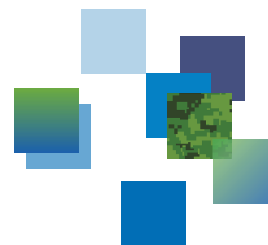




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Determining Fleet Size for a Modernized Canadian Maritime Patrol Aircraft

Sean Bourdon
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Prepared for:

Directorate of Aerospace Requirements

Defence Research and Development Canada

Scientific Report
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Abstract

The *Canada First* Defence Strategy announced that the CP-140 Aurora, Canada's long-range maritime patrol aircraft, will be replaced by a fleet of Canadian Multi-Mission Aircraft (CMA). This report details analyses provided in support of developing requirements on speed, endurance, and fleet size to enable the CMA to fulfill surveillance and patrol missions. The analysis was repeated to determine the number of Auroras that would require modernization if the acquisition of the CMA were to be delayed, as was announced in February 2014.

Significance for defence and security

Given the serviceability/operational availability rates expected for a new aircraft, the *Canada First* Defence Strategy's proposed fleet size for CMA of 10 to 12 appears to be a bare minimum for sustaining surveillance on two coasts simultaneously. It is recommended that if the CP-140 is modernized at least 14 should be maintained to meet the surveillance requirements as described in this study, a course of action that was followed by the Government of Canada with the announcement in February 2014 that the lifespan of 14 CP-140 would be extended. Finally, it is strongly recommended to define the speed and endurance requirements for the CMA as a trade-off curve, as setting hard minima on both would overly restrict the potential options.

Résumé

La Stratégie de défense *Le Canada d'abord* prévoyait le remplacement du CP-140 Aurora, l'aéronef de patrouille maritime à long rayon d'action des Forces canadiennes, par une flotte d'avions multi mission canadiens (CMA). Ce rapport fournit une description détaillée des analyses appuyant l'établissement de critères comme la vitesse, l'endurance et la taille de la flotte pour permettre au CMA de remplir ses missions de surveillance et de patrouille. On a procédé à une nouvelle analyse afin de déterminer le nombre d'avions Aurora qui nécessiteraient une mise à jour si on devait retarder l'acquisition des CMA, comme on l'annonçait en février 2014.

Importance pour la défense et la sécurité

Compte tenu du taux de bon fonctionnement/disponibilité opérationnelle auquel on est en droit de s'attendre de la part d'un nouvel aéronef, une flotte de 10 à 12 constituerait le strict minimum pour assurer la surveillance simultanée des deux côtes selon la Stratégie de défense *Le Canada d'abord*. Si on procède à la mise à jour du CP-140, cette étude conclue qu'il en faudra au moins 14 pour satisfaire aux critères de surveillance énoncés. C'est l'option que le gouvernement du Canada privilégie dans sa décision annoncée en février 2014 de prolonger la durée de vie de 14 CP-140. Enfin, l'utilisation d'une courbe d'arbitrage afin de déterminer les critères de vitesse et d'endurance du CMA est fortement recommandée, car en fixant un minimum absolu à ces deux critères les options envisageables seraient restreintes.

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Acknowledgements

Special thanks are due to Maj Bob Trerice and Maj Pete Burrell for their initial support and guidance in defining the work, and in shepherding the results up their chain of command. The authors would like to acknowledge their current clients (the Canadian Forces Maritime Warfare Centre, Director General Naval Force Development and the Canadian Forces Warfare Centre) for allowing them the time to complete the formal write-up of this work. Alex Bourque and Andrew Wind provided valuable feedback which improved the final version of the report.

1 Introduction

The *Canada First* Defence Strategy (CFDS) provides a roadmap for the modernization of the Canadian Armed Forces (CAF) [1]. An important part of this effort consists of a recapitalization of several key pieces of equipment that deliver capability directly to the Canadian warfighter. Among the platforms slated for replacement is Canada's long-range Maritime Patrol Aircraft (MPA), the CP-140 Aurora. The Canadian Multi-Mission Aircraft (CMA) is the name being used to designate this follow-on capability, with a projected fleet size of 10 to 12 aircraft [1].

The Directorate of Aerospace Requirements (DAR) is responsible for writing a Statement of Operational Requirement (SOR) which outlines the specifications that the CMA must fulfill in order to provide sufficient capability to enable the aircraft to accomplish its intended mission set. DAR requested the assistance of the Directorate of Air Staff Operational Research (DASOR) in setting some of these requirements on a more rigorous analytical footing. Specifically, DAR is interested in establishing performance benchmarks to enable surveillance and patrol missions for, e.g., Anti-Submarine Warfare (ASW) and Anti-Surface Warfare (ASuW). During the course of the study, interest also arose in modernizing the CP-140 Aurora as a stop-gap for acquiring a new aircraft; this course of action was in fact taken by the Government of Canada in February 2014 as this report was in the final stages of editing [2]. This document provides the analytical background for the advice previously delivered and briefed in support of these two decisions [3, 4].

1.1 Problem statement

The ability to provide continuous tracking of a vessel in Canada's maritime AOR (see Figure 1) depends on a complex interplay of aircraft speed, aircraft endurance, and the number of aircraft available to the task. The goal of this study is to establish conditions under which these factors combine in a manner that enables a continuous rotation of aircraft to be sustained.

The general approach taken is to look at the 'best case' assumptions regarding the aircraft operations (aside from correcting for assumed availability) applied to worst-case scenarios. That is to say, the requirements will be set in a manner such that if all goes perfectly, the fleet will be able to handle the worst-case scenario. Most operational scenarios will be less challenging, but will likely need to contend with more realistic issues such as: imperfect handovers; performance degradations due to winds or other meteorological conditions; competing aircraft deployments; and, allowing for preferred rather than minimum crew rest and aircraft check times. On the other hand, any aircraft that does not satisfy the requirements as identified here, will not be able to meet the most challenging circumstances even if all serviceable aircraft are dedicated to purely domestic operations.



Figure 1: Canada's Maritime areas of responsibility, including Main Operating Bases and Forward Operating Bases considered usable by the MPA.

2 Assumptions and background

The plain language problem stated in the introduction is constrained both by external factors – e.g., the maximum crew day allowed for air crew, the size and shape of Canada’s AOR – and by the objectives specified by the requirement developers. These foundational assumptions are described immediately below. The following subsection then derives some further implications that result from those assumptions and givens, which are fundamental to the approach taken to analyzing the problem.

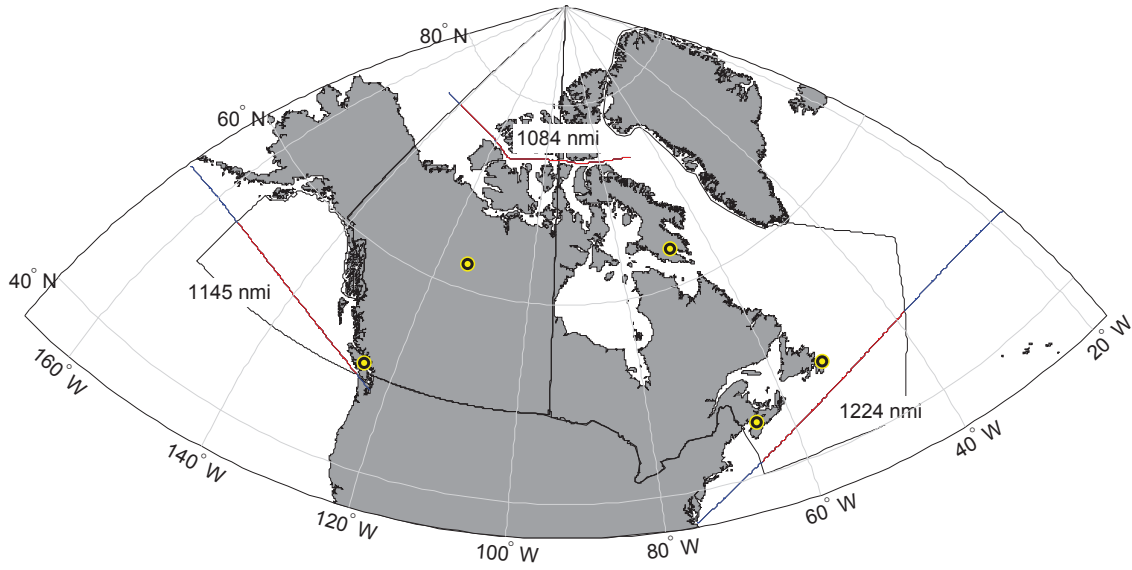
2.1 Assumptions and givens

In order to render the analysis tractable within the allotted timeframe,¹ several assumptions were necessary. Some of these were made solely to limit the number of options under consideration, while others were used to simplify the problem space. Many of these were given by the client. The most significant of these assumptions and givens are:

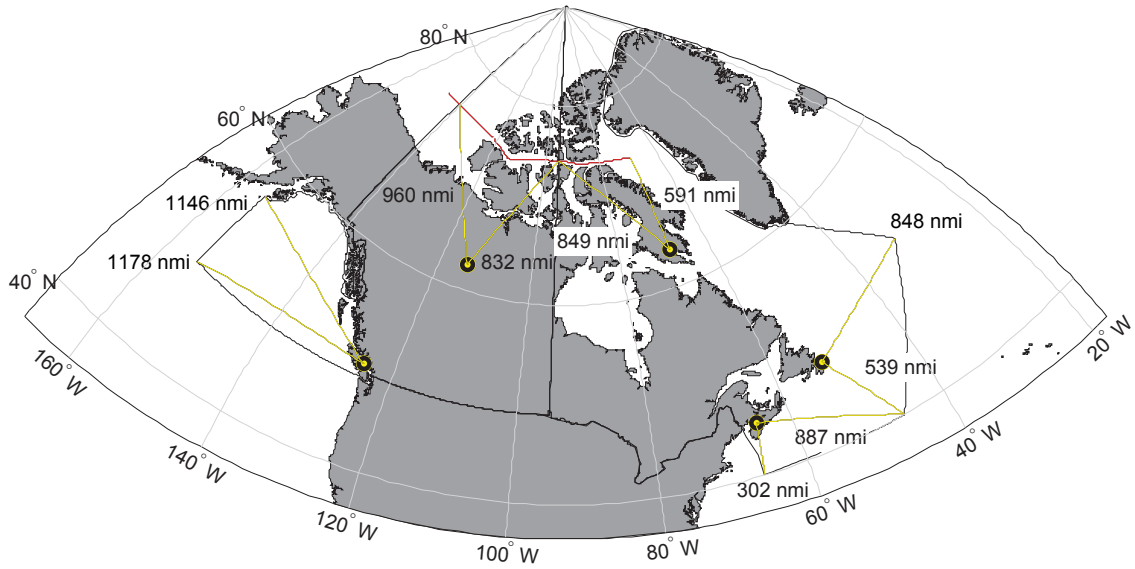
1. The remit from DAR was to look at the number of aircraft required to sustain continuous coverage of (i.e., to track) a vessel moving through one or more AORs.
2. The mission always takes place entirely within Canada’s maritime AOR, as shown in Figure 1. A vessel transiting this zone at regular speeds may easily spend many days within the AOR (see Table 1 and Figure 2(a)).
3. Vessels of interest are under no obligation to transit the zone of surveillance with any particular haste, and may even hold their position for extended periods. All countries have freedom of navigation in the Exclusive Economic Zone (EEZ), and the AOR being considered extends well beyond into purely international waters.
4. Handover of surveillance from one on-station aircraft to the next can happen during the transit of the incoming aircraft.
5. Fuel consumption is close to uniform throughout all phases of flight. This means that an hour of transit time can be traded off against an hour on station.² This assumption was found to be reasonable when checked against aircraft performance models in a similar study done in Australia [5].

¹The initial analysis was undertaken over the course of several weeks, specifically for the CMA. The analysis was extended over the course of the following year, as assumptions were tweaked and the modernization of CP-140 also entered as a possibility.

²In particular, on the flight to and from the surveillance area, the aircraft is assumed to fly at optimal cruising altitude and speed. Given the relatively slow speed of the vessels they are assumed to be surveilling, it is further assumed that once on station they can fly at an optimal speed for whatever altitude from which they must observe. It would be difficult to refine this assumption without dealing with specific aircraft performance characteristics, which would be more appropriate during the development of acquisition criteria.



(a) Sample challenging transit paths through the Canadian AOR.



(b) Distances to extreme points in the Canadian AOR.

Figure 2: Extreme distances used for each of the three coasts.

Table 1: Potential transit times through the Canadian AOR (see Figure 2(a)).

