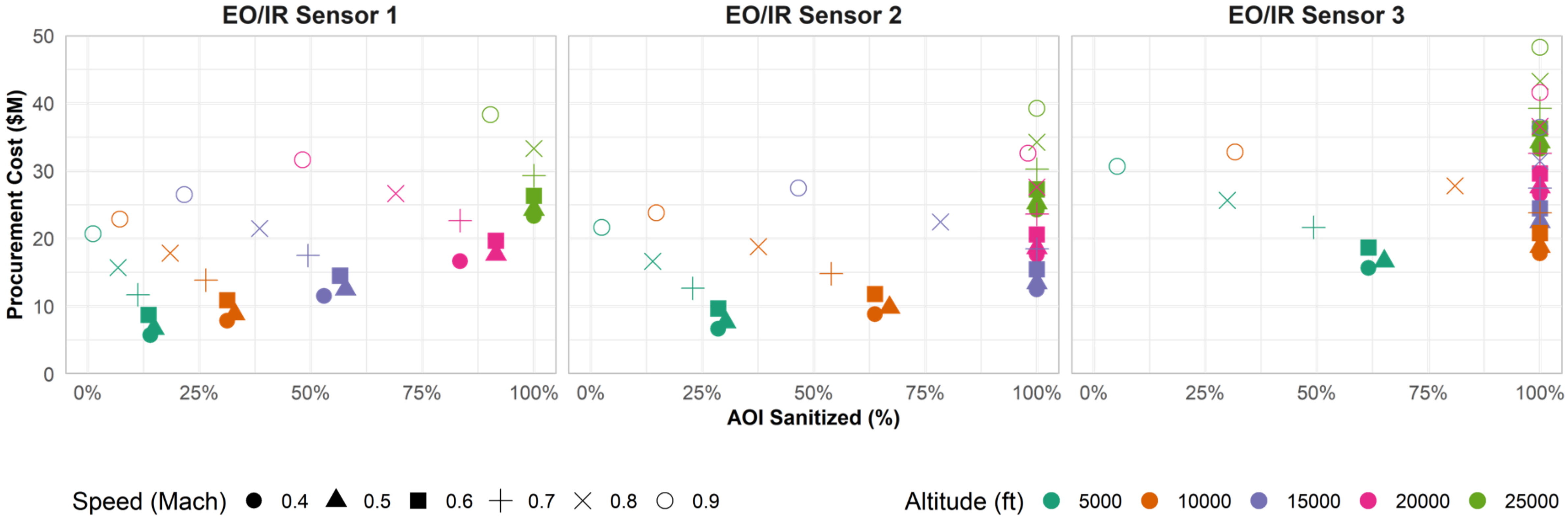
Sensor 3

- \$10.0 Million
- 30x30° FOV
- $1920x1920_{px}FPA$
- IFOV: $0.545_{mrad/px}$
- $GSD(20{,}000') = 3.3m/px$

