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UAV SENSOR AND SURVIVABILITY ISSUES

Gregory H. Canavan

This note discusses the most significant tradeoffs between the operating altitude and the complexity and cost of UAVs and sensors. Low altitudes allow less complex, smaller sensors and platforms, but are vulnerable to ground fire. High altitudes require more numerous and capable sensors, but provide wider swaths for more rapid coverage and reduced vulnerability to ground fire. It is shown that for reasonable mission requirements and air defenses that higher is not necessarily better and that optimal flight altitudes exist that can be determined analytically.

Performance and cost. The weight W and cost of infrared and visible sensors for UAVs scale on range R approximately as

$$W \approx CR^n, \quad (1)$$

where $C \approx 2 \text{ kg/km}^n$.¹ The value of n is not known precisely, but is bounded roughly by the values $n \approx 2-3$ implied by a simplified version of the NVL sensor model² and the value $n \approx 4/3$ derived by NRC.³ The weight and cost of the UAV are generally proportional to weight of sensor, which is usually about 10% of the total weight and 25% of the total cost of the UAV.⁴

The UAV's search rate, and hence the number of targets it finds per unit time, is proportional to its swath width times its speed V . Since the swath width is generally comparable to the sensor range, the search rate is $\approx RV$. A simple figure of merit for a UAV used in a search mode is the search rate divided by the cost of the UAV. As this cost is proportional to the weight of the sensor, the search rate/cost figure becomes

$$F \propto RV/R^n \propto 1/R^{n-1}. \quad (2)$$

For the NRC scaling, the search rate/cost scales as $1/R^{1/3}$, which means it is possible to increase the UAV's altitude to increase swath or survivability with little penalty in performance. For the NVL scaling, search rate/cost ranges from $1/R$ to $1/R^2$, which means an increase in altitude from 2 to 4 km would incur a factor of 2 to 4 penalty in cost effectiveness. Thus, in the absence of survivability considerations, UAVs should operate at the lowest altitude permitted by terrain. However, there are additional survivability considerations at both low and high altitudes, which are discussed in the next section.

Survivability. At ranges less than 2 to 4 km, 35mm, 40mm, 2S6s, and ZSU-23s become increasingly lethal;⁵ the locations of the air defense units of mobile forces are not known; and UAVs cannot maneuver for survivability like manned aircraft. All suggest operation at altitudes above 2 to 4 km, where the UAV probability of survival can be modeled as

$$P_{lo} \approx 1 - e^{-az}, \quad (3)$$

where $a \approx 1/4\text{km}$ for the defensive systems indicated above. At high altitudes, UAVs are intermittently unmasked to EO, IR, and radar systems. If a non-low-observable UAV overflies a radar, its probability of survival is roughly

$$P_{hi} \approx e^{-L/VT}, \quad (4)$$

where $V \approx 30\text{-}50\text{ m/s}$ is the UAV's speed, $T \approx 20\text{-}30\text{ s}$ is the radar system delay time, and L is the radar's lethal radius, which is $\approx (\text{altitude})(\text{mask angle}) \approx z \tan \theta$.⁶ The probability that a UAV flying at altitude z will surviving defenses with both high and low components, each of which can detect, acquire, and track the UAV is

$$P = P_{lo}P_{hi} \approx (1 - e^{-az})e^{-z \tan \theta / VT}, \quad (5)$$

which is shown in Fig. 1. For the above parameters and $a = 1/(4\text{ km})$, $P_{lo} \approx 0.2$ at $z = 1\text{ km}$, and ≈ 0.4 at 2 km . Conversely, $P_{hi} \approx 0.4$ at 1 km , but ≈ 0.15 at 2 km . The product of these increasing and decreasing functions has a broad maximum at $\approx 1\text{ km}$ altitude, where $P \approx 0.09$, which means that at even the optimum altitude, a UAV would be unlikely to survive one encounter with alert, capable defenses. The altitude that maximizes P can be determined by differentiating Eq. (5)

$$z_m = \ln(1 + aVT/\tan \theta)/a, \quad (6)$$

which is shown in Fig. 2 for $V = 30\text{ m/s}$, $T = 20\text{ s}$, and mask angles from $\theta = 20$ to 60 degrees.

The low altitude defenses scale principally on their range, $1/a$. The high altitude defense's parameters are combined into $VT/\tan \theta$; thus, it is only necessary to vary one of these parameters. For $a = 1/(4\text{ km})$, the optimum z is $\approx 1.5\text{ km}$ for $\theta = 20$ degrees; it falls exponentially to $\approx 0.3\text{ km}$ at 60 degrees. The former corresponds roughly to defenses that are suppressed or in motion; the latter to properly positioned defenses. The corresponding survival probabilities fall from ≈ 0.13 at 20 degrees to 0.03 at 60 degrees.

