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Metrics for Unmanned Air Vehicles

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Prepared for: LCdr G. Zuliani, Directorate of Naval Requirements

Scientific Letter

Metrics for Unmanned Air Vehicles

Background

The Director of Naval Requirements (DNR) has tasked the Maritime Operational Research Team (MORT) of Defence Research and Development Canada – Centre for Operational Research and Analysis (DRDC CORA) to examine the effectiveness of a small fleet of UAVs.

This Scientific Letter describes a number of metrics for such a fleet. The data that we use are generic. However, they reflect existing UAVs that are available in the open market.

Scenario

We consider the following scenario.

a. Altitude: 4000 feet;
b. Maximum detection range: 50 nm;
c. Speed: 55 knots;
d. Endurance: 6 hours, 7 hours, and 8 hours, and
e. Mission: 12 hours and 24 hours.

In order to maintain a continuous mission of 12 hours or 24 hours, we may need more than one UAV due to the endurance of an UAV. Generally, one or more UAV would transit to the area of interest before the UAV on site runs out of fuel so that the latter can fly back to base and the former replace the latter in its duty. In addition, there is a maintenance cycle for the fleet of UAVs. Hence, there is a period where an UAV does not operate and we need to account for this in determining the number of required UAVs to meet an ambition level (12 hours of continuous mission for example).

We consider three types of fleets:

a. An endurance of 10 hours, a Time On Station of 8 hours, a Down Time of 2 hours per 8 hours sortie;
b. An endurance of 8 hours, a Time On Station of 6 hours, a Down Time of 2 hours per 6 hours sortie and
c. An endurance of 6 hours, a Time On Station of 3.5 hours, a Down Time of 2 hours per 6 hours sortie.

From the above, we determine these metrics which we name Deterministic Metrics

a. The Response Time;
b. The Time On Station;
c. The Coverage;

d. The Number Of Flights required; and
e. The Number Of UAVs required.

The Response Time is the time needed for an UAV to reach its area of interest. The Time On Station is the time available to an UAV to conduct its operation once it reaches the area of interest. The Coverage is the largest size of the area that an UAV can cover during its operation. The Number Of Flights is the demand for the number of flights to maintain constant presence for the duration of the mission. The Number Of UAVs is the number of UAVs in the fleet to meet the demand when scheduling such as maintenance cycle is considered. Some of these metrics come from Ref [1].

In addition to the above metrics, we also determine the probabilities of detecting a liferaft, a dhow and a frigate as a function of range and as a function of cross section which we name Probabilistic Metrics.