Results

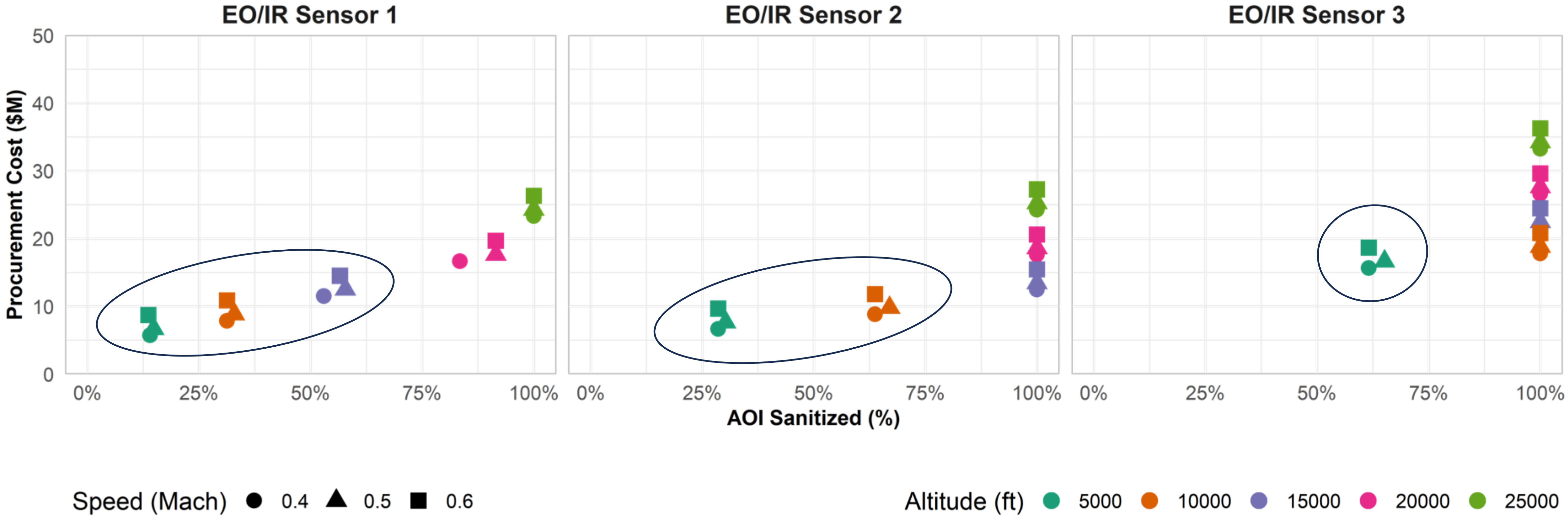
High MPA Speed Does not Mitigate Endurance Degradation

- Assuming time-to-complete mission is not a significant factor in mission effectiveness, slower (0.4-0.6 Mach) MPAs can sanitize more area *and* are more cost effective
- For all sensor and altitude combinations, the faster (> 0.6 Mach) MPA cost more per area sanitized, and do not increase overall mission success



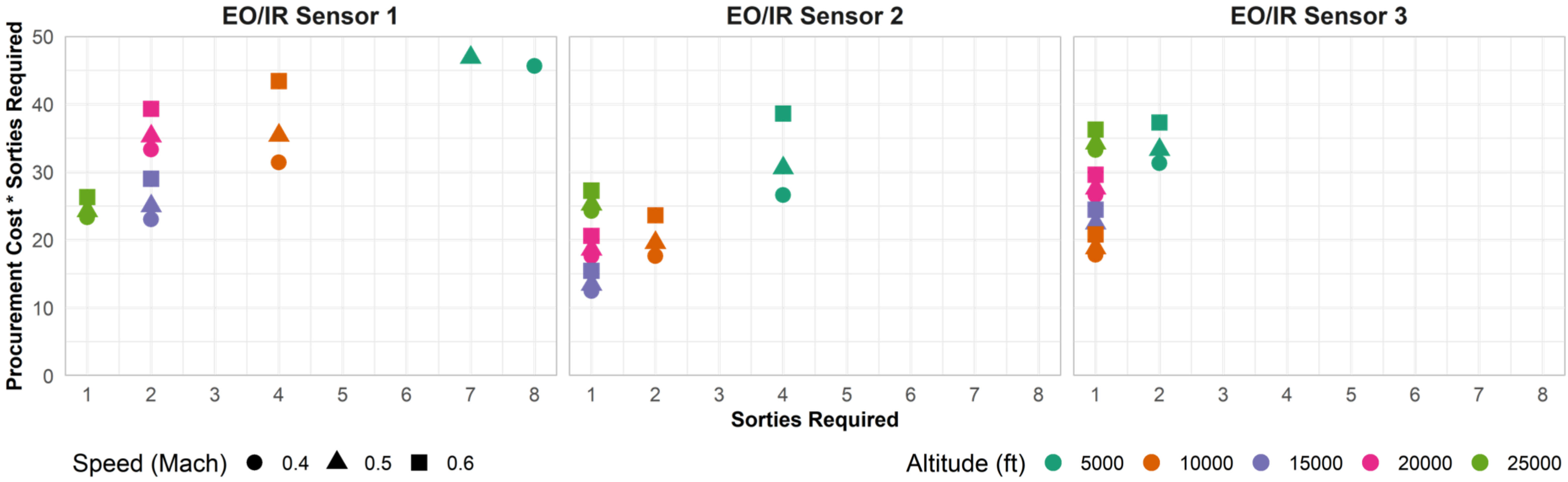
Single vs Multiple Sorties for Mission Accomplishment