Defense degradation. In practice, not all defenses are alert, and not all can detect, acquire, and track UAVs that have modest acoustic, visible, infrared, and radar signatures. Moreover, the defenses may be significantly suppressed prior to overflight by the UAVs. These degradations are modeled below by introducing the probabilities Q_{lo} and Q_{hi} that low and high altitude defenses are available, activated, and capable of detection, acquisition, and track. Given successful performance of those functions, the kill probabilities are as given in Eqs. (3) and (4). The probability that a UAV will be destroyed in an engagement with a low altitude defense then becomes $Q_{lo}e^{-az}$, so the probability that it will survive is

$$P_{lo}' \approx 1 - Q_{lo}e^{-az}, \quad (7)$$

which reduces to Eq. (3) for $Q_{lo} = 1$, and approaches unity for Q_{lo} small. The probability that it will survive an engagement with a high altitude interceptor is

$$P_{hi}' \approx 1 - Q_{hi}(1 - e^{-z \tan \theta / VT}), \quad (8)$$

which reduces to Eq. (4) for $Q_{hi} = 1$, and approaches unity for Q_{hi} small. The probability that it will survive both engagements is

$$P' \approx P_{lo}' P_{hi}' \approx (1 - Q_{lo} e^{-az}) (1 - Q_{hi} (1 - e^{-z \tan \theta / VT})), \quad (9)$$

which is shown in Fig. 3 for $\theta = 45$ degrees and $Q_{lo} = Q_{hi} = 0.1$, which are nominal values that are varied below. For them, $P_{lo} = 1 - Q_{lo} = 1$ at $z = 0$, ≈ 0.92 at $z = 1$ km, and ≈ 1 for $z = 8$ km. $P_{hi} = 1$ at $z = 0$, ≈ 0.92 at $z = 1$ km, and ≈ 0.9 for $z > 2$ km. Their product, $P_{lo}' P_{hi}'$, is 1 at $z = 0$, $\approx 0.92^2 \approx 0.85$ at $z = 1$ km, and ≈ 1 for $z = 8$ km. For these parameters, single-engagement survivability would be maximized by operation at very low or very high altitudes. There is a minimum in overall survivability in the range of 1 to 2 km.

Distributed defenses. In flying a distance D over an area A containing M low-altitude and N high-altitude defenses, a UAV would encounter an average of MD/Aa low and $N DL/A$ high altitude defenses, so its probability of survival is

$$P \approx (1 - Q_{lo} e^{-az})^{MD/Aa} (1 - Q_{hi} (1 - \exp(-z \tan \theta / VT)))^{N DL/A}, \quad (10)$$

which is illustrated in Fig. 4 for $Q_{lo} = Q_{hi} = 0.1$, a search area $A = 10,000$ km², and a UAV flight distance of $D = 3,000$ km, which corresponds to roughly 10 flights over hostile territory. Compounding P_{lo} and P_{hi} by MD/Aa and $N DL/A$ times, respectively, produces a curve with a broad maximum at about 5 km, where it has a value of ≈ 0.44 , so a UAV's mean lifetime at that altitude is about 3,000 km against these defenses. Equation (10) can be solved directly for the mean lifetime

$$D_{1/2} = A \ln(1/2) / \ln[(1 - Q_{lo} e^{-az})^{M/a} (1 - Q_{hi} (1 - \exp(-z \tan \theta / VT)))^{NL}], \quad (11)$$

which is shown in Fig. 5. For the parameters above, the lifetime only varies from about 16 to 25 km as altitude varies over the range accessible to the UAV.

Performance metric. These results can be used to evaluate the performance metric of Eqs. (1) and (2). If it is assumed that the swath is about twice the altitude, the weight is $W \approx C(2z)^n$. The metric can now be extended to

$$F = (D_{1/2} / V)(RV/KW), \quad (12)$$

where the first term is the total expected flight time of the UAV, the numerator of the second term is the area covered per unit time, and the denominator is the cost of the UAV to give a measure of the number of targets per unit investment. V is the velocity, which cancels out. K is a constant that relates the cost of the UAV to the weight of the sensor. Typically, the sensor is about 10% of the weight of the UAV and the cost of the UAV is about \$1K/kg, so $K \approx \$10K/kg$. F for that value and the range from Eq. (11) is shown in Fig. 6. For the NRC $n \approx 4/3$ scaling, F varies little with altitude. For the $n \approx 2$ of lightweight optical systems, the metric drops from ≈ 100 km²/\$K at 1 km to ≈ 15 km²/\$K at 8 km, which would represent a significant penalty for operating at high altitudes. For the $n \approx 3$ of standard optical systems, the metric drops from ≈ 70 km²/\$K at 1 km to ≈ 1 km²/\$K at 8 km, which would probably represent an unacceptable penalty for operation above about 1-2 km.