Distance (nmi)	Transit Time (days)		
	@5 kts	@10 kts	@15 kts
500	4.2	2.1	1.4
1000	8.3	4.2	2.8
1224	10.2	5.1	3.4
1500	12.5	6.3	4.2

6. All flight operations occur under no wind conditions. This eliminates the need to evaluate the complex effects on cruise altitude and aircraft endurance that are induced with the introduction of winds. Under more realistic flight conditions, pilots can adjust their speed and altitude in an effort to optimize their flight plans based on factors such as aircraft endurance or fuel consumption. Regardless, it is possible to define fuel reserves in a way that allows the pilot to achieve desired flight performance in the face of unfavourable weather conditions, including winds, provided these are not unrealistically extreme in nature.
7. In addition to the two Main Operating Bases (MOBs) in Comox, BC and Greenwood, NS, the aircraft and their crews can avail themselves of three Forward Operating Bases (FOBs): Iqaluit, NU; St. John's, NL; and Yellowknife, NT (see Figure 1). All of these bases can be used indefinitely to support operations within the AOR. Handover issues (including recovery at a different site) in which the Vessel of Interest (VOI) moves closer to a different FOB are not considered.
8. Solutions with more than 16 crews were considered inadmissible by DAR.
9. DAR requested that 50% of the aircraft be considered serviceable at any given time when calculating overall fleet size for the CP-140 Aurora and 70% for the CMA (the subtly different term 'operational availability' was used for the CMA – these terms will be applied to the two fleets as needed). Section 3.4 will expand on this assumption. It is further assumed that in the demanding conditions considered here – i.e., maintaining continuous coverage on two of Canada's coasts – any aircraft allocated to an operational training unit would be reallocated to meet the demand.

2.2 Implications

The assumptions and givens above have several important consequences, specifically:

1. Due to Assumption 1, a probabilistic, reconnaissance type approach (see e.g., [6, 7]) to coverage was not appropriate.
2. Due to Assumptions 2 and 3, the patrol aircraft must be able to maintain a continuous handover essentially indefinitely, potentially at a worst-case point in the AOR. The analysis will therefore consider the number of aircraft and crews needed to maintain

continuous surveillance at these points in steady-state. In this manner, the results obtained herein are mission-agnostic; in other words they apply to any mission whereby a continuous on-station presence is required at an arbitrary point in the AOR. This obviates the need to search for optimal rostering over a set of possible missions (see e.g., [8]), as a closed form solution can be calculated. The worst-case distances used are as shown in Figure 2(b). Notably, the distances used for the West and East coasts are those to the furthest point in the AOR (making the analysis independent of the sample paths), whereas for the Arctic the distance used is the worst-case point on the sample path. The Subject Matter Experts (SMEs) did not judge coverage to the extreme Northern point of the Arctic AOR to be reasonable, so instead the furthest point on the most northerly of the various ‘North West Passage’ routes likely to be taken by a vessel was used.

3. Similarly, the requirement to maintain a steady-state operation over days or weeks implied by Assumptions 2 and 3 makes it impractical to consider in detail the scheduling implications of using alternate landing sites (see [7] for an example of this scheduling problem). Although the use of FOBs is considered, it is tacitly assumed that the entire force (aircraft and crews) conducting the surveillance is operating from whichever base is optimal for a given point.
4. Due to Assumption 3, it cannot be assumed that the track of the vessel of interest will be known. Therefore, it is not in general appropriate to try to optimize the patrol schedule for a specific pathway (as in, e.g., [5, 9, 10]). It is assumed simply that the first aircraft will have sufficient cueing to be able to fly out to meet the vessel at or near its entry to the AOR, and further aircraft can only plan to rendezvous with the aircraft already on station.
5. Due to Assumption 4, it can be assumed that exactly one aircraft is ‘on-station’ at any time – i.e., a buffer does not need to be added to the time-on-station to allow for handover.

3 Method

This section will describe the calculations used to develop the results in the following section. Although the calculations themselves are relatively straightforward, care must be taken to ensure the definitions of the terms are clear. The main complicating factor is the requirement that the number of aircraft be integer on each coast. The form of the equations are very similar to those developed in a recent Australian study, although they were only applied to aircraft [5, 11].

3.1 Definitions

Endurance (E) – is the *time* that an aircraft can remain airborne. Specifically, it is assumed that the aircraft will be flown as close as possible to its most fuel efficient speed and altitude both in transit and when orbiting on station, in order to maximize endurance; given an assumed equal fuel flow in both circumstances, this can then be treated simply as the time the engine can be run. Although in reality this is dependent on a number of factors such as cruising altitude, the speed at which the aircraft is flown, aircraft loading, and environmental factors, it is assumed that this can be reasonably approximated by a constant value (see Assumption 5).

Speed (S) – is the average ground speed at which the aircraft can most efficiently transit, which for simplicity is assumed to be the same as the average airspeed an aircraft can maintain. This is in reality quite variable due to winds and other factors.

Distance (D) – is the distance to the point to be surveilled.

Transit Time (TT) – is the time the aircraft spends flying to the location being surveilled from its base. It is assumed that this is equal to the time spent returning from the point to its base (see Implication 3). It is assumed the aircraft will fly at its most efficient altitude and speed.

Time on Station (TOS) – is the time an aircraft spends surveilling a given location. It is assumed that the aircraft will fly at the most efficient speed for the altitude it must maintain to effectively conduct surveillance (see Assumption 5). TOS_D is the time on station an aircraft can maintain at distance D from its base.

Cycle Time (CT) or Turn-around Time – is the time needed for the aircraft or crew to be mission ready again after having completed a sortie. Note that these will generally be different lengths for crew, meaning that crews will not necessarily remain paired with a specific aircraft in each cycle. Cycle time – crew (CT_{crew}) and Cycle time – aircraft (CT_{ac}) will be used to disambiguate as necessary.

3.2 Endurance calculations

Given Assumption 5 that the fuel flow is the same while on station as it is during transit, the endurance of the aircraft can be stated as:

$$E = 2 \times TT + TOS_D = \frac{2D}{S} + TOS_D, \quad (1)$$

from which it can easily be seen that:

$$TOS_{D_2} = TOS_{D_1} + \frac{2(D_1 - D_2)}{S} \quad (2)$$

for two different distances D_1 and D_2 .

Equation 2 can be used to convert the maximum estimated TOS at one distance to another for the same aircraft. This was judged to be useful to the client, as many aircraft designed for this mission report their range and endurance as being capable of maintaining x hours of on-station time at a range of y nmi, where y is not necessarily one of the distances of interest for this study. In particular, DAR was often interested in knowing the effective TOS at 1000 nmi.

3.3 Crew and aircraft calculations

Recall that multiple aircraft are being used to form a continuous rotation at a given location of interest. The amount of time it takes for an aircraft to complete one cycle through the rotation is simply $2 \times TT + TOS + CT$, that is the sum of the time spent in transit to and from the location or vessel of interest, the time spent on station, and the turn-around time. By considering the time between that aircraft leaving the scene and returning, the number of additional aircraft n that are sufficient to provide continuous surveillance must satisfy:

$$n \times TOS \geq 2 \times TT + CT. \quad (3)$$

That is to say n additional aircraft must each provide a block of coverage of length TOS , to allow time for the original aircraft to return to the station point without allowing a gap in coverage. The overall cycle can then repeat.

From this last equation, it is easy to see that N , the minimum number of aircraft required to maintain continuous coverage, is simply equal to $n + 1$ and must therefore be the lowest integer that satisfies:

$$N \geq \frac{2 \times TT + CT}{TOS} + 1, \quad (4)$$

which is to say

$$N = \left\lceil \frac{2 \times TT + CT}{TOS} \right\rceil + 1, \quad (5)$$

where $\lceil \cdot \rceil$ denotes rounding up to the nearest whole number. As mentioned above, the definition of cycle time is different for the aircraft and the crew, and the calculations for each will be elaborated separately below. Notwithstanding this, the calculation for both

the number of crews and the number of aircraft needed to maintain continuous coverage takes the same general form; the crew must spend the same time in all the phases of flight as the aircraft and so those factors remain the same, but the crew will generally take longer to be ready to fly again than the aircraft, necessitating more crews than aircraft. Structuring both requirements around expected transit time and time on station ensures that the calculations do not consider crew changeovers in mid-flight.

The relevant reference for determining CT_{crew} is the *1 Canadian Air Division Orders: Volume 2: Flying Orders* [12], which states:

Crew Rest – A minimum of 12 hours of rest must be taken between crew days. For crew days exceeding 14 hours a minimum of 14 hours of crew rest should be attained. A temporary period of lower rest may be declared, although in no case should it be lower than 8 hours.

Brief/Debrief – Duty time commences either two hours before planned departure time, or at brief time. Duty time ends approximately one hour after arrival.

Noting the ‘should’ in the 14 hour crew rest requirement, a minimum of 15 hours of time between landing and take-off was used: accounting for a fixed one-hour value for the debrief, the minimum 12 hour rest period,³ and a two-hour pre-flight brief (i.e., $CT_{crew}=15$).

The Flying Orders further state that “the maximum Crew Duty Day shall be 18 hours and the maximum planned itinerary time shall be 14 hours. Planned itinerary times should not normally exceed 12 hours” [12]. Allowing that the scenarios contemplated herein would not be ‘normal,’ 14 hours is considered to be the maximum itinerary for the crew on each sortie: which necessarily implies that aircraft endurance of greater than 14 hours is irrelevant.

SME guidance was relied upon to approximate CT_{ac} , and includes:

A-check – The ‘after’ check performed on return of the aircraft. Estimated to last two hours.

B-check – The ‘before’ check performed prior to pre-flight. Estimated to last two hours.

Pre-flight – The pre-flight work-up of the aircraft. Estimated to last two hours.

Of note, whether these periods occur ‘before’ or ‘after’ each flight is essentially irrelevant; they must all happen once between two consecutive flights to achieve minimum turn-around, for an overall estimate of six hours (i.e., $CT_{ac}=6$).

A visual aide to understanding the relation between the aircraft and crew cycles is provided in Figure 3. The example was chosen specifically to show cases where the schedules for neither aircraft nor crew can be perfectly aligned, and so some idle or slack time is introduced for each aircraft and crew.

³Given the potential length of the surveillance mission, a temporary period of lower rest was not considered an appropriate assumption.

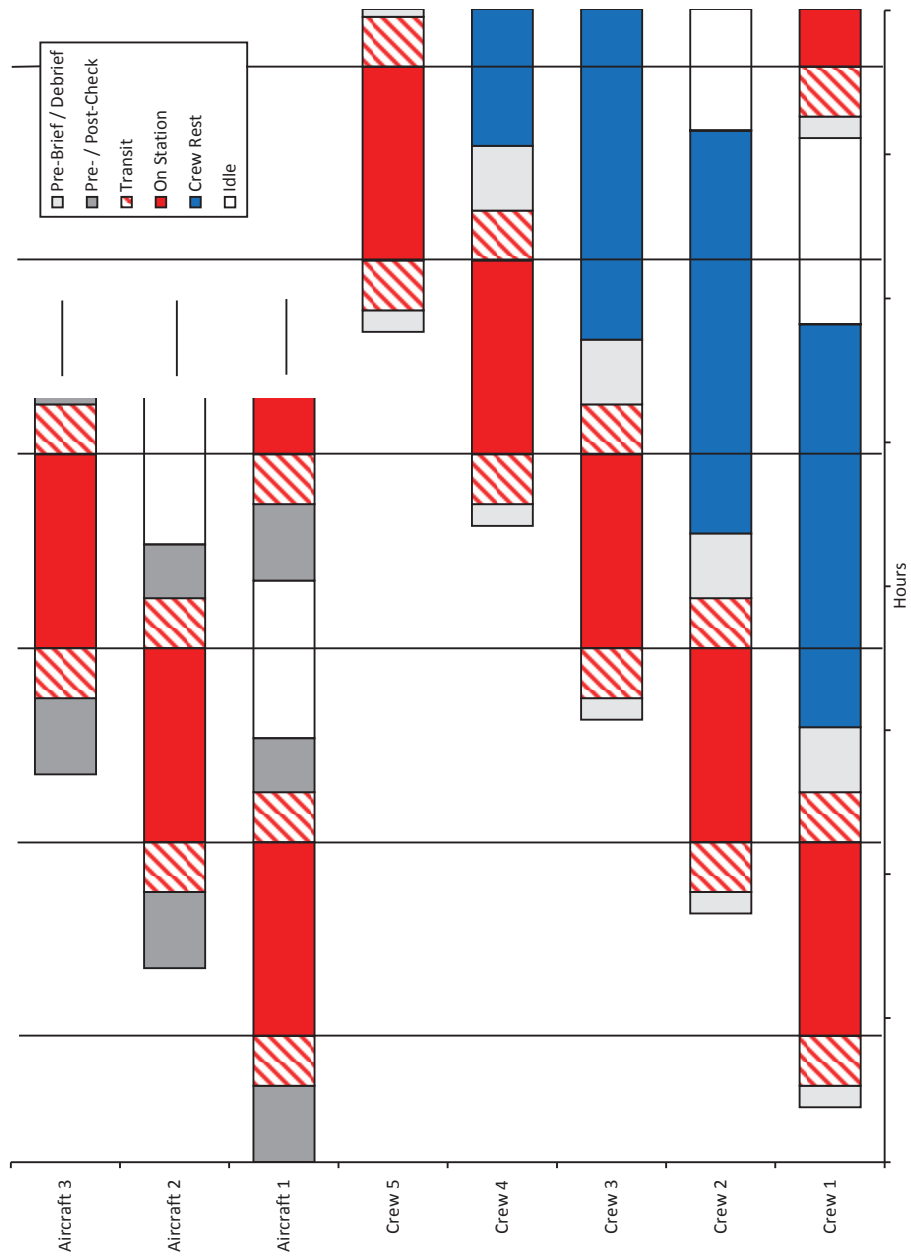


Figure 3: An aircraft and crew schedule to maintain continuous coverage in an example scenario.