Deterministic Metrics

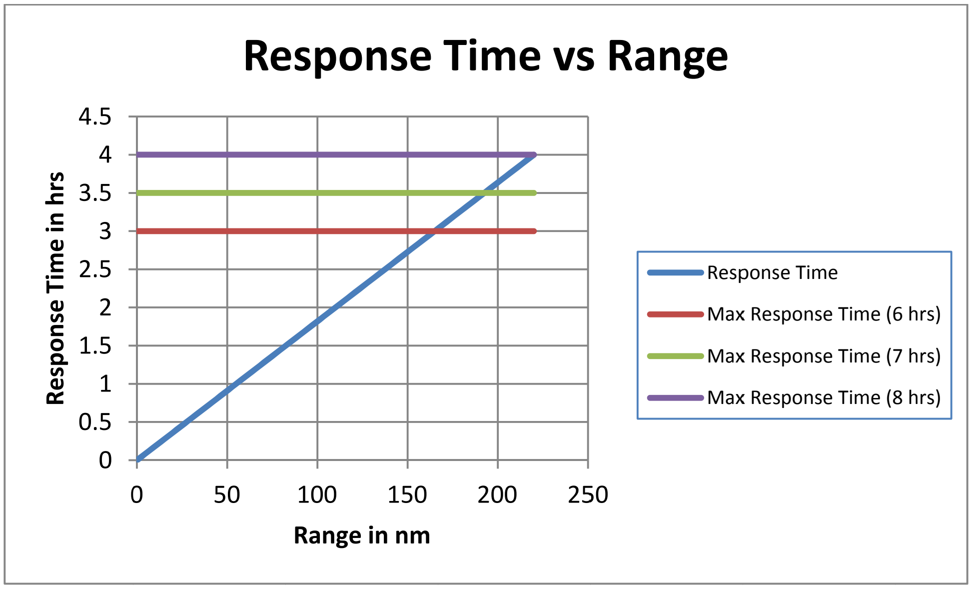

***Figure 1:** Response Time in hours versus Range in nautical miles.*

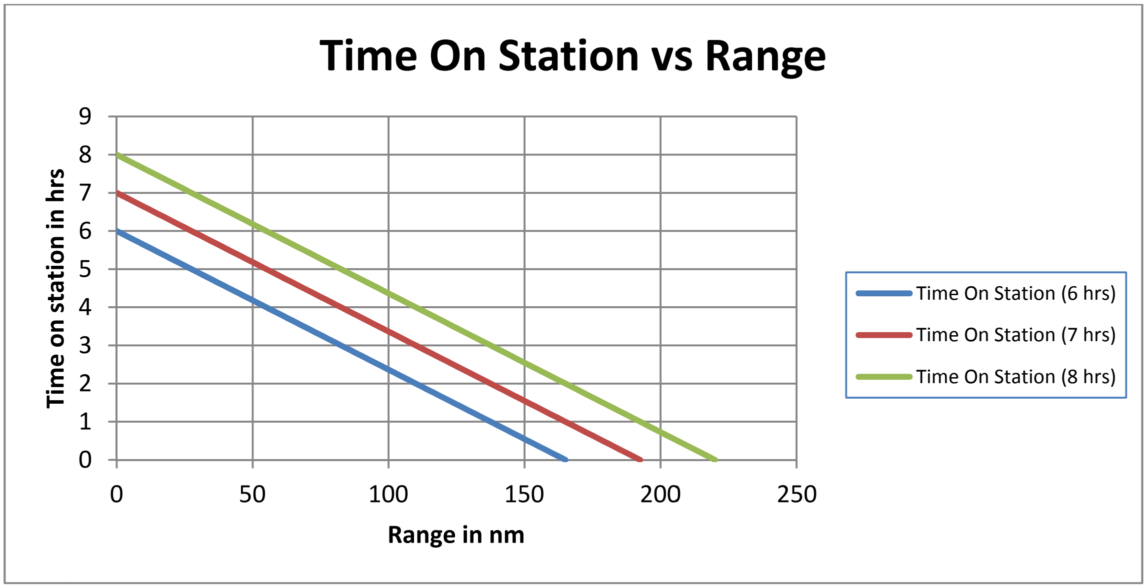

Figure 2: *Time On Station in hours versus Range in nautical miles.*

Figure 1 shows the Response Time as a function of Range; the further the area of interest the greater the Response Time. The Response Time is calculated by the following equation:

$$Response\,Time = Range/(2 \cdot Speed)$$

where the factor $1/2$ allows the UAV to get to the area of interest and come back to the base; the further the area of interest the longer the response time.

Figure 2 shows the Time On Station as a function of Range. The Time On Station is calculated by the following Equation:

$$Time\ On\ Station = Endurance - 2 \cdot Response\ Time$$

The Time On Station is the time available to an UAV to conduct its operation excluding Transit Time (twice of the Response Time).

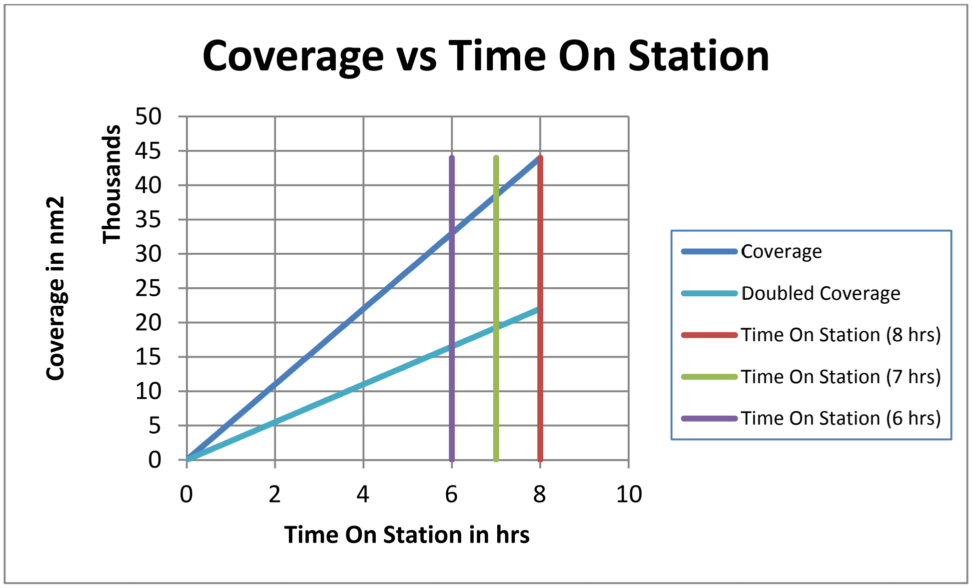

Figure 3: *Coverage in thousands of nautical miles squared vs Time On Station in hours.*

Figure 3 shows the Coverage as a function of Time On Station; the longer the Time On Station the larger the Coverage. Note that we also plot a Doubled Coverage curve that represents half of the original Coverage. This allows an UAV to conduct a hatching search pattern that significantly improves the probability of detection in a search and detection kind of mission, Refs [2–3]. The search patterns are shown in Figure 4.

