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# Determining fleet size for a Canadian maritime patrol aircraft ☆

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**Abstract.** Maintaining the ability to continuously track vessels in a maritime area of responsibility involves a mixture of factors relating to the performance of the aircraft, its sensor systems and the operators on board. This paper presents a series of simplifying assumptions and equations for considering trade-offs between three of the most important of these factors: aircraft speed, endurance and fleet size. The paper briefly presents the results obtained for a life-extended fleet of Canadian Maritime Patrol Aircraft, while also allowing the consideration of requirements for its replacement.

**Keywords:** fleet size; endurance; maritime patrol; trade-off

## Introduction

As part of their work at the Department of National Defence's Directorate of Air Staff Operational Research, the authors were asked by the Directorate of Aerospace Requirements to help develop speed and endurance requirements for the acquisition of a new fleet of 10 to 12 long-range maritime patrol aircraft as part of the *Canada First* Defence Strategy (DND, 2008). This was to be based on a proposed requirement to track



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two vessels of interest (VOIs) simultaneously off any two of Canada's three coasts. As the work progressed, a related question was also asked: if the life of the current fleet of CP-140 Aurora aircraft were to be extended, how many of them should be retained and modernized to meet the same objectives in the interim. In February 2014, the Government of Canada announced that it would proceed with the modernization and life extension of fourteen CP-140 aircraft until 2030 (TBS, 2014), in keeping with the recommendations developed by the authors (Bourdon *et al*, 2014). While this delays the need to acquire a new aircraft, the analysis presented herein will remain relevant as planning for the eventual transition continues.

While the mathematics of the problem are relatively straightforward, the constraints interact in interesting ways to create a rich set of outputs to support the recommendations. The posing of the problem is also different than that considered in previous work on determining the number of patrol aircraft required in a given situation. Often a probabilistic approach was taken to meet an objective of detecting a certain percentage of contacts, or covering a certain percentage of the area of interest over a given period (Fisher, 1993; Desmier and Roggenkamp, 2002); here a deterministic solution to continuously tracking a vessel is sought. The assumptions described below also allow the problem to be reduced to coverage of a single, worst-case point in steady-state, obviating the need to search for an optimal crew roster as in e.g. (Asiedu, 2010), or to optimize the patrol schedule for a given vessel approach pattern as in e.g. (Bocquet, 2009; Carson and Caron, 2010). Similar basic equations were used in an Australian study (Bocquet, 2009; Bocquet and Tri, 2009), but the analysis diverged in that three specific and known aircraft were compared and the required fleet size of each determined, rather than deriving the requirements that any competitor could propose a solution to meet; they then moved on to consider the impact of distance to home station on the classic area search and barrier patrol problems (Morse and Kimball, 1959; Koopman, 1980). The defining characteristics of the problem defined by the authors will be outlined below.

## Assumptions, Givens, and Implications

The general approach taken was 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 were 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: 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 herein will not be able to meet the most challenging circumstances even if all serviceable aircraft were dedicated to purely domestic operations.

In order to render the analysis tractable, 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 (numbered for ease of reference, not due to priority):

1. The remit from 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 coastal areas of responsibility (AORs).
2. The mission always takes place entirely within Canada's maritime AOR (see black outline in Figure 1). A vessel transiting this zone at regular speeds may easily spend many days within the AOR.
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 Canada's 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 so that the handover is complete just as the current on-station aircraft leaves and the new aircraft arrives.
5. Fuel consumption is close to uniform throughout all phases of flight. This means than an hour of transit time can be traded off against an hour on station. This assumption was found to be reasonable when checked against aircraft performance models in a similar study done in Australia (Bocquet, 2009).
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 two main operating bases (MOBs) in Comox, British Columbia and Greenwood, Nova Scotia, the aircraft and their crews can avail themselves of three forward operating bases (FOBs): Iqaluit, Nunavut; St. John's, Newfoundland and Labrador; and Yellowknife, Northwest Territories (see dots in 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 VOI moves closer to a different FOB are not considered.
8. Solutions requiring more than sixteen crews were considered inadmissible by the client.
9. The client requested that 50% of the aircraft be considered serviceable at any given time when calculating overall fleet size for the CP-140 Aurora. 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 or other duty would be reallocated to meet the demand.

These assumptions and givens have several important implications for the analysis, specifically:

1. Due to Assumption 1, a probabilistic, reconnaissance type approach to coverage is not appropriate, as mentioned in the background section.

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: they apply to any mission wherein 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, and a closed form solution can be calculated. The worst-case distances used are as shown in Table 1. 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 client 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. 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 VOI will be known. Therefore, it is not in general appropriate to try to optimize the patrol schedule for a specific route. 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.

## Method

The calculations described here are relatively straightforward, but some 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. 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 from its base to the location being surveilled. 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).

**Cycle Time** (*CT*) – 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.

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:

$$E = 2 \times TT + TOS = \frac{2D}{S} + TOS,$$

We know move on to the main issue, calculating the number of crews and aircraft required to maintain a continuous rotation at a given distance 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 cycle 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:

$$n \times TOS \geq 2 \times TT + CT.$$

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:

$$N \geq \frac{2 \times TT + CT}{TOS} + 1,$$

which is to say that:

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

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.

Flight crews are required to rest a minimum of 12 hours between crew days (1 Canadian Air Division, 1999). Considering a fixed one-hour debrief and a two-hour pre-flight brief, a $CT_{crew}$ of 15 hours was used. Subject matter experts approximated the aircraft cycle time ($CT_{ac}$) to be 6 hours. 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.

## Results

The surveillance requirement was assessed along each of Canada's three coasts. Given the assumptions above, to cover the entire AOR requires an aircraft that is capable of remaining on station for a sufficient amount of time at a distance of 848 nmi from St. John's, a distance of approximately 960 nmi from Yellowknife, and 1178 nmi from Comox. The CP-140 Aurora is capable of cruising at approximately 350 knots providing 6 hours on station at 1000 nmi from its launch point (an endurance of approximately 11.5-12 hours). Using the previously defined equations, this translates into the fleet size requirements shown in Table 1 below. The table also shows the total number of aircraft needed to fulfill the requirement assuming a serviceability rate of approximately 50% as well as the number of crews needed to maintain a constant rotation given crew duty day constraints.

**Table 1.** Fleet size requirements for Canada's three coasts (assuming 50% serviceability)

| *Surveillance scenario* | *Maximum distance (nmi)* | *Serviceable aircraft required* | *Total aircraft required* | *Crews required* |
|---|---|---|---|---|
| East Coast | 848 | 3 | 6 | 4 |
| West Coast | 1178 | 4 | 8 | 6 |
| Arctic | 960 | 3 | 6 | 5 |

From the table, it is easy to see that with an assumed serviceability of 50%, at least fourteen aircraft are required in order to maintain continuous surveillance on any combination of two coasts simultaneously. Furthermore, a maximum of eleven crews are needed to sustain this coverage, provided they are used in an optimal fashion. Note that the results presented here are contingent upon all of the identified aircraft being available to the assigned task. If additional aircraft are needed for an operational training unit or are undergoing scheduled maintenance, then these aircraft requirements go over and above those identified in this paper.

Using the equations above, it is straightforward to identify the range of distances for which a given number of aircraft (or crews) can provide a continuous on-station presence. Figure 1 shows these distances relative to the MOBs and FOBs used during this analysis. As such, it serves to not only confirm the results of Table 1 but also to show how robust these solutions are. This is important when it comes to attempting to apply this report's results to a real-world setting where aircraft performance is degraded for any number of reasons, such as inclement weather.

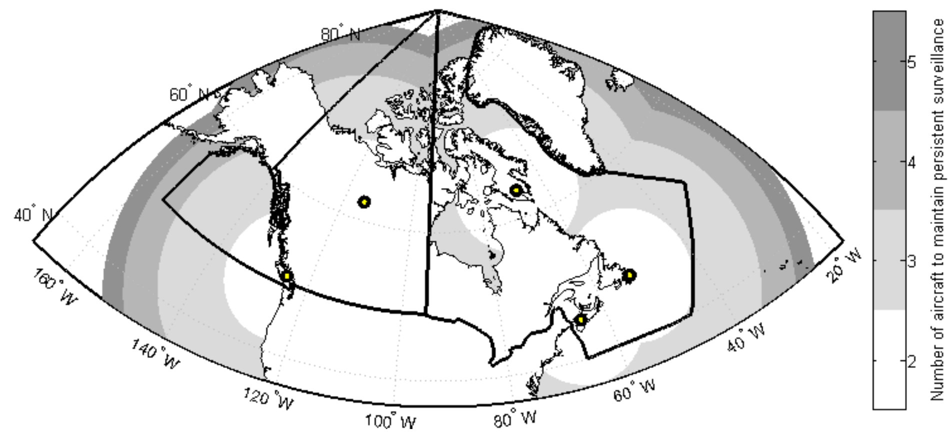


**Fig. 1.** Number of serviceable CP-140 Aurora aircraft required to cover Canada's maritime AOR.

To better understand both the sensitivity of this solution to variations in speed and endurance – and to understand the general problem of trading off endurance and speed for a maritime patrol aircraft – the authors generated several plots of the form in Figure 2, the interpretation of which will be briefly described. At and 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. These charts can also be generated for crew requirements, but three is the lowest feasible number: the required rest period combined with briefing time is longer than the maximum duty day, so 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 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 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. Charts combining two coasts at once were also produced to answer the initial question, and can be found in (Bourdon *et al*, 2014).

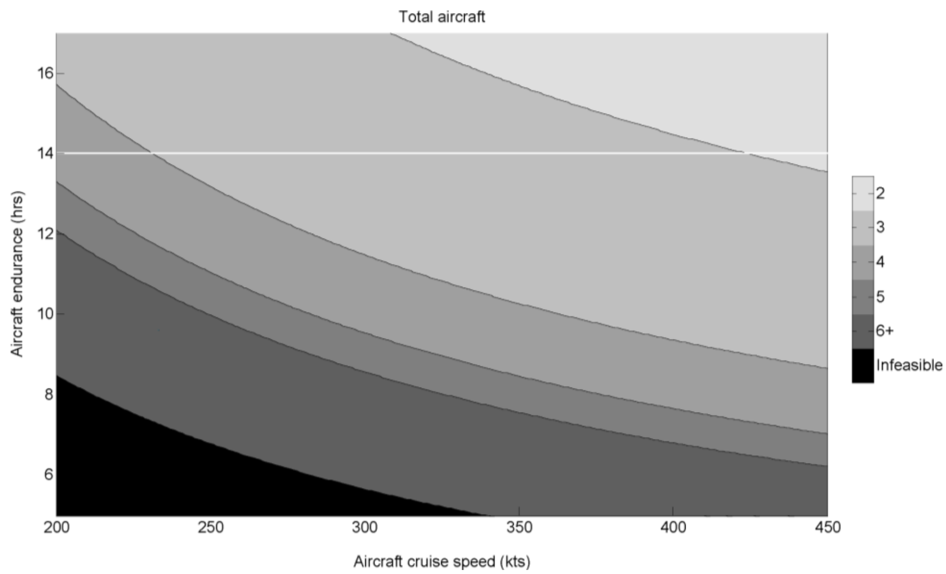


**Fig. 2.** Aircraft requirements for the East Coast AOR.

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