One can see that in order to be able to replace Aircraft 1 on station, Aircraft 3 must start its pre-check before Aircraft 2 has completed its post-check; i.e., two aircraft would be insufficient to achieve continuous coverage in this scenario. Similarly, Crew 1 is still in its rest period when Crew 5 must start pre-briefing in time to be on station to relieve Crew 4, and so four crews would be insufficient. We can also see that due to CT_{crew} being two and a half times longer than CT_{ac} , more crews than aircraft will generally be necessary, and crews will not normally be paired with a specific aircraft in the cycle.

3.4 A note on serviceability

As noted in Assumption 9, the authors were asked to assume a serviceability rate of 50 % for a modernized Aurora fleet and 70 % for the CMA.⁴ A simplistic viewpoint of the implications of these values was taken for this study, which will be justified following a brief discussion of previous work. An aircraft will be declared unserviceable if it fails any of its checks. It is clear that if an aircraft does not pass either its pre-flight or B-check, another aircraft must then be found and those checks commenced anew – leading to additional time in the cycle. In [6], an average aircraft unserviceability time of 22.3 h *over and above* the A- and B-checks was extracted for the CP-140 fleet for FY01.

Instead of modelling this per aircraft, the approach taken here treats unavailable aircraft as a fixed percentage of the fleet at each base. The authors considered that the time required to model this with greater precision would not be worth the effort, particularly given that the actual serviceability of an arbitrary to-be-acquired aircraft cannot be forecast accurately.

To briefly elaborate on the difficulties created by considering a target serviceability percentage for an integer number of aircraft, one can consider two coastal squadrons using a CFDS-sized fleet of 10 to 12. With fleets of 5 or 6 on each coast, the possible values of serviceable aircraft at each squadron are restricted to $\{0, 20\%, 40\%, 60\%, 80\%, 100\%\}$ or $\{0, 17\%, 33\%, 50\%, 67\%, 83\%, 100\%\}$, respectively. For an overall fleet size of 10, for instance, if the requirement was to guarantee greater than 50 % availability at all times at each squadron, a fleet of 10 aircraft would actually need to be at least 60 % available. If the requirement is stated a bit more flexibly, e.g., at least 50 % available 90 % of the time, there are still multiple ways to round.

Given the above, the key point to consider is that if one wants to guarantee that they will meet a specific serviceability target with a small fleet, one will generally not be able to meet it exactly. Conventionally one wants to *at least* meet that target, so one will actually

⁴Recent economic analyses on fleet replacement have noted that overall CP-140 fleet Operational Availability has suffered in recent times [13, 14]. It was between 40 % to 50 % from the period of 1995 to 2000, dropped below 40 % in 2001, below 30 % in 2003, and finally remained below 20 % from 2005 to 2007. However it is important to note that the denominator used for those calculations was the entire fleet size of 18, which included aircraft that were off the flight line for extended periods undergoing modernization. When only those aircraft that were actually available to the operational squadrons are considered, Operational Availability was above 50 % from 1998 to 2001, and only fell below 40 % once in the period from 1998 to 2008. The expectation is that once all aircraft undergoing modernization have been returned to the flight line, 50 % Operational Availability is achievable.

need to exceed the goal; i.e., one will have to ‘round up’ a decimal number of aircraft to an integer. By only dealing with 50 % availability for the Aurora this problem is avoided. It is important to note this is actually an optimistic assumption in the sense that it is quite brittle – if serviceability were to drop at all (e.g., to 49.5 %), two additional aircraft would need to be added to the fleet (one on each coast). For 70 % serviceability generally the fleet will be fractionally larger than it would need to be if aircraft were divisible; put another way a fleet that can provide the required number of aircraft with a serviceability rate of 70 % will generally still be able to operate if it drops somewhat lower (anywhere from 60 % to 67 % for the fleet sizes of interest).

The authors also note that using a probabilistic serviceability metric would also likely increase the number of aircraft required; i.e., that the simplistic approach taken here is optimistic. For instance, if one wanted to guarantee that the squadrons were at least 50 % serviceable 75 % or 90 % of the time, the average serviceability would almost certainly have to be higher than 50 % (unless the underlying distribution has an unusual degree of skewness).

As will be seen later in the report, even the most stringent requirements considered generate fleets that are at the high end of what the CFDS assumes. Given that using a more complicated approach to serviceability would if anything increase the size of each hypothetical fleet, the authors determined that using average serviceability allows decision makers enough resolution to draw useful comparisons within the range of feasible fleet size, while introducing an implicit risk that the required fleet may not successfully accomplish the most stringent of scenarios if serviceability is below target.

4 Results

Using the formulæ developed in the previous section, the authors calculated the required minimum fleet and crew sizes to support the mission as described in the introduction. The primary difficulty is in visually summarizing the results in an easy-to-understand yet complete manner; the interplay between speed and endurance cannot be captured well in a single value, which impedes direct representation on an already two-dimensional map.⁵ If one is willing to abandon the geographical implications, the trade-offs in speed and endurance can be better captured in a two-dimensional chart; for these a single value (or set of values) for the range from base of the vessels being surveilled must be fixed.

Given those limitations, a reasonable set of fixed values must be selected for which to present maps and charts when one or more of the data dimensions cannot be directly incorporated.⁶ Ranges of interest are directly motivated by the problem definition; the worst-case points for each coastal AOR were shown in Figure 2(b) and are summarized in Table 2 for ease of reference.

Selecting representative values for speed and range is somewhat more subjective. Given that it is both currently utilized, and being considered for modernization, it makes sense to include the capabilities of the CP-140 Aurora as one of the points [15].⁷ Also considered as part of this analysis are a “jet-powered” aircraft (faster with lower endurance⁸), and a “light” aircraft (slower with longer endurance). The values used are in Table 3.

Part of the intent of this study was to determine minimum requirements for endurance and speed, to allow the consideration of the widest array of possible aircraft for acquisition. It will be shown that setting independent minima for either is overly restrictive, as they can be traded-off when minimizing the number of aircraft required to sustain continuous surveillance.

4.1 Aircraft and crew requirements

Section 3 succinctly lays out a series of equations for calculating the number of aircraft and crews required to maintain continuous surveillance at a given point.⁹ Although Equation 4 can be used to calculate both, separate charts are needed for each; best-case cycle time for air crews is more than double that for aircraft.

⁵It is here that the analysis departs significantly from the Australian study cited earlier [5, 11]. For ASW missions, that study used three fixed values for aircraft performance (two Unmanned Aerial Vehicles (UAVs) and one MPA) and produced a single plot of distance to station versus number of aircraft required. It then proceeds to consider the impact of distance to station on the classic area search and barrier patrol problems.

⁶This is simply to make the presentation herein tractable, there is no fundamental constraint preventing the production of a very large number maps and charts for other values.

⁷The value used was chosen in consultation with SMEs in DAR and is consistent with those provided in the CP-140/CP-140A Statement of Operating Intent (SOI).

⁸Examples of jet-powered MPA include the recently retired Nimrod and the in-development P-8 Poseidon.

⁹See Section 2.2 regarding reducing the tracking problem to maintaining continuous coverage at the worst case point in each AOR.

Table 2: Maximum distance from a MOB/FOB to the edge of the AOR in each surveillance scenario.

Surveillance Scenario	Maximum Distance (nmi)
East Coast	848
West Coast	1178
Arctic	960

Table 3: Speed and endurance of representative aircraft. Endurance is expressed as the Time on Station of the aircraft at 1000 nmi

Aircraft Type	Speed (knots)	TOS_D (hrs)
CP-140	350	6
Jet-powered	400	5
Light	300	6

The results for the West Coast (the most challenging of the three) are shown in Figure 4, with the other two coasts presented in Annex A. Interpretation of the two types of charts is essentially the same. At or beyond the upper-right region of a chart is a region where only two aircraft are needed; if the aircraft fleet is fast enough and has sufficient endurance, one aircraft can return to base, be ‘turned around,’ and fly back to the station in time to relieve the other. Generally three is the lowest feasible number for crews; as the required rest period combined with briefing time is longer than the maximum duty day, a crew cannot be rested and ready in time to replace the crew which immediately followed them. In the lower left is an infeasible region wherein an aircraft cannot even make it to the station and back with the given combination of speed and endurance. In between are several coloured regions, each of which represents an area where aircraft performance figures require an equivalent number of aircraft or crew. The 14 hour constraint on crew day length noted in Section 3.3 is also indicated on the figures. As one approaches the infeasible region from the right or top of the chart, in general the number of aircraft or crews begins to rapidly approach infinity; where regions would be too thin to easily distinguish a region of ‘ $N+$ ’ is indicated on the legend.

While considering the coasts individually provides valuable information and context, the remit of the study was to examine the requirement to conduct surveillance options on two coasts simultaneously. Data for two coasts can be combined on one chart (see Figures 5 and 6 as examples), although the effect can be jarring (if not deceiving) to the eye. Where the borders between regions on the individual charts cross when overlaid, the result is lines that seem to ‘bounce’ off each other (note e.g., the point near 260 kts and 13 h in Figure 6(a)). These intersections are due to differing slopes on the two source charts, indicating that there is a different trade-off between speed and endurance for different coasts. Regions around these points are where the calculations are the most sensitive to small changes in aircraft capability, where a small decrease in either endurance or speed may require an extra aircraft on both coasts in order to maintain continuous coverage. For the modernized Aurora’s assumed serviceability of 50%, the total fleet required would then jump by four.