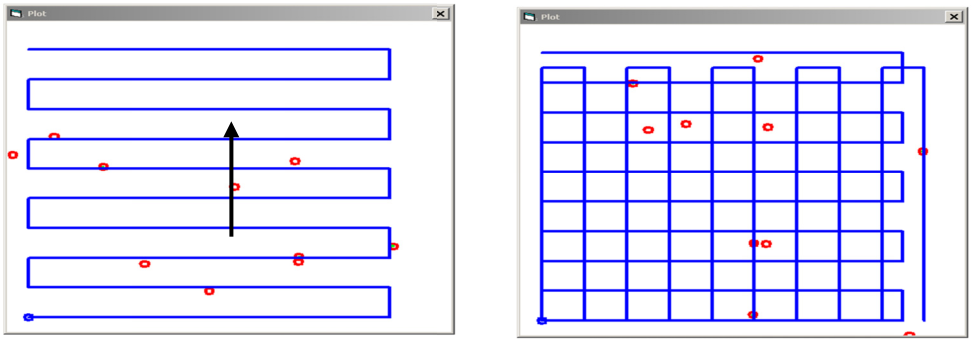

Figure 4: *A simple search pattern and a hatching search pattern.*

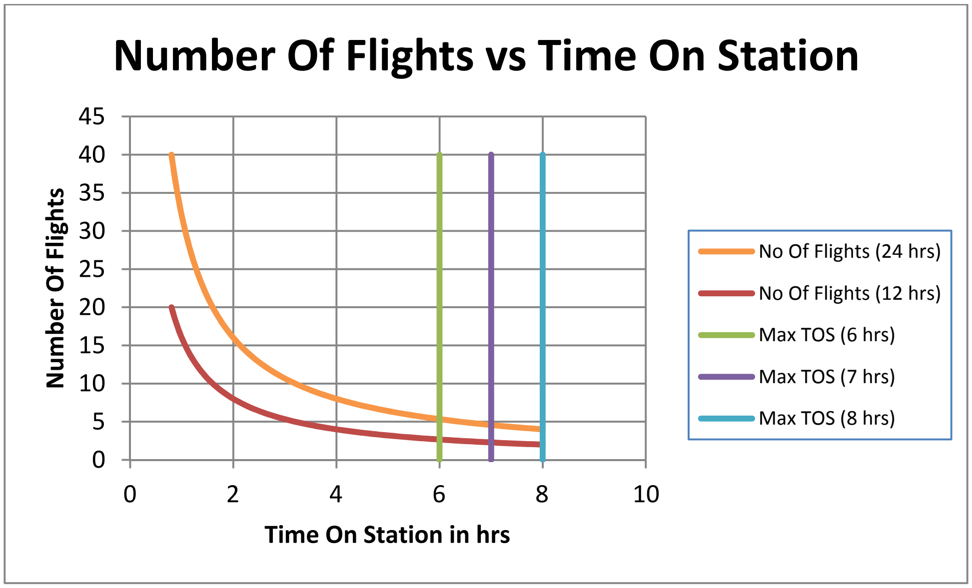

Figure 5: *Number Of Flights vs Time On Station in hours.*

Figure 5 shows the Number Of Flights required for a continuous mission of 12 hours and 24 hours as a function of Time On Station; the longer the Time On Station the smaller the Number of Flights required.

Scheduling for a small fleet is well understood and can be modelled using integer programming, Refs [4–5]. We found that:

a. Fleet a requires 2 UAVs and 2 or 3 flights for a continuous mission of 12 hours or 24 hours;
b. Fleet b also requires 2 UAVs and 2 or 4 flights for the same missions; and
c. Fleet c requires 3 UAVs and 4 or 7 flights for the same missions.

Their schedules for 12 hour missions are shown below for illustrations.