- Assuming flying multiple sorties for mission accomplishment is within customer requirements:
  - No design point suggests buying more of a cheaper, less capable platform reduces overall cost
  - Increasing fleet-buy would have operations and sustainment implications



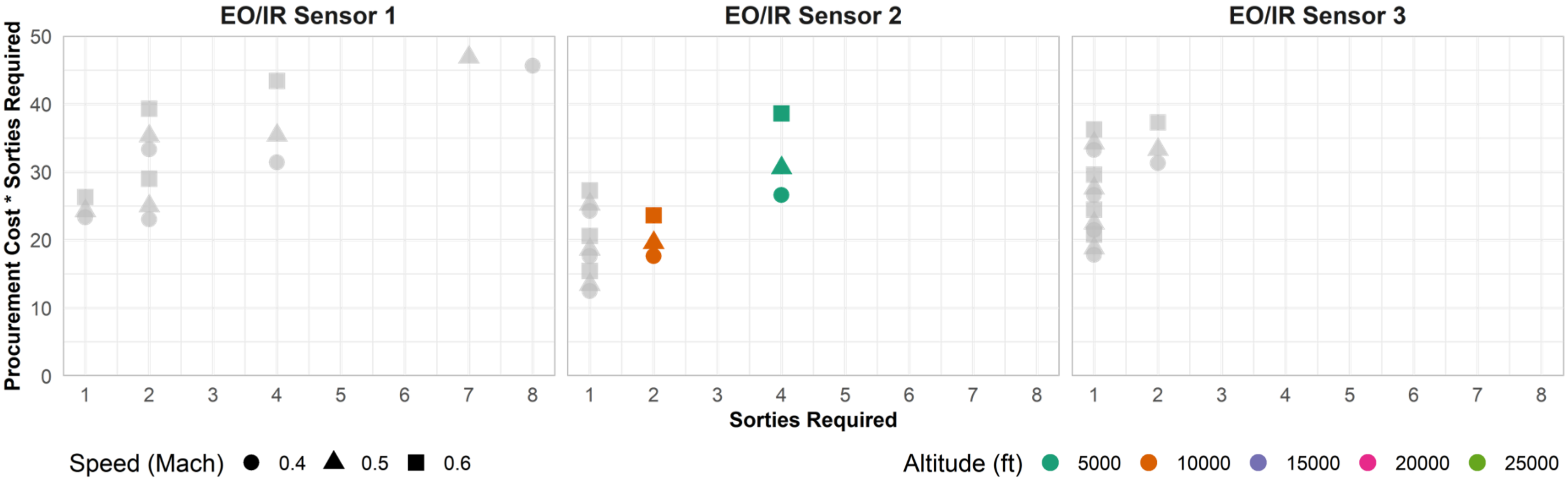
Single vs Multiple Sorties for Mission Accomplishment

- If delivering mass is important, operational losses are likely, or there are mission sets with multiple small AOIs, this trade would require further consideration
- EO/IR Sensor 2 offers the best tradeoffs for procuring more of a less capable platform