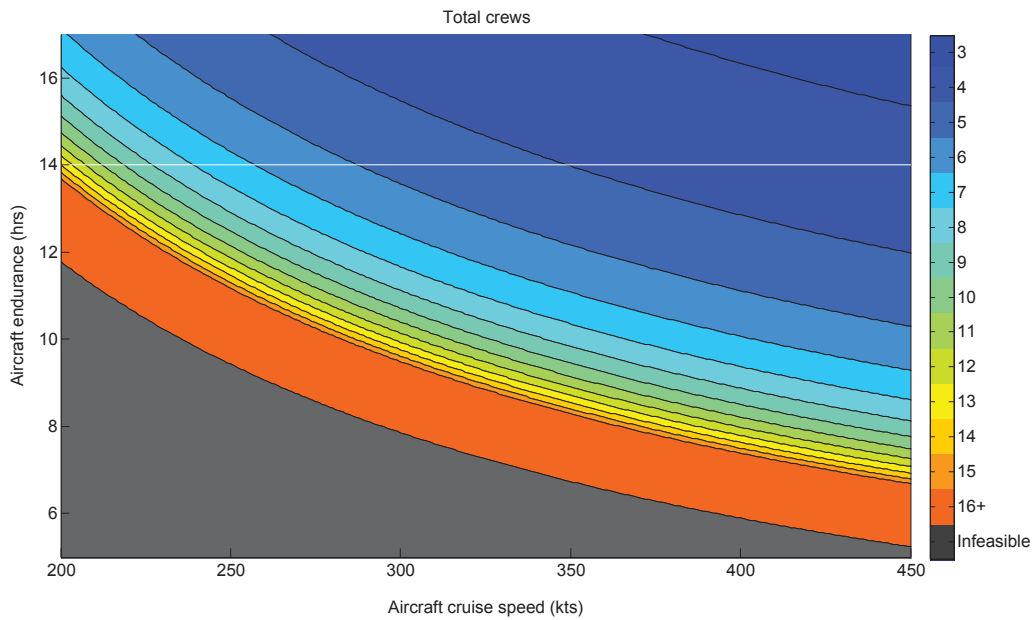
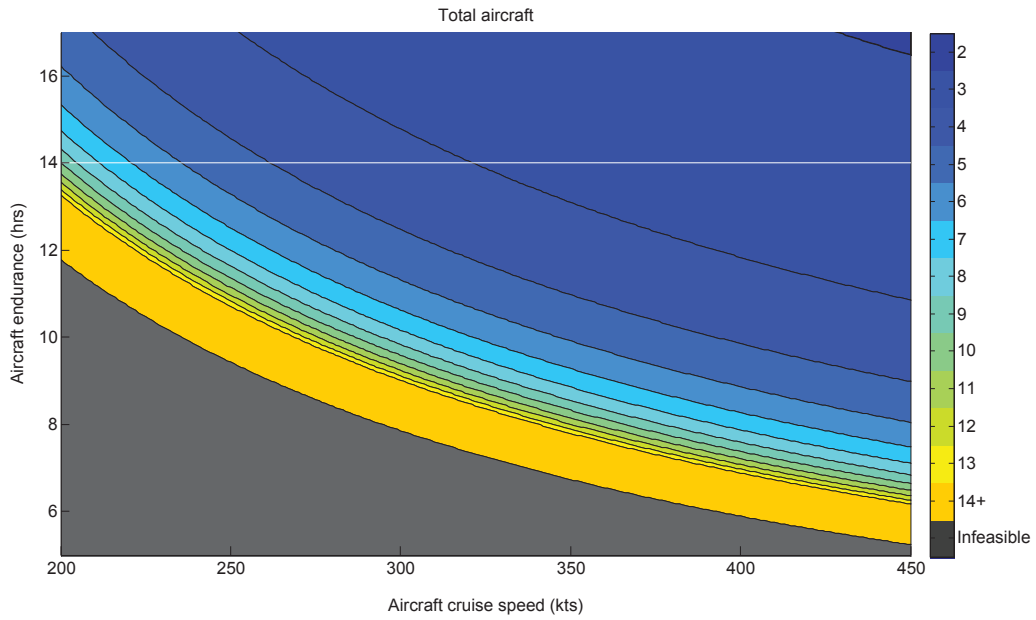
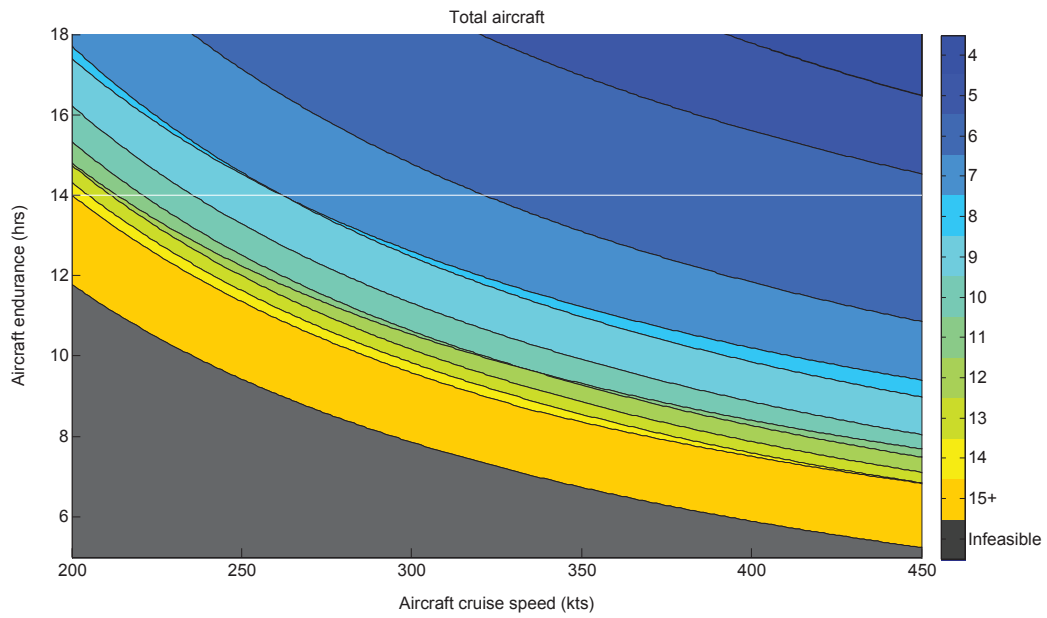
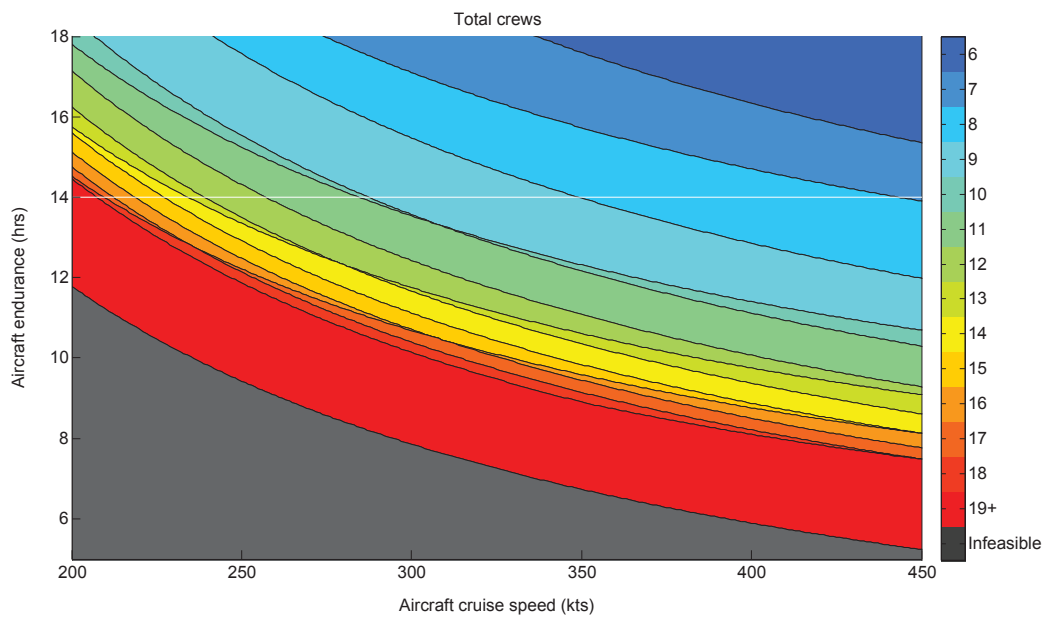


Figure 4: Aircraft and crew requirements for the Western AOR.

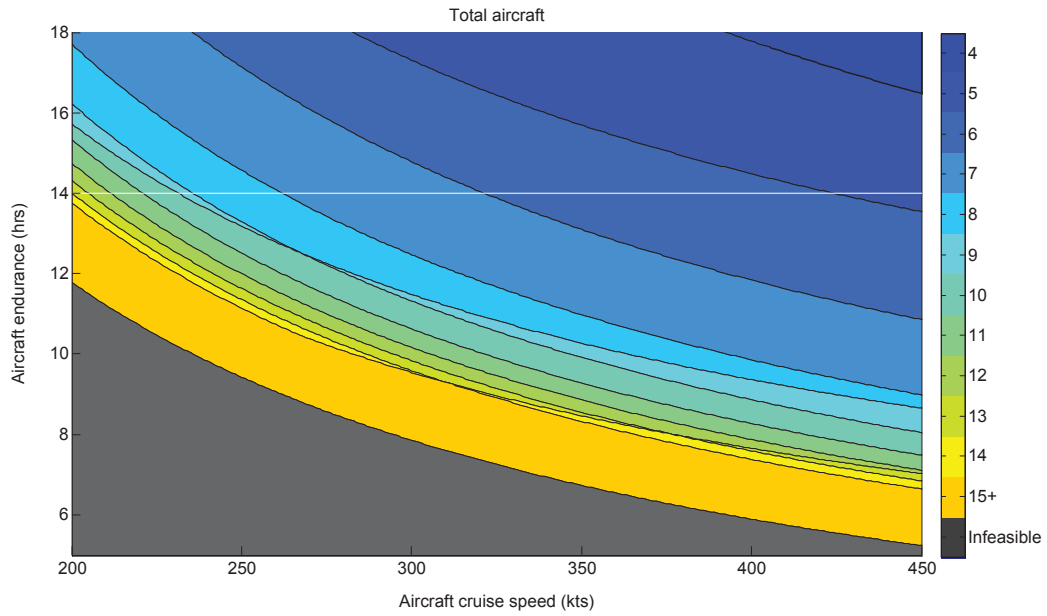


(a) West Coast and Arctic – Serviceable Aircraft

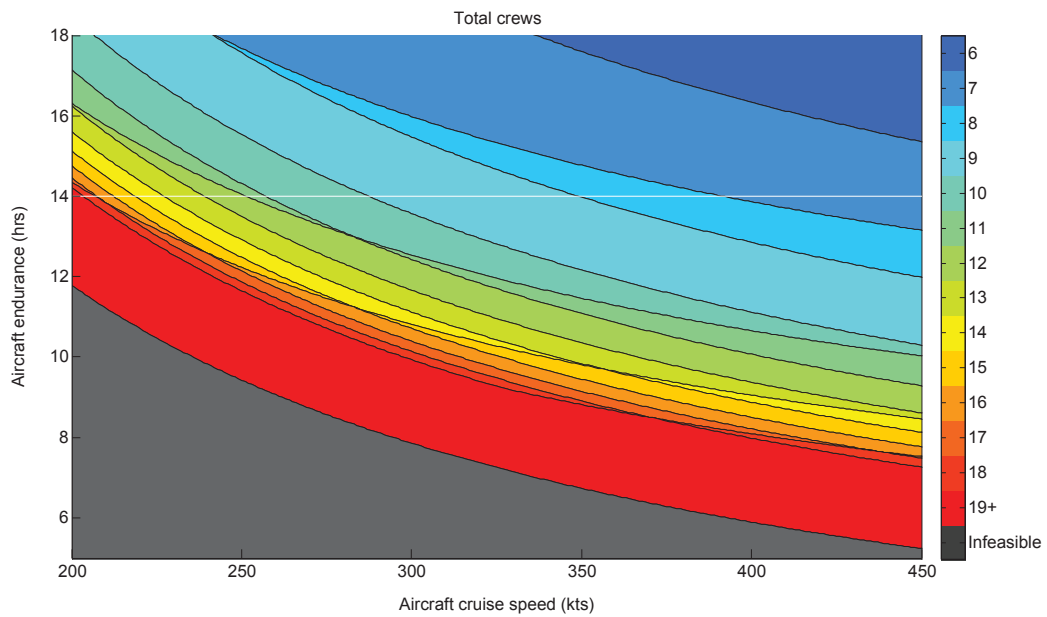


(b) West Coast and Arctic – Crews

Figure 5: Combined aircraft and crew requirements for the West Coast and Arctic AORs.



(a) East and West Coast – Serviceable Aircraft



(b) East and West Coast – Crews

Figure 6: Combined Aircraft and crew requirements for the East and West Coast AORs.

This sensitivity calls for consideration of the impact of setting requirements such that capability proposals right on one these lines are considered as acceptable as those further away.

4.2 Geographic context

While the figures in the previous subsection are useful for directly reading off minimum values for the required missions, they are less useful for understanding the impact of being just below the requirement or having fewer aircraft; in other words to understand how much of the AOR would go uncovered if fewer aircraft or crews were available than necessary. The authors judged that plotting the geographic area various fleet sizes could cover (as determined by combining Equations 1 and 5) was useful for conveying risk to decision-makers when they were considering various fleet sizes, particularly as throughout the procurement process questions would likely be raised about the impact of a smaller fleet. The figures can also be used to visualize the impact of degraded availability in a real-world setting, due to e.g., extended repairs or upgrades.

Figure 7 gives an example for an aircraft with similar speed and endurance to the CP-140. The scale is the number of serviceable aircraft required at that MOB or FOB to create the depicted coverage, and so conversion to recommended fleet size requires further calculation (adding up coasts, dividing by serviceability rate, and rounding up).