Transit	TOS	Transit	Maintenance	Free time	Transit
TOS	Transit	Maintenance	Free time	Transit	TOS

Figure 6: *Fleet a schedule.*

TOS	Transit	Maintenance	Free time	Transit
Transit	Maintenance	Free time	Transit	TOS

Figure 7: *Fleet b schedule.*

Transit	TOS	Transit	Maintenance	Free time	Transit
Maintenance	Free time	Transit	TOS	Transit	Maintenance
TOS	Transit	Maintenance	Free time	Transit	TOS

Figure 8: *Fleet c schedule.*

Note that Figures 6, 7 and 8 are correlated with Figure 5. That is, the Number Of Flights depends on the Time On Station (TOS) and the Number Of UAVs depends on the Number Of Flights and the maintenance cycle. In Figure 5, we vary the TOS while in Figure 6, 7 and 8 we fix the TOS at 6, 7 and 8 hours which are at the high end of the spectrum shown in Figure 5. Therefore, the Number Of Flights and the Number Of UAVs depicted in Figures 6, 7 and 8 are at the low end of their spectrum.

Probability Of Detection

One mission that is often undertaken by an UAV is to search for a target such as a liferaft, a dhow or a frigate. To assess an UAV effectiveness in a search & detection mission, we evaluate the probabilities of detection as a function of cross section and as a function of range. We make use of the following equation to determine the probability of detection (Ref [6]), P:

$$P = 1 - \int_0^{\sqrt{-2 \cdot \ln(p_{fa})}} dx \cdot x \cdot I_0\left(x \cdot \sqrt{SNR}\right) \cdot e^{-\frac{1}{2}\left(x^2 + SNR\right)}$$

where p_{fa} is the probability of a false alarm and I_0 is the Bessel function of the first kind with order zero. SNR is the Signal to Noise Ratio defined by:

$$\sqrt{SNR} = 10 \cdot \log_{10}\left(\frac{SNR_{dB}}{20}\right)$$

with SNR_{dB} the standard Signal to Noise Ratio measured in decibels.

We assume the following input:

- Liferaft's dimension: $8\ feet\ by\ 4\ feet$ which yields a cross section equal to $2.975\ m^2$;
- Dhow's dimension: $25\ feet\ by\ 20\ feet$ which yields a cross section equal to $46.45\ m^2$;
- Frigate's dimension: $60\ feet\ by\ 60\ feet$ which yields a cross section equal to $334.5\ m^2$;
- SNR for a frigate: $SNR_{dB} = 30\ dB, 40\ dB\ and\ 50\ dB$ at a range of $R_{\det} = 30\ nm$ and
- $p_{fa} = 10^{-7}$.

To determine the probability of detection as a function of cross section, we use $P(u \cdot SNR)$ where $u \in [0,1]$. Similarly, the probability of detection as a function of range can be determined by:

$P\left(SNR \cdot \left(\frac{R_{\det}}{R}\right)^4\right)$ since $SNR \propto 1/R^4$, Ref [7].