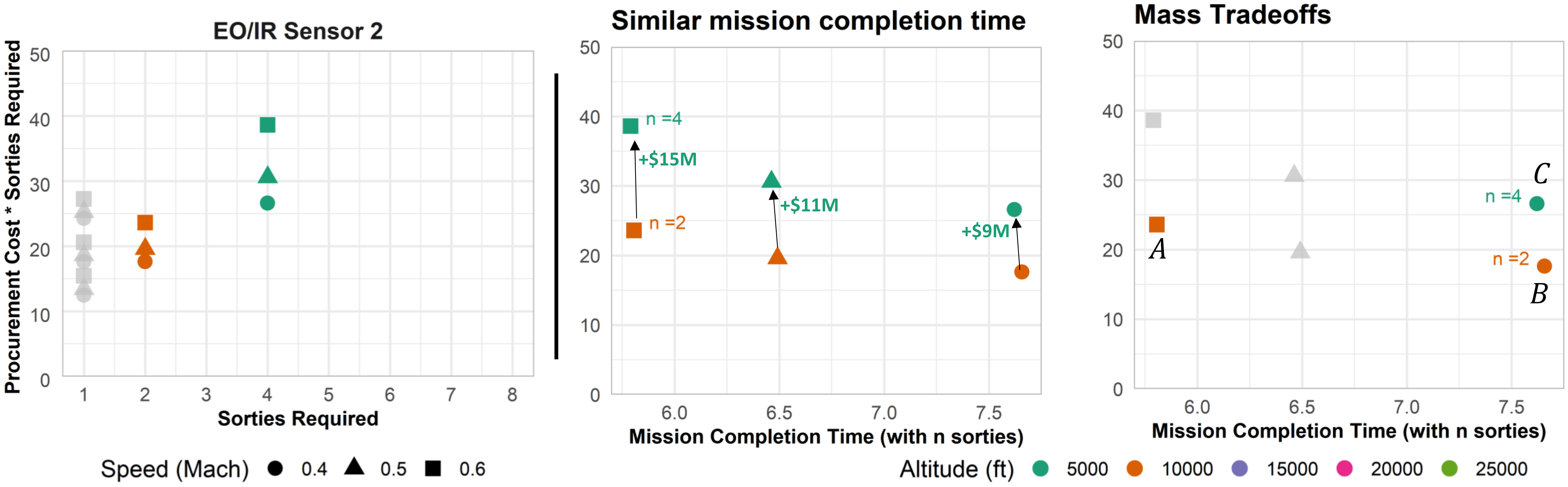
Single vs Multiple Sorties for Mission Accomplishment

- The 5000’ platform with sensor package 2 would quadruple your fleet size compared to the more exquisite options
- Alternatively, the 10,000’ platform doubles your fleet size at ~ 67% the cost



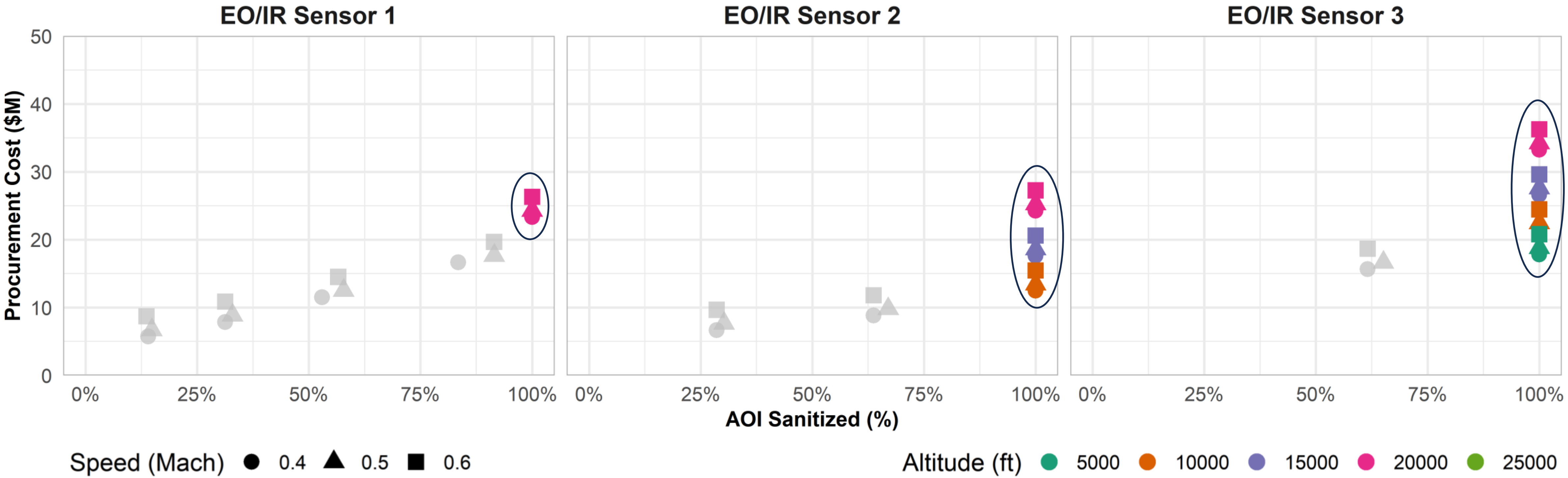
Single vs Multiple Sorties for Mission Accomplishment