Several features are notable. Although the Eastern AOR looks larger and more challenging, the placement of the MOB and FOB on this coast allows coverage to be extended out further with fewer aircraft than on the West Coast, where the single MOB is located essentially in one of the corners of the AOR. On the East Coast, it is worth remembering Assumption 7, in that these figures (and all calculations in this paper) assume away the problem of handing over control from one MOB/FOB to another. Looking at the area mid-way between Iqaluit and St. John's in Figure 7 where three aircraft are required to maintain coverage, one should keep in mind the logistical hurdles of handing control, aircraft and crews over from St. John's to Iqaluit if a VOI was transiting North towards the Davis Strait. It is also clear that there are areas to the North of the typical Arctic transit considered for this study that are extremely difficult to cover with the current operating bases, yet still well within Canada's AOR – particularly as Canada submits claims to extend its EEZ in this area.

Figure 8 is similar to Figure 7, instead showing how many crews are required to provide coverage of the AOR rather than the number of aircraft. Unlike aircraft calculations, the total number of crews needed to provide a continuous presence on two coasts simultaneously can be obtained by simply adding the required number of crews from each of the individual coasts.

Maps for the other two representative aircraft types are provided in Annex A. One area to note in Figure A.4 for the 'jet-powered' aircraft is that the Southwestern corner of the AOR is quite close to the boundary between four and five aircraft, suggesting sensitivity to these figures. Additionally, two aircraft operating out of Comox cannot even operate out to the edge of Haida Gwaii.

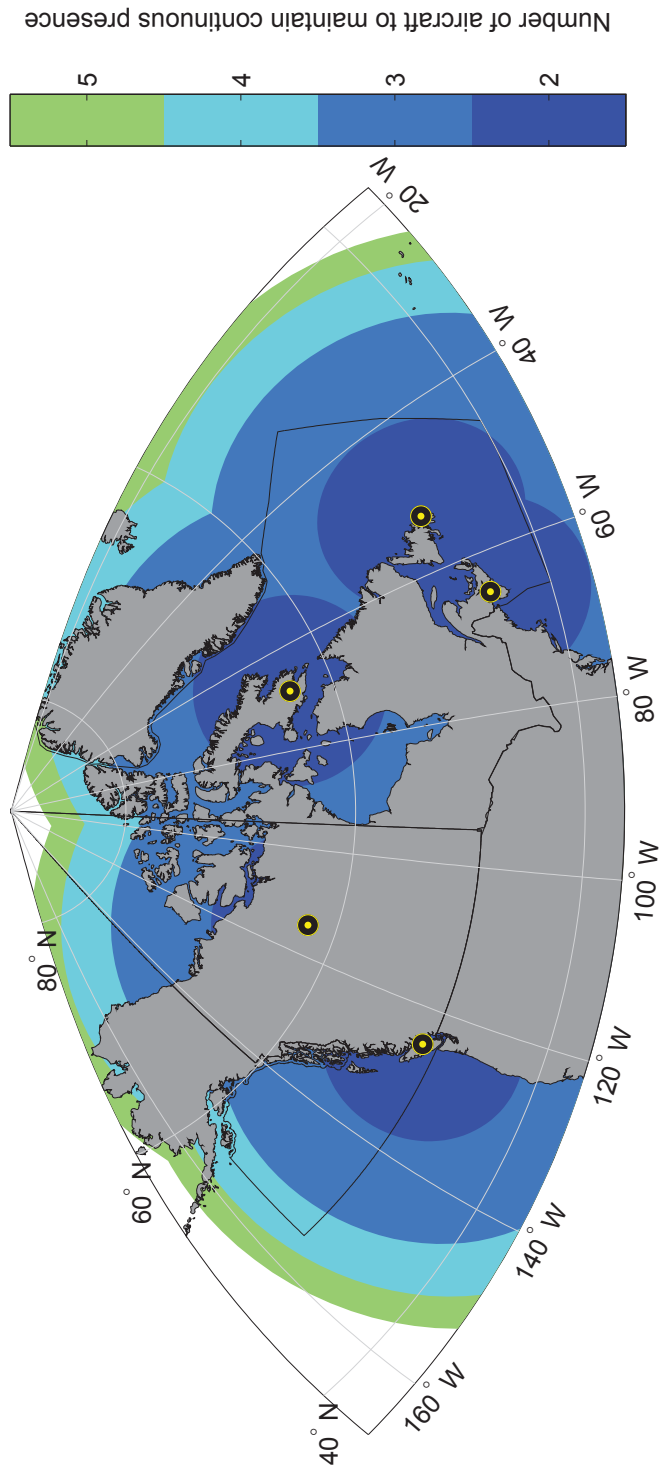


Figure 7: Number of serviceable CP-140 needed to maintain a continuous presence in Canada's AOR.

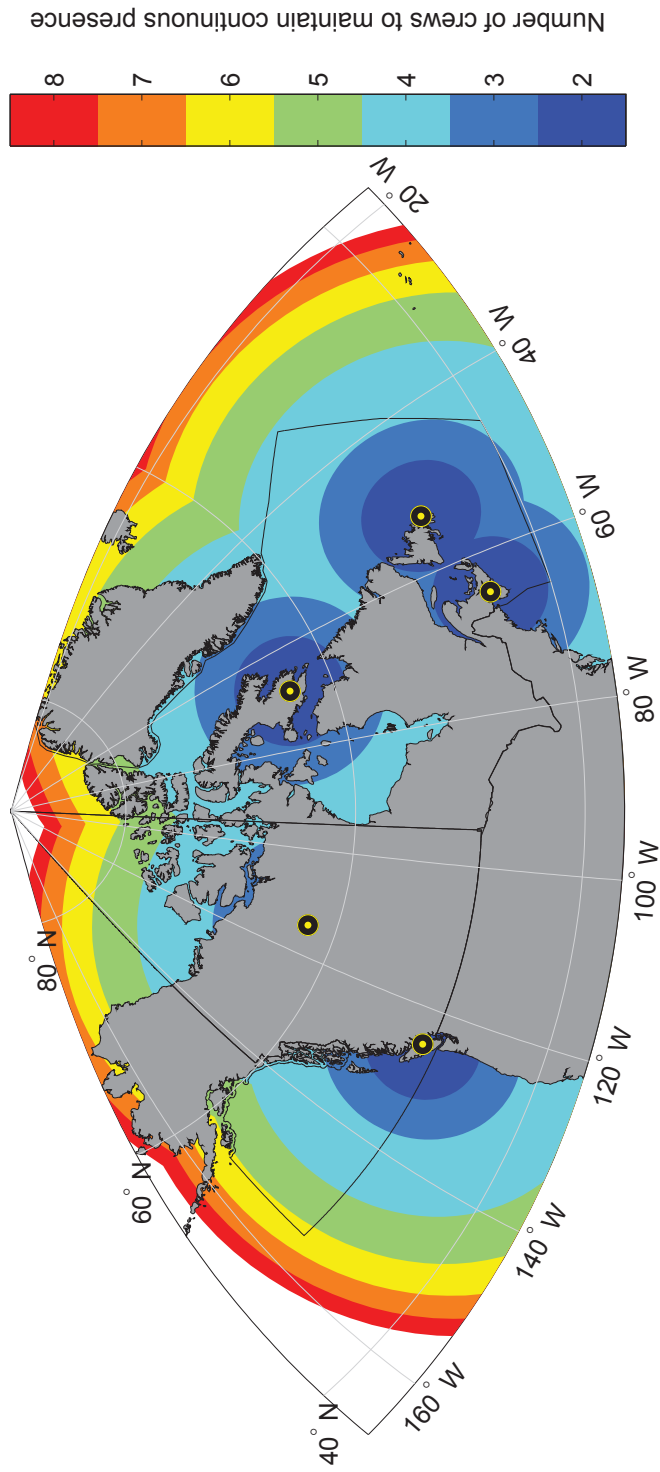


Figure 8: Number of CP-140 crews needed to maintain a continuous presence in Canada's AOR.

5 Discussion

The charts in the previous section convey a great deal of information about the trade-offs between endurance and speed, at the cost of some intelligibility. Particularly for purposes of writing statements of requirements, the clients desired clearer statements of cut-off values. The authors noted that using single minimum values for both endurance and speed would unduly restrict the space of acceptable solutions, and proposed as a compromise to develop a tabular list of data points of most interest. The tables presented for both the Aurora modernization and the CMA project are presented and discussed below. When comparing to the charts in the previous section, the most important difference to note is that the aircraft numbers in the tables *include the effect of serviceability* (or operational availability). These tables were used to directly convey to senior decision makers the total fleet size necessary given a range of possible requirements [3, 4].

The tables below show number of aircraft and crews for increments of 30 minutes in time on station and 20 knots for speed. These choices are arbitrary and can easily be adjusted to provide more or fewer points upon which to base a requirement, as the case may warrant. The most appropriate choice is a function of identifying the best compromise between increasing ease of use of these criteria (and having fewer data points in the tables as a result) and increasing fidelity (by adding additional points to the lookup tables). The figures in the previous section have the benefit of providing the exact answers for any combination of speed and time on station.

5.1 CP-140 modernization (50 % serviceability)

The fleet size and number of crews for aircraft of varying performance are presented for the two most challenging bi-coastal cases in Tables 4 and 5. Cells coloured red in Tables 4 and 5 are those requiring more than eighteen aircraft – given that the Royal Canadian Air Force (RCAF) currently only operates eighteen CP-140, it is extremely unlikely that more than that would be available in an upgraded fleet. There was interest in considering upgrading only a subset of the current fleet, and so yellow cells highlight those solutions toward the high end of the current fleet size, with blue cells representing those that would allow a substantial savings (fourteen or fewer aircraft to be modernized).

Given the CP-140's capability of cruising at approximately 350 kts and providing approximately 6 h on station at 1000 nmi, one can see from the boxed values in the table that a fleet size of fourteen modernized Auroras is required to fully cover the two most challenging coasts simultaneously. A total of ten crews are required in the combined West and East Coast scenario, while eleven are required in the West Coast and Arctic scenario. This is exclusive of any aircraft assigned to an operational training unit or on long-term maintenance.

Table 4: Combined aircraft and crew requirements for West Coast and Arctic scenarios, assuming 50% serviceability. Cell values ‘ m/n ’ are the number of ‘aircraft/crews’ required given the corresponding speed and TOS_D .

Cruise Speed (kts)	Number of aircraft/crews for a given TOS_{1000} in hrs								
	3.0	3.5	4.0	4.5	5.0	5.5	6.0	6.5	7.0
220				24/16					
240				22/16	20/15				
260				20/15	20/14	18/12	18/12		
280				20/15	18/14	18/12	18/11	14/11	
300				20/14	18/13	18/12	14/11	14/11	14/9
320			20/15	18/14	18/12	18/12	14/11	14/11	14/9
340			20/15	18/14	18/12	16/11	14/11	14/11	14/9
360			20/15	18/14	18/12	14/11	14/11	14/10	14/9
380			18/14	18/13	18/12	14/11	14/11	14/9	14/9
400			18/14	18/13	16/12	14/11	14/11	14/9	12/9
420		20/16	18/14	18/13	16/11	14/11	14/10	14/9	12/9
440		20/16	18/14	18/13	14/11	14/11	14/10	12/9	12/9
460		20/16	18/14	16/13	14/11	14/11	14/10	12/9	12/9

Table 5: Combined aircraft and crew requirements for East and West Coast scenarios, assuming 50% serviceability. Cell values ‘ m/n ’ are the number of ‘aircraft/crews’ required given the corresponding speed and TOS_D .

Cruise Speed (kts)	Number of aircraft/crews for a given TOS_{1000} in hrs								
	3.0	3.5	4.0	4.5	5.0	5.5	6.0	6.5	7.0
220				22/15					
240				22/15	20/14	16/13			
260				20/14	20/13	16/12	16/12		
280			22/16	20/14	16/13	16/12	16/10	14/10	
300			20/16	20/13	16/12	16/12	14/10	14/10	14/9
320			20/15	18/13	16/12	16/12	14/10	14/10	14/9
340		22/16	20/15	18/13	16/12	14/11	14/10	14/10	14/9
360		20/16	20/15	18/13	16/12	14/11	14/10	14/9	14/9
380		20/16	18/14	16/12	16/12	14/11	14/10	14/9	14/9
400		20/16	18/14	16/12	14/12	14/11	14/10	14/9	12/9
420		20/15	18/14	16/12	14/11	14/11	14/9	14/9	12/9
440		20/15	18/14	16/12	14/11	14/11	14/9	12/9	12/9
460		20/15	18/14	14/12	14/11	14/11	14/9	12/9	12/9

5.2 Canadian Multi-Mission Aircraft (70 % operational availability)

For the CMA fleet, the authors were asked to assume that 70 % operational availability can be attained. This has no effect on the number of crews required to sustain surveillance on a coast, but it does reduce the number of aircraft needed. The authors were asked to focus on the most challenging scenario for the CMA, and so only Table 6 is provided for the West Coast and Arctic combination.