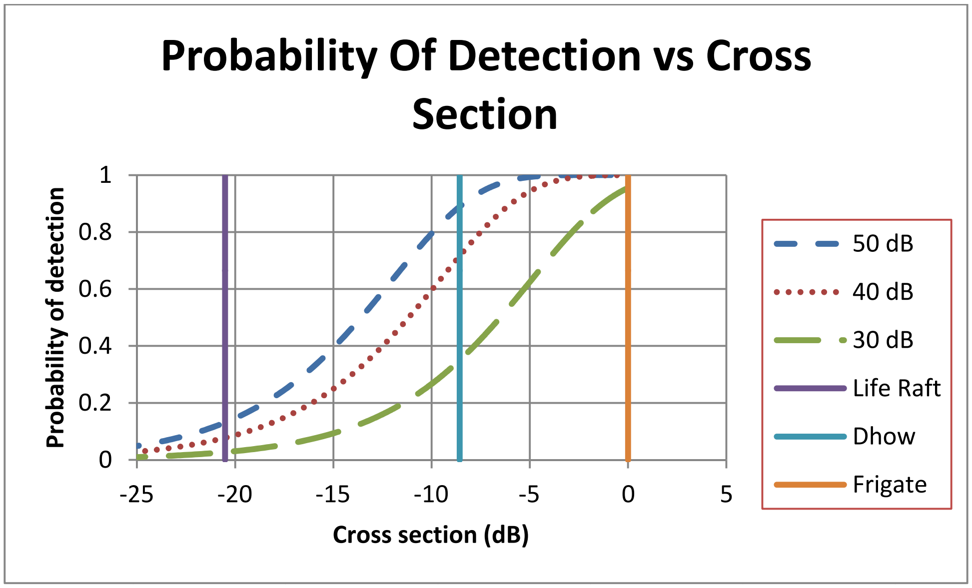

Figure 9: *Probability Of Detection vs Cross Section (dB).*

Figure 9 shows the probability of detection as a function of cross section where we assume three values for the SNR that correspond to: $SNR_{dB} = 30\ dB, 40\ dB\ and\ 50\ dB$ for a frigate at a range of: $R_{\det} = 30\ nm$. We measure the cross section in dB: $\sigma_{dB} = 10 \cdot \log_{10}\left(\frac{\sigma}{\sigma_{frigate}}\right)$. This gives $\sigma_{liferaft\,(dB)} = -20.512\ dB$, $\sigma_{dhow\,(dB)} = -8.573\ dB$ and $\sigma_{frigate\,(dB)} = 0\ dB$. It can be seen that the greater the cross section the higher the probability of detection. Also, the probability of detecting a liferaft is the lowest (less than 15%) followed by the probability of detecting a dhow (between 35% and 89%) and followed by the probability of detecting a frigate (above 95%).

Figure 10 shows the probability of detection as a function of range assuming an $SNR_{dB} = 30\ dB$ for a frigate at a range of $R_{\det} = 30\ nm$. It can be seen that the probability of detecting a frigate at a range of $30\ nm$ is high (above 90%) while the probability of detecting a dhow or a liferaft at the same range is still low (below 15%).

Figure 11 shows the probability of detection as a function of range assuming an $SNR_{dB} = 40\ dB$ for a frigate at a range of $R_{\det} = 30\ nm$. The same trend as the one in Figure 10 is seen. However, the probability of detecting a dhow has increased and is now almost 70% due to the increase in the SNR_{dB} relative to the one in Figure 10.

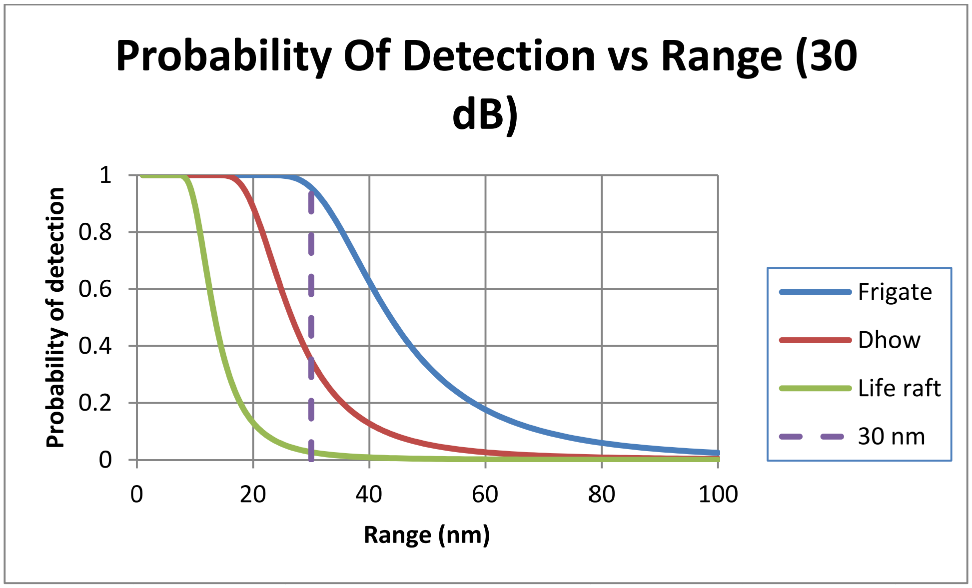

Figure 10: *Probability Of Detection vs Range in nm* ($SNR_{dB} = 30\ dB$).

Figure 12 shows the probability of detection as a function of range assuming an $SNR_{dB} = 50\ dB$ for a frigate at a range of $R_{\det} = 30\ nm$. The same trend as the ones in Figure 10 and in Figure 11 is seen. However, the probability of detecting a dhow has increased and is now almost 90% due to the increase in the SNR_{dB} relative to the ones in Figure 7 and in Figure 8. Note that the probability of detecting a liferaft is still low (less than 20%) at the $R_{\det} = 30\ nm$ range. A liferaft can be detected with an 80% chance or higher only when range is less than or equal to $16\ nm$.