Sensitivity. The calculations above assume nominal, modest values of defenses. This section performs some studies of their sensitivity to excursions in those defenses. From Eq. (11), it is clear that D scales directly as A , i.e., with the dilution of defenses. It also scales on M/a and NL , the product of defense number time range, and the Q s of the low and high altitude defenses. Thus, it is adequate to vary M , N , and the Q s. Moreover, the dependence of D on M and N and on Q_{lo} and Q_{hi} are similar, so it is useful to assume that $Q_{lo} = Q_{hi} = Q$ for preliminary calculations. Figure 7 shows $D_{1/2}$ as a function of Q for the nominal $M = 10$ and $N = 3$. The mean lifetime is about 2,500 km for the $Q = 0.1$ used above. For $Q = 0.05$, which would correspond to unprepared or very strongly suppressed defenses, it increases to about 5,000 km. For $Q > 0.3$, which corresponds to prepared, unsuppressed defenses, the mean range falls to about 500 km, and the effectiveness of the UAVs falls below $10 \text{ km}^2/\$K$, at which the cost for a 10^4 km^2 area would be $\approx 10^4 \text{ km}^2 / 10 \text{ km}^2/\$K \approx \$10M$.

Figure 8 shows $D_{1/2}$ as a function of $M = N$ for the $Q_{lo} = Q_{hi} = 0.1$ used above. The mean lifetime is about 1,500 km for the $M = 10$ used above. For $N = 2$, which corresponds to 10% of the levels encountered in recent engagements, the mean range increases to about 5,000 km. For $N = 150$, which is a few times the Brigade densities in recent conflicts, it falls to about 150 km, where the UAVs' effectiveness would fall to a few $\text{km}^2/\$K$, at which the cost for a 10^4 km^2 area would be $\approx \$100M$. $D_{1/2}$ falls as $1/M$ because for $M = N$, $D_{1/2} \propto 1/\ln(P(M/a+ML)) = 1 / (M(1/a+L)\ln P)$ in Eq. (11). Thus, UAV effectiveness falls rapidly with the capability and even more rapidly with the number of defensive units. It is clear that UAVs would have limited effectiveness for defense numbers or capabilities above the nominal values used in constructing Figs. 1-6; thus, the prior suppression of defenses in both numbers and capability would appear to be an essential prerequisite for their effectiveness against competent forces.

Summary and conclusions. This note discusses significant tradeoffs between the operating altitude and the complexity and cost of UAVs and sensors. Lower altitudes allow less complex, smaller sensors and platforms. Higher altitudes require more numerous and capable sensors, but provide wider swaths for more rapid coverage and reduced vulnerability to ground fire. However, guns are lethal at low altitudes, while IR and radar systems are effective at high altitudes. It is possible to determine the optimal altitudes, which are typically in the range of 2-4 km, depending on defense alertness and number. Moderate distributed defenses limit ranges to a few thousand kilometers, and areas covered to a few thousand square kilometers. This gives areas covered per cost of $10\text{-}100 \text{ km}^2/\K . The nominal results are for modest defenses. UAV effectiveness falls rapidly with the capability and more rapidly with the number of defenses. Thus, prior suppression of defenses appears to be an essential prerequisite for the effectiveness of modest UAVs against competent forces.

References

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1 survivability single encounter

Fig. 1. Survival probabilities against low, high, & combined defenses (20 s delay).

z_{opt} & p_{surv} vs θ ; $a=1/41$

radar mask angle (degrees from vertical)

2. Optimal altitude and survival probability per encounter.

3 surv indiv engagements

Fig. 3. Single-engagement survival probabilities.

Fig. 4 Probability of surviving degraded low & high altitude defenses.

5 mean dist vs altitude

5 Mean lifetime vs altitude for degraded defenses.

area/cost vs z

6 Area per cost for various cost-range scalings.

D vs Q

7 Mean lifetime vs Q for $M = 10$, $N = 3$, & $A = 10,000 \text{ km}^2$.

D vs M = N

8 Mean lifetime vs number of defensive units for $Q = 0.1$.