The colour code for Table 6 is different than that presented above for the CP-140, and is as follows: cells coloured blue have fleets within the CFDS specified range of 10 to 12; cells coloured green are for those with smaller fleets; yellow cells are those slightly above the CFDS range (13 to 15); and red cells are anything above that. Yellow cells in particular were of interest, as recent experience with Fixed Wing SAR (FWSAR) has suggested that questions will be asked about whether a less capable (and presumably cheaper) aircraft could meet the requirements if the fleet size was allowed to expand (presumably still for a cheaper overall price).

The boxed values in Table 6 show the positions of the two non-CP-140 representative aircraft from Table 3. Even with the relatively generous assumption of 70 % operational availability, aircraft with these characteristics are right on the edge of the area within the CFDS fleet size. That is to say any fleet of similar aircraft that were either a little bit slower, or had a little bit lower TOS_{1000} ,¹⁰ would require greater numbers of aircraft. Those same cells in Table 4 have a fleet size of fourteen, meaning that if operational availability were to drop to a value that is still above today's observed value (50 %), sustaining these missions would require extra aircraft.

It is also worth considering the impact of trying to establish a hard lower limit on either endurance, speed, or both. If one wanted to be sure to stay within a CFDS fleet range, one could use a minimum of 6.5 hours for TOS_{1000} . This excludes all likely candidates, however. There is no single speed value that would be sufficient to exclude all fleets of size greater than twelve. If one used both together, there is no combination of values that would include both the 'light' and 'jet-powered' aircraft, without also allowing fleets of at least thirteen; this can be visualized as the region including cells below and to the right of the yellow cell at 300 kts and 5.0 h. Hard limits would have to bias the requirements to either one type or the other. This makes clear the importance of writing the requirements such that the limit is defined as a trade-off (whether in a table or by a function), regardless of whether a hard limit is set and/or a rated requirement is developed.

¹⁰It is important to note here that speed is not independent of TOS_{1000} . An aircraft with a lower speed but the same TOS_{1000} must have greater overall endurance, as it will take it longer to reach 1000 nmi.

Table 6: Combined aircraft and crew requirements for West Coast and Arctic scenarios, assuming 70% operational availability. Cell values ‘m/n’ are the number of ‘aircraft/crews’ required given the corresponding speed and TOS_D .

Cruise Speed (kts)	Number of aircraft/crews for a given TOS_{1000} in hrs								
	3.0	3.5	4.0	4.5	5.0	5.5	6.0	6.5	7.0
220				18/16					
240				16/16	15/15	13/13			
260				15/15	15/14	13/12	13/12		
280				15/15	13/14	13/12	13/11	10/11	
300				15/14	13/13	13/12	10/11	10/11	10/9
320			15/15	13/14	13/12	13/12	10/11	10/11	10/9
340			15/15	13/14	13/12	12/11	10/11	10/11	10/9
360			15/15	13/14	13/12	10/11	10/11	10/10	10/9
380			13/14	13/13	13/12	10/11	10/11	10/9	10/9
400			13/14	13/13	12/12	10/11	10/11	10/9	9/9
420		15/16	13/14	13/13	12/11	10/11	10/10	10/9	9/9
440		15/16	13/14	13/13	10/11	10/11	10/10	9/9	9/9
460		15/16	13/14	12/13	10/11	10/11	10/10	9/9	9/9

6 Summary

This report outlined the mathematical basis for advice delivered to DAR in support of decisions surrounding the size of Canada's future MPA fleet. While the method relies on a few simplifying assumptions (most notably surrounding use of FOBs), it allows one to calculate the exact number of aircraft of a given speed and endurance required to maintain continuous tracking of one or more vessels of interest through Canada's AOR. Although the underlying mathematics are simple, the richness of the results clearly demonstrate an interplay between aircraft speed and endurance that precludes treating them as separate requirements.

6.1 Observations

1. Setting hard minima on speed and/or endurance will necessarily exclude aircraft that can meet the requirements of the mission within the desired fleet size.
2. Given the serviceability/operational availability rates observed and expected, the CFDS fleet size of 10 to 12 appears to be a bare minimum for sustaining surveillance on two coasts simultaneously. Maintaining any sort of continuous rotation clearly requires at least two functioning aircraft, and considering distances near 1000 nmi will almost certainly require three. Applying a 50 % or even 70 % serviceability factor to that, and considering two coasts at once, puts one immediately into the CFDS range – even for relatively high performing aircraft. This does not take into account any extra aircraft needed to take into account handovers between MOB/FOBs.
3. The sensitivity of the requirements must be considered, as the serviceability rates of the CP-140 in particular means that the fleet size jumps by at least two (if not four) at each boundary: 14 % to 20 % of the fleet sizes considered.
4. Despite what may appear to be a smaller and simpler shape, the West Coast AOR provides the most difficult challenge in terms of maintaining continuous surveillance under the assumptions used in this study. This is primarily due to the only operating base available being located nearly in a corner of the AOR. While the East Coast requirement seems easier due to the greater FOB options used in this study, it is worth remembering that the difficulties in handing off between bases were not considered; in practice this may make maintaining Eastern surveillance more challenging.¹¹

6.2 Recommendations

1. Based on the results presented in Tables 4 and 5, if the CP-140 is modernized at least fourteen should be maintained to meet the surveillance requirements as described in

¹¹For reference, the furthest point in the Western part of the AOR from Comox is 1178 nmi away. It is this distance that drives the requirement on the West Coast. If St. John's is no longer used as an FOB, then the distance from the furthest point in the Eastern AOR increases from its current 848 nmi to 1369 nmi, which would make the East Coast the most challenging of the three coasts.

this study. Depending on the coasts considered, a minimum complement of either ten (Arctic/West) or eleven (East/West) crews should be maintained.

2. Observation 1 necessitates a strong recommendation that the speed and endurance requirements for any future CMA be defined as a trade-off, rather than as two hard minima.
3. Given the sensitivity noted in Observation 3, it is worth considering setting the minimum requirement curve slightly above the values calculated – particularly as meteorological conditions in the given AORs can easily eat into an aircraft’s best case speed and endurance.

6.3 Future work and CP-140 Life Extension

The results of the work show that speed and endurance can be traded off by an aircraft in meeting the requirements of the surveillance mission described herein. While the methodology herein can be used to develop a curve delineating the minimum acceptable combinations of these requirements, it can be naturally extended to comparing options that exceed that minimum – particularly if they enable a lower fleet size. Although the remit of DASOR is to help DAR establishing requirements for aerospace assets, DRDC – Centre for Operational Research and Analysis analysts in the Directorate of Materiel Group Operational Research (DMGOR) may pick up the work in supporting generation of future CMA bid evaluation criteria.

In the final stages of the finalization of this report, the Government of Canada announced that it would add another four aircraft to the ten already being updated under the Aurora Incremental Modernization Project, and extend the lifespan of those fourteen aircraft to 2030 under the Aurora Structural Life Extension Project [2]. This is in line with Recommendation 1 above.

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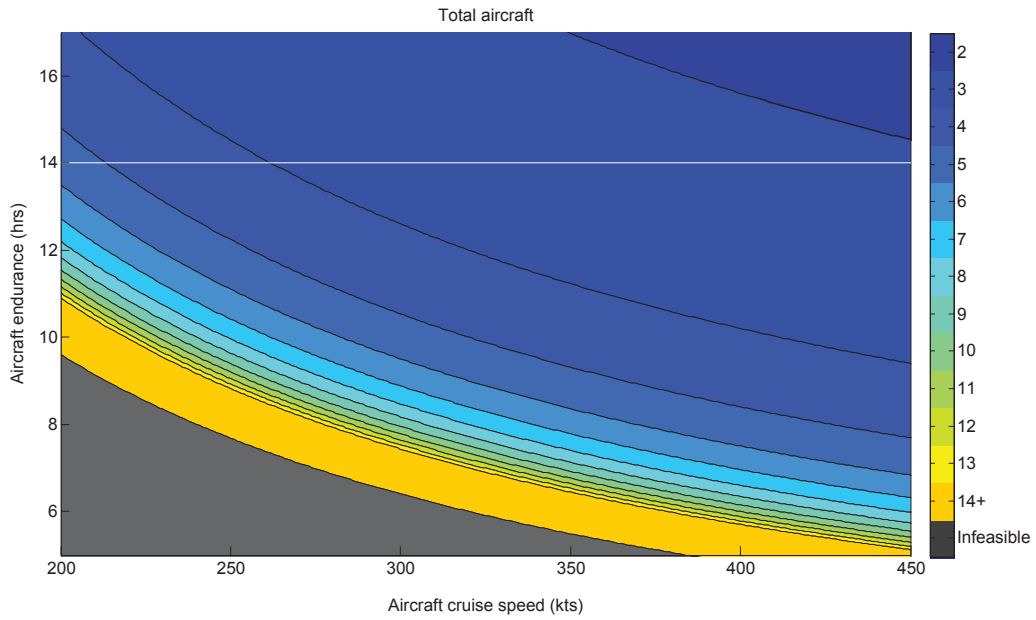
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Annex A: Additional Figures

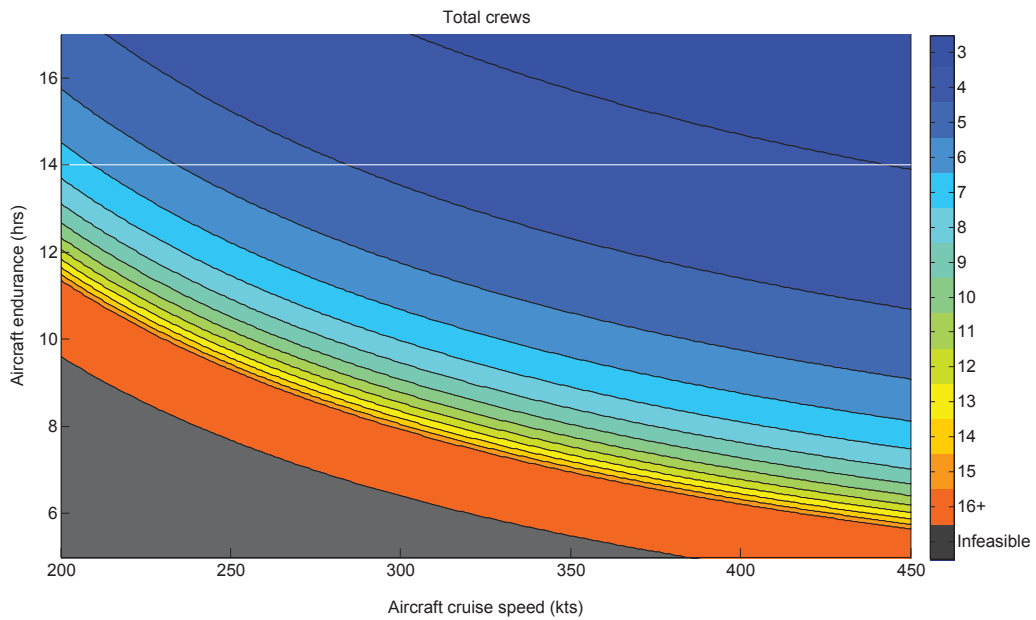
This Annex contains several additional variants of the figures presented in the main body of the report. They are presented separately here in order to help maintain the overall flow of the document.

A.1 Aircraft and crew requirements

The first set of figures shows how many aircraft and crews are needed to provide a continuous presence on the Arctic and East Coasts individually. Figure A.3 shows the requirements when these two coasts are patrolled simultaneously.