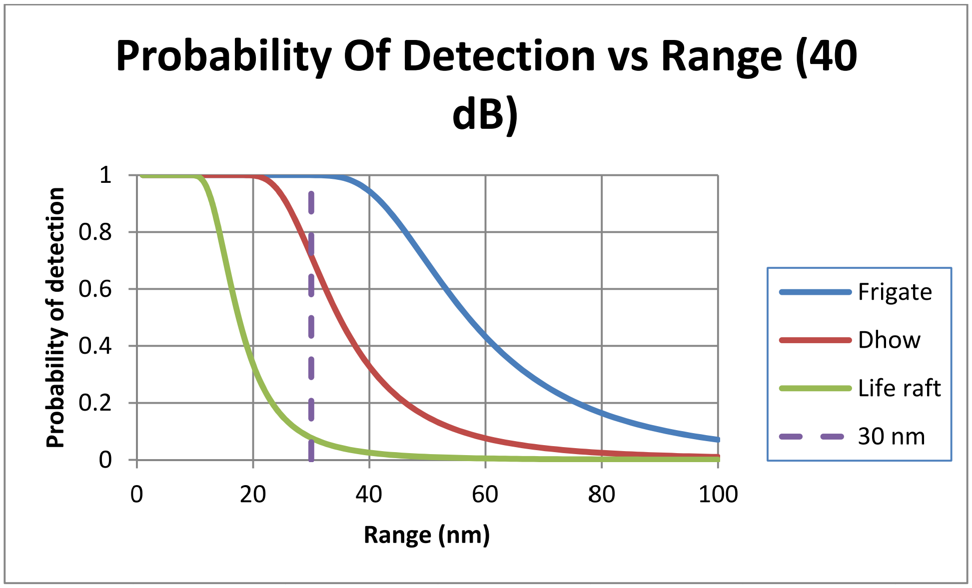

Figure 11: *Probability Of Detection vs Range in nm* ($SNR_{dB} = 40\ dB$).

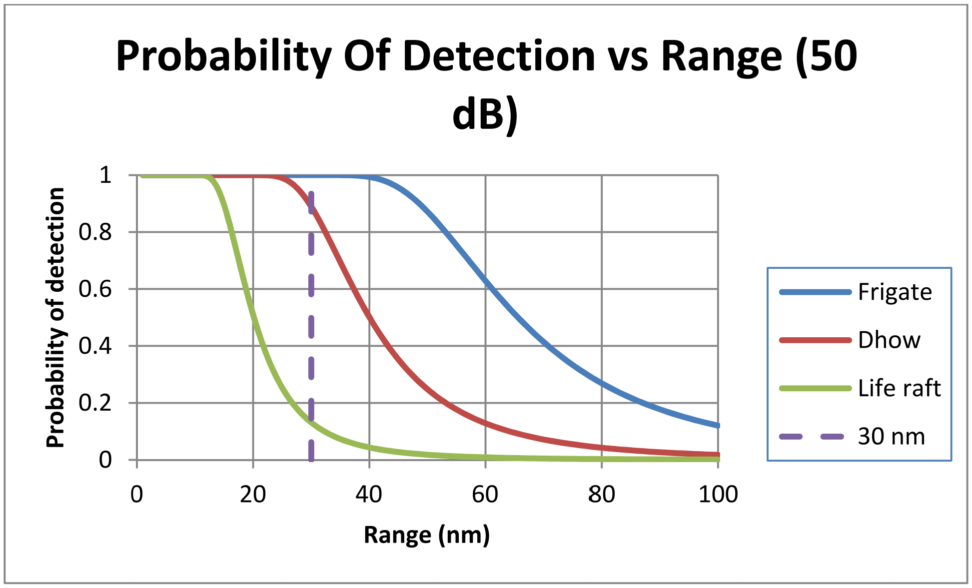

Figure 12: *Probability Of Detection vs Range in nm* ($SNR_{dB} = 50\ dB$).

Conclusion

In this SL, we have examined the effectiveness of UAVs with simple metrics: the Response Time, the Time On Station, the Coverage, the Number Of Flights, the Number Of UAVs, the scheduling of UAVs and the Probability Of Detection. We have made use of a simple scenario and parameters that reflect commercial UAVs. Even though, weather impact on UAV operations has not been discussed in the main text, we provide in the Annex a few illustrative examples.

We hope that these findings will be useful to the clients when time comes to choose a type of UAVs for Canadian Force's missions.

Prepared by: Bao Nguyen (DRDC – Centre for Operational Research and Analysis).

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[7] https://en.wikipedia.org/wiki/Radar, Sep 17.