- At each Mach (0.4-0.6), 2 sorties of the 1000’ MPA accomplish the mission in about the same time as 4 of the 5000’ MPAs.
- 4X vs. 2X mass comes at a cost ($) which decreases as mission completion time is sacrificed.
- For *mission completion time*, choose A. For *budget mass*, choose B. For *bulk savings*, choose C.

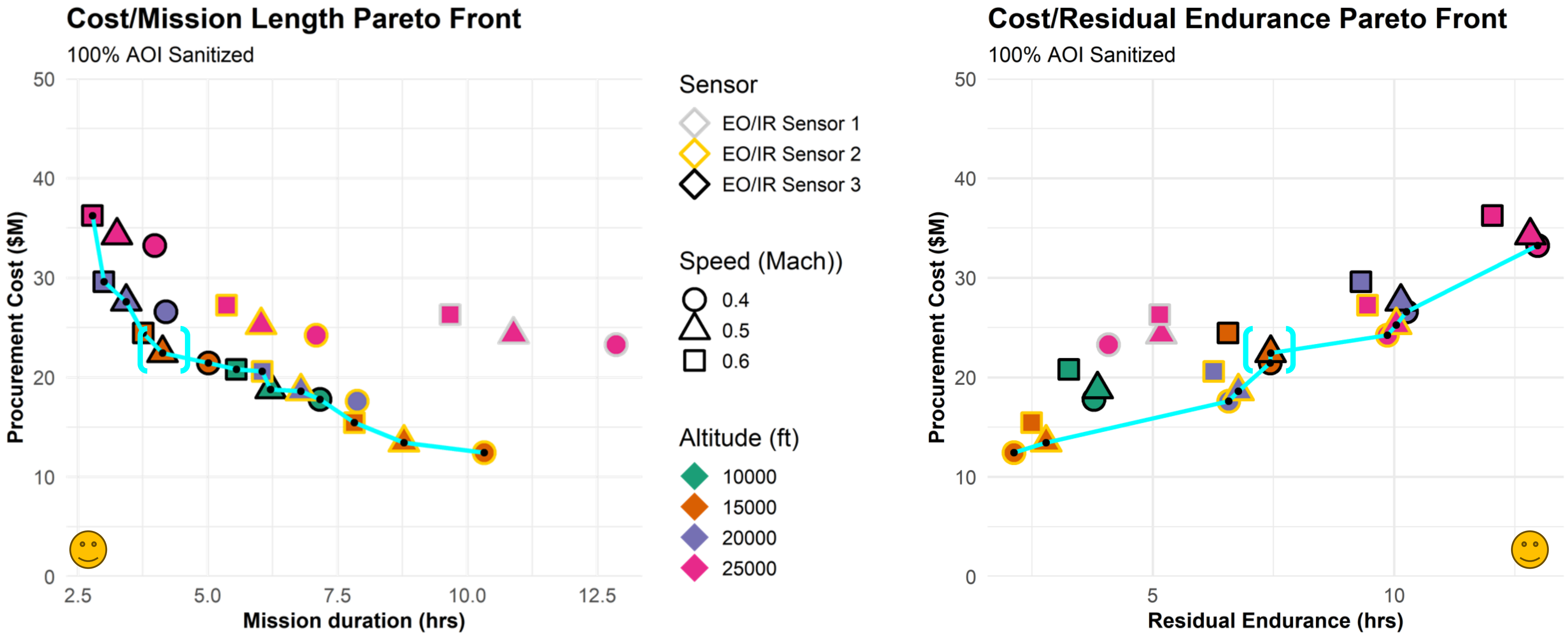


Single-Sortie Mission Completion

- If generating mass is not a priority, consider design points that complete the mission in a single sortie
- Although our analysis suggested an AOI of 100x100km, we should consider residual capacity



Choose along pareto fronts according to mission needs



The 15,000’, 0.5M platform balances cost, with extremely endurance. Sensor 3’s large footprint results in rapid mission accomplishment and flying at 15,000 feet preserves GSD enabling better detection of smaller targets

Model Refinement

Sensor Modeling: Replace with probabilistic, detection-based model. Incorporate slant range, GSD, and sensor dwell time. Map resolution to probability of detection. Run separately for each band (EO / IR) and compute combined probability of detection. Incorporate random targets type, location, and orientation. Ignores additional sensor physics and detection algorithms

Aero performance and fuel: Augment surrogate endurance model with a drag polar to better account for drag during different stages of flight.

- Compute drag, convert to fuel-flow
- Account for drag/fuel-flow based on phase of flight (climb, cruise, turn, descent)
- Vary flight profile for optimal performance (vary airspeed for best endurance, turn radius)