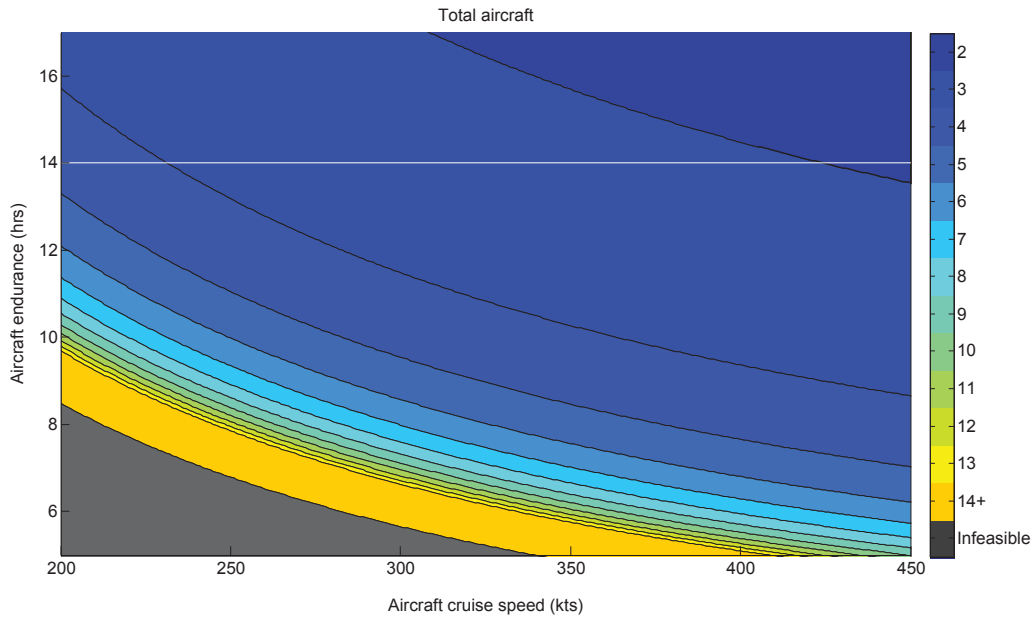


(a) Arctic – Serviceable Aircraft

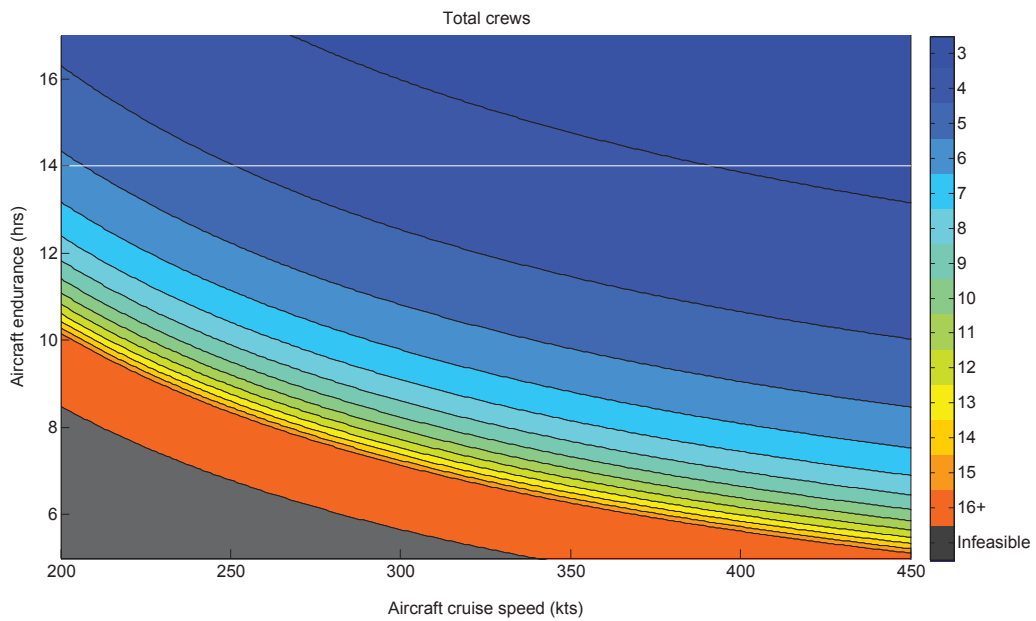


(b) Arctic – Crews

Figure A.1: Aircraft and crew requirements for the Arctic AOR.

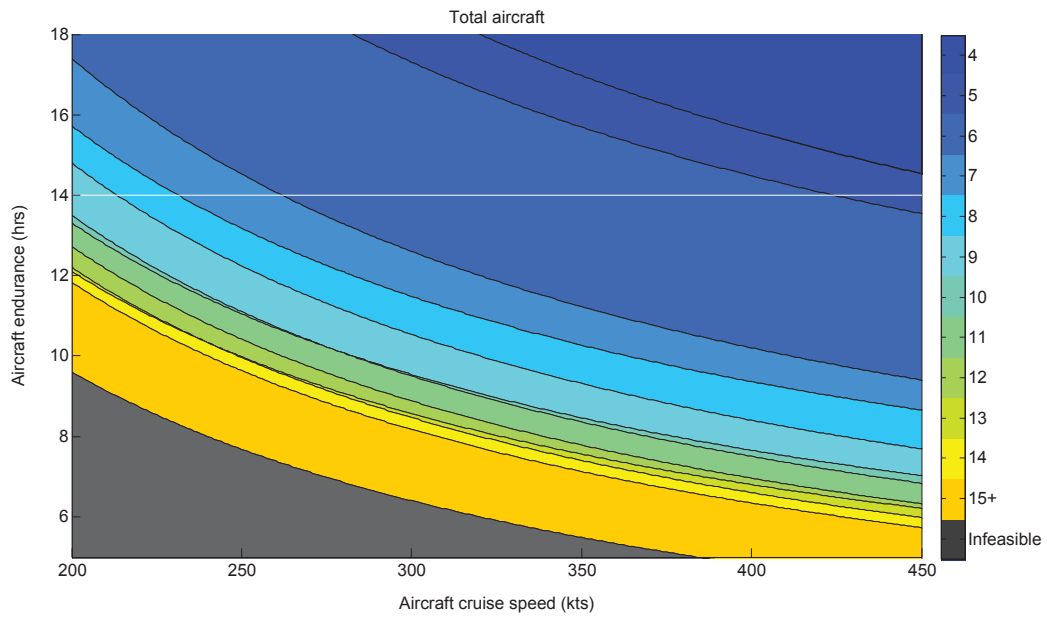


(a) East – Serviceable Aircraft

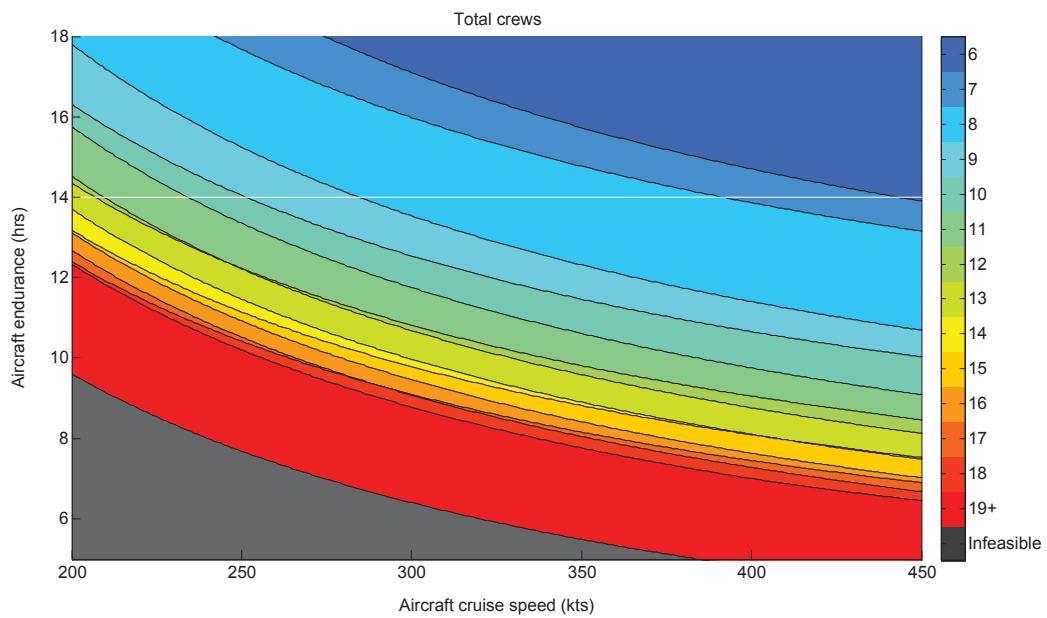


(b) East – Crews

Figure A.2: Aircraft and crew requirements for the Eastern AOR.



(a) East Coast and Arctic – Serviceable Aircraft



(b) East Coast and Arctic – Crews

Figure A.3: Combined aircraft and crew requirements for the Arctic and Eastern AORs.

A.2 Geographic context

The figures in this part of the annex present the requirements for the 'jet-powered' and 'light' aircraft in a geographical context. The requirements for both aircraft and crews are presented.

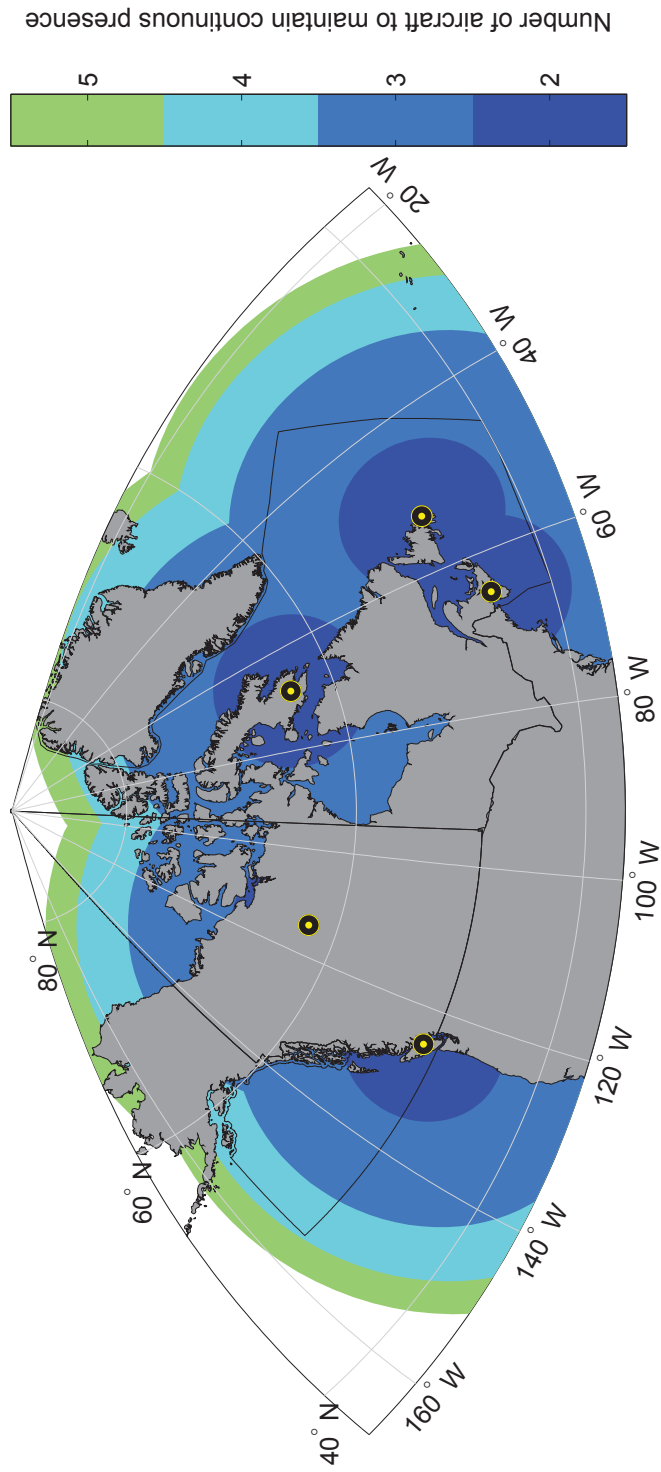


Figure A.4: Number of representative 'jet-powered' aircraft needed to maintain persistent surveillance in Canada's AOR

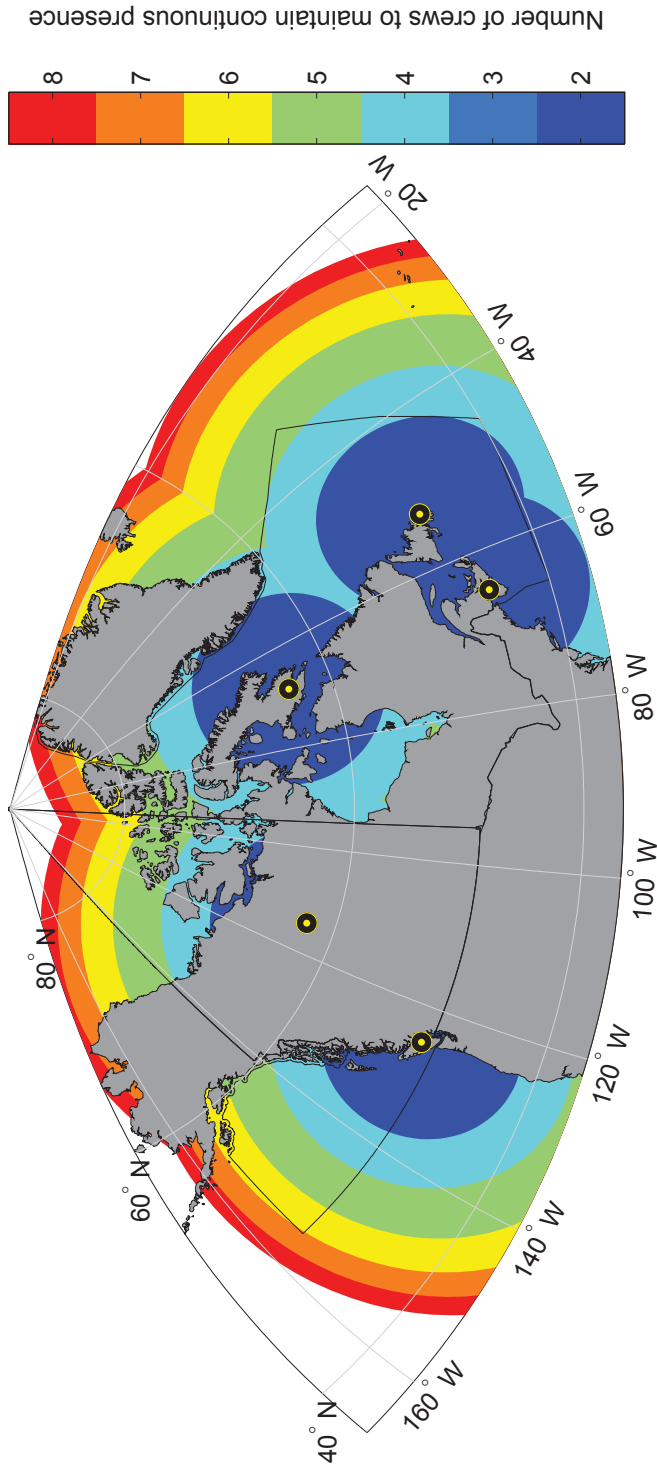


Figure A.5: Number of crews aboard a representative 'jet-powered' aircraft needed to maintain persistent surveillance in Canada's AOR

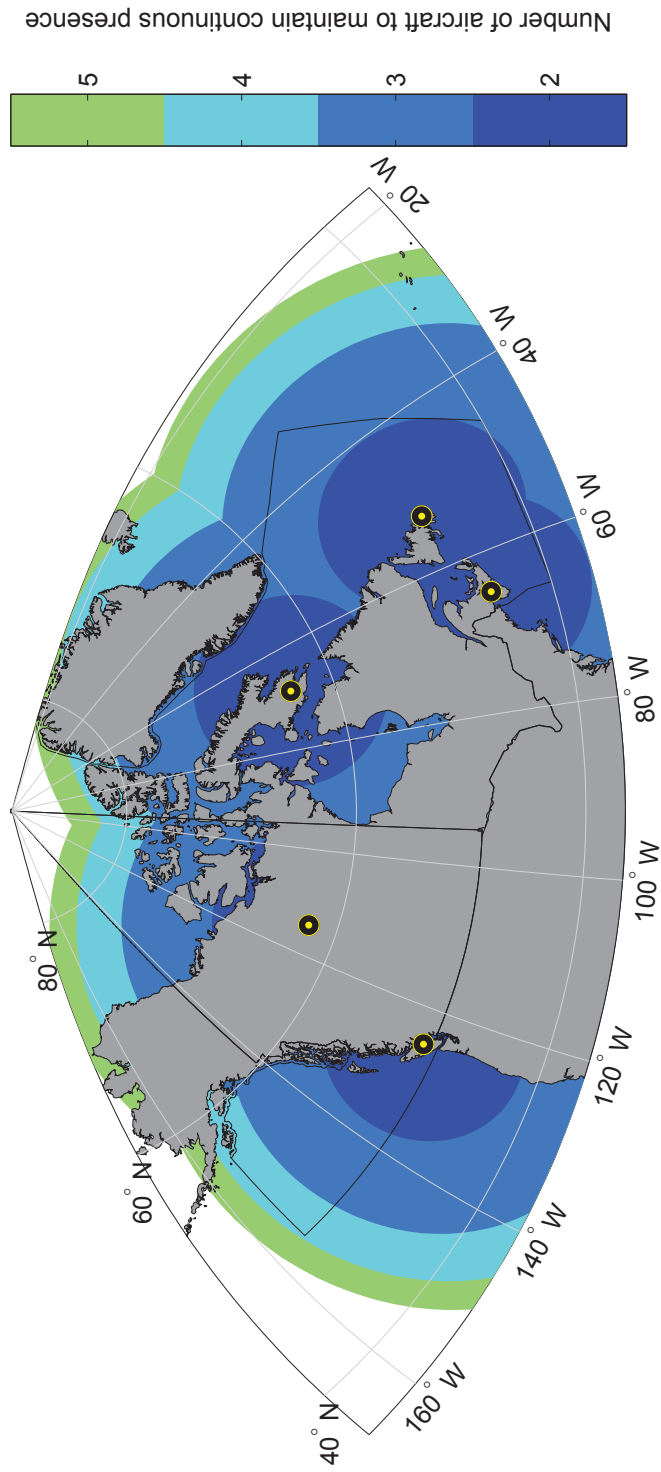


Figure A.6: Number of representative 'light' aircraft needed to maintain persistent surveillance in Canada's AOR

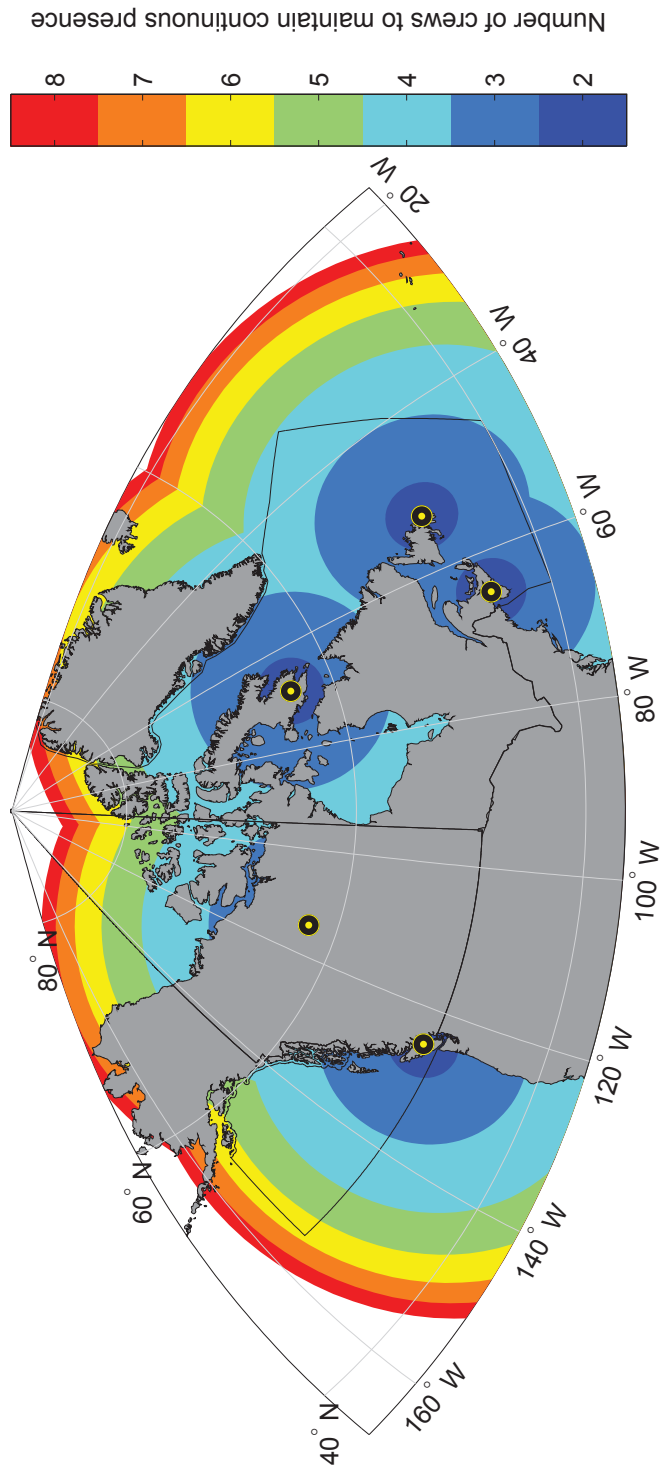


Figure A.7: Number of crews aboard a representative 'light' aircraft needed to maintain persistent surveillance in Canada's AOR

List of symbols and abbreviations

AOR	Area of Responsibility
ASuW	Anti-Surface Warfare
ASW	Anti-Submarine Warfare
CAF	Canadian Armed Forces
CFDS	<i>Canada First</i> Defence Strategy
CMA	Canadian Multi-Mission Aircraft
<i>CT</i>	Cycle Time
<i>CT_{ac}</i>	Cycle time – aircraft
<i>CT_{crew}</i>	Cycle time – crew
<i>D</i>	Distance
DAR	Directorate of Aerospace Requirements
DASOR	Directorate of Air Staff Operational Research
DMGOR	Directorate of Materiel Group Operational Research
<i>E</i>	Endurance
EEZ	Exclusive Economic Zone
FOB	Forward Operating Base
FWSAR	Fixed Wing SAR
MOB	Main Operating Base
MPA	Maritime Patrol Aircraft
RCAF	Royal Canadian Air Force
<i>S</i>	Speed
SAR	Search and Rescue
SME	Subject Matter Expert
SOI	Statement of Operating Intent
SOR	Statement of Operational Requirement
<i>TOS</i>	Time on Station

TOS_D	Time on Station at D nmi
TT	Transit Time
UAV	Unmanned Aerial Vehicle
VOI	Vessel of Interest

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1. ORIGINATOR (The name and address of the organization preparing the document. Organizations for whom the document was prepared, e.g. Centre sponsoring a contractor's report, or tasking agency, are entered in section 8.) DRDC – Centre for Operational Research and Analysis Dept. of National Defence, MGen G. R. Pearkes Bldg., 101 Colonel By Drive, 6CBS, Ottawa ON K1A 0K2, Canada		2a. SECURITY MARKING (Overall security marking of the document, including supplemental markings if applicable.) UNCLASSIFIED
		2b. CONTROLLED GOODS (NON-CONTROLLED GOODS) DMC A REVIEW: GCEC APRIL 2011
3. TITLE (The complete document title as indicated on the title page. Its classification should be indicated by the appropriate abbreviation (S, C or U) in parentheses after the title.) Determining Fleet Size for a Modernized Canadian Maritime Patrol Aircraft		
4. AUTHORS (Last name, followed by initials – ranks, titles, etc. not to be used.) Bourdon, S.; MacLeod, M. R.; McCourt, R.		
5. DATE OF PUBLICATION (Month and year of publication of document.) February 2014	6a. NO. OF PAGES (Total containing information. Include Annexes, Appendices, etc.) 50	6b. NO. OF REFS (Total cited in document.) 15
7. DESCRIPTIVE NOTES (The category of the document, e.g. technical report, technical note or memorandum. If appropriate, enter the type of report, e.g. interim, progress, summary, annual or final. Give the inclusive dates when a specific reporting period is covered.) Scientific Report		
8. SPONSORING ACTIVITY (The name of the department project office or laboratory sponsoring the research and development – include address.) Directorate of Aerospace Requirements		
9a. PROJECT OR GRANT NO. (If appropriate, the applicable research and development project or grant number under which the document was written. Please specify whether project or grant.) 13ri	9b. CONTRACT NO. (If appropriate, the applicable number under which the document was written.)	
10a. ORIGINATOR'S DOCUMENT NUMBER (The official document number by which the document is identified by the originating activity. This number must be unique to this document.) DRDC-RDDC-2014-R2	10b. OTHER DOCUMENT NO(s). (Any other numbers which may be assigned this document either by the originator or by the sponsor.)	
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The *Canada First* Defence Strategy announced that the CP-140 Aurora, Canada's long-range maritime patrol aircraft, will be replaced by a fleet of Canadian Multi-Mission Aircraft (CMA). This report details analyses provided in support of developing requirements on speed, endurance, and fleet size to enable the CMA to fulfill surveillance and patrol missions. The analysis was repeated to determine the number of Auroras that would require modernization if the acquisition of the CMA were to be delayed, as was announced in February 2014.

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CMA; Canadian Multi-Mission Aircraft; MPA; Maritime Patrol Aircraft; CP-140; Aurora; Fleet size

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