[8] http://climate.weather.gc.ca, Apr 17.

Annex A Weather Effects

One hundred percent visibility is assumed to be three miles and one hundred percent ceiling is assumed to be one thousand feet. These parameters define the flying conditions for the UAVs that are considered. Weather data came from Ref [8].

Figures A.1–A.4 show monthly averages from 2012 until 2016. Two cities on the west coast (Vancouver and Comox) were chosen for illustration as well as two cities on the east coast (Halifax and St-John's), The overall metric is the compound of the visibility percentage with the ceiling percentage. Often the blue overall metric is hidden below the ceiling percentage. The results were obtained using Excel 2013 and historical data downloaded from Ref [8].

Roughly on average, an UAV can operate fifty percent of the time on the west coast and less than thirty percent on the east coast. The best months on the west coast are approximately the summer months while on the east coast the flying conditions have little variability over the months.

These observations indicate that when it comes to weather, a manned aircraft such as the CP-140 Aurora have an advantage over the UAVs especially the light UAVs which are more susceptible to winds while an CP-140 Aurora can operate in all weather, Ref [1]. UAV accidents also tend to occur more frequently than those of manned aircraft. It is expected, however, that with time, UAV's technologies will mature in the next ten years that will reduce the rates of UAV accidents, Ref [1].

We want to acknowledge the help from Jean-Denis Caron who wrote the code in excel and generated these Figures.

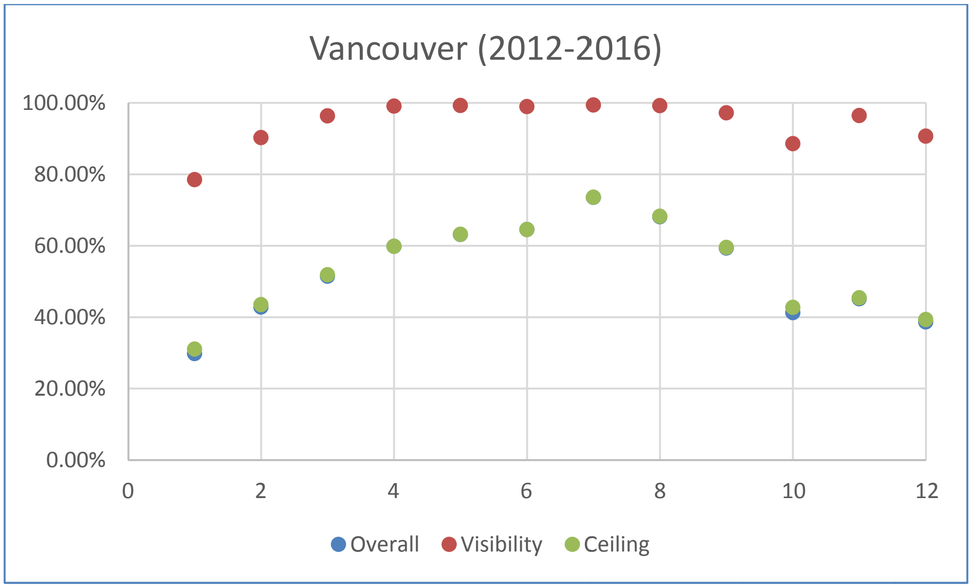

Figure A.1: Weather in Vancouver.