Operational Environment: Analysis ignores the effects of weather (clouds, humidity, precipitation) and time of day (EO sensor severely degraded in low light)

- Add environment model based on suspected operational areas, modulate SNR/P_d accordingly for each sensor band ent of induced drag

$$C_{D_i} \propto n^2$$

$\downarrow$

al drag changes

$$\boxed{D = D_p + D_i}$$

g, mostly independent of
ad or bank factor)

$\downarrow$

tive change in drag

$$\frac{D}{\quad_{evel}} = \frac{D_p + Dn^2}{D_p + D_i}$$

$\downarrow$

of total drag due to induces

el Burn Multiplier
$1 + k\left(n^2 - 1\right)$

$$n = \frac{L}{W}$$

nce in a banked turn:

$$L = \frac{W}{\cos\phi}$$

or L into $n = L/W$:

$$n = \frac{\frac{W}{\cos\phi}}{W}$$

$$n = \frac{1}{\cos\phi}$$

2. Induced drag formula

Induced drag comes from lift. The coefficient of induced drag is usually modeled

$$C_{D_i} = \frac{C_L^2}{\pi e AR}$$

where:

- $C_L = \frac{L}{qS}$ (lift coefficient),
- e = Oswald efficiency factor,
- AR = aspect ratio,
- $q = \frac{1}{2}\rho V^2$ = dynamic pressure,
- S = wing reference area.

So $C_{D_i} \propto C_L^2$.

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3. Relating C_L to load factor

Since $L = nW$:

$$C_L = \frac{L}{qS} = \frac{nW}{qS}$$

At constant speed and altitude, q, W, and S are constant, so

$$C_L \propto n$$

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4. Put it together

Because $C_{D_i} \propto C_L^2$, and $C_L \propto n$:

$$C_{D_i} \propto n^2$$

And induced drag force $D_i = qSC_{D_i}$ is also $\propto n^2$.