Estimating the required number of security cameras for the Afghan National Police Academy: *An application of the Terrain Guarding Problem*

Gerald Woodill
DRDC CORA

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Abstract

In 2012, the Afghan National Police Academy (ANPA) requested of the NATO Training Mission – Afghanistan (NTM-A) the funds to provide and install security cameras for the Kabul campus. The Deputy Commander – Police (DCOM-P) had no basis on which to estimate the cost of granting such a request and a study was conducted to provide an estimate of the required number of cameras. This request was similar to a museum guarding problem or its variant the Terrain guarding problem. Seven estimates were developed using Chvàtal's theorem, five others identified using Ghosh's formulae, and one manually compiled from an engineer's drawing of the compound. Two problems were identified for Chvàtal's and Ghosh's theorems. None of them were identified as useful for a combination of vertex, edge and point guards and they did not consider the effects of curved edges instead of straight lines and vertices. While the theorems were intended to provide an upper bound on the estimate of the minimum number of cameras required to monitor the compound, when compared to the estimate developed using a manual procedure applied to an engineer's drawing, they were found to be overestimating by a minimum of 29% and a maximum of 196%. These were considered undesirable for the purpose of estimating the potential cost of a contract. The estimate developed using the manual method was provided to DCOM-P as insight into the decision to be made.

Résumé

En 2012, l'Académie de Police Nationale Afghane a demandé à la Mission de formation de l'OTAN en Afghanistan (MFO-A) les fonds pour fournir et installer des caméras de sécurité au camp de Kaboul. Le commandant adjoint – Police ne disposait pas des bases lui permettant d'estimer les coûts liés à l'acceptation d'une telle requête et une étude a été réalisée dans le but de fournir une estimation du nombre de caméras nécessaires. Cette requête était semblable à un problème de surveillance de musée ou à sa variante, le problème de surveillance de milieu. Sept estimations ont été élaborées selon le théorème de Chvàtal, cinq autres ont été indiquées par celui de Ghosh et une a été compilée de façon manuelle à partir des dessins d'un technicien du complexe. Deux problèmes ont été cernés dans les théorèmes de Chvàtal et de Ghosh. Aucun d'eux ne s'est avéré utile à cause d'une combinaison de sommets, d'arêtes et de points vitaux et du fait qu'ils n'envisageaient pas les effets des bords recourbés au lieu de lignes droites et de sommets. En comparaison avec l'estimation développée en utilisant la méthode manuelle appliquée aux dessins d'un technicien, on a découvert que ces théorèmes surestimaient d'au minimum 29 % et d'au maximum 196 % le nombre minimum de caméras requises pour surveiller le complexe alors qu'ils visaient à en donner une limite supérieure. Ces théorèmes ont donc été jugés inappropriés en vue de l'estimation des coûts potentiels d'un contrat. L'estimation obtenue à partir de la méthode manuelle a été fournie au commandant adjoint – Police comme aperçu pour la décision à prendre.

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Executive summary

Estimating the Number of Security Cameras at the Afghan National Police Academy: An Application of the Terrain Guarding Problem

Gerald Woodill; DRDC CORA TM 2013-237; Defence R&D Canada – CORA; December, 2013.

Introduction or background: In 2012, the Afghan National Police Academy (ANPA) requested of the NATO Training Mission – Afghanistan (NTM-A) the funds to provide and install security cameras for the Kabul campus. The Deputy Commander – Police (DCOM-P) had no basis on which to estimate the cost of granting such a request and a study was conducted to provide an estimate of the required number of cameras. This request was similar to a museum guarding problem or its variant the Terrain Guarding problem. Seven estimates were developed using Chvàtal's theorem, five others identified using Ghosh and