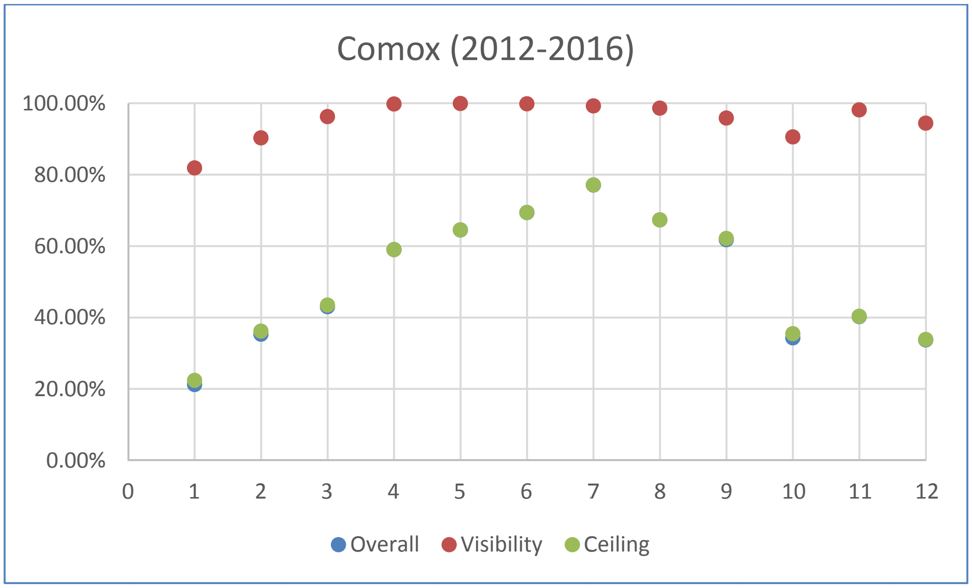

Figure A.2: *Weather in Comox.*

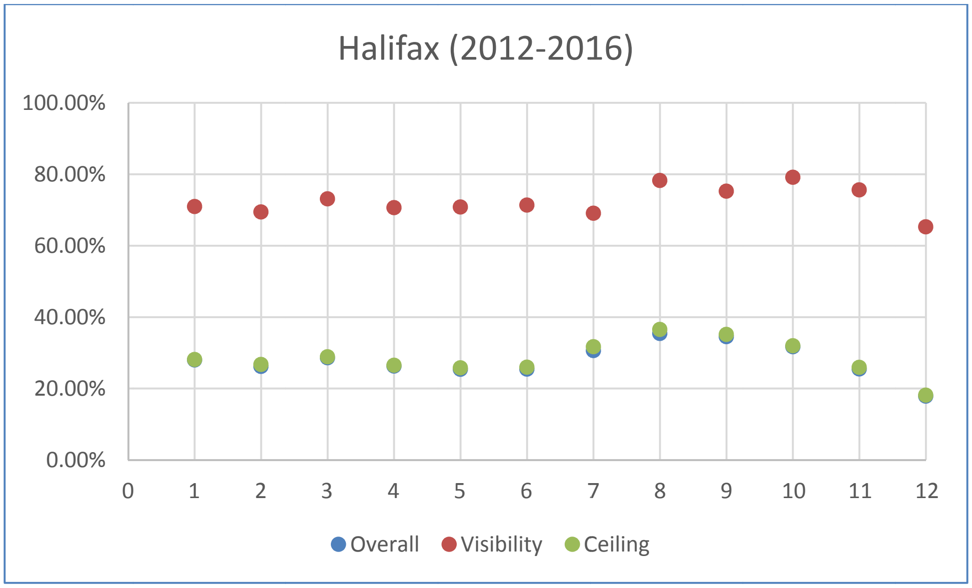

Figure A.3: *Weather in Halifax.*

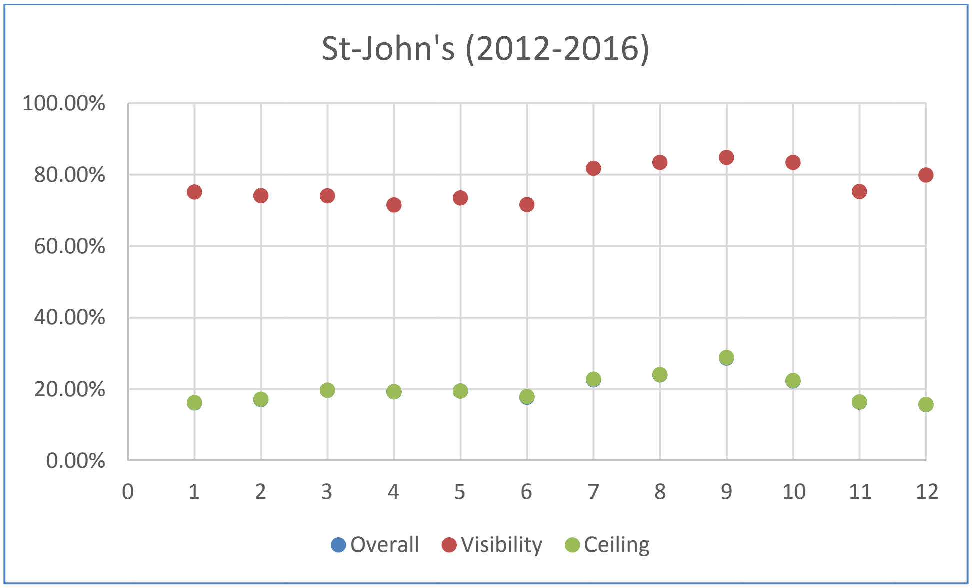

Figure A.4: *Weather in St-John's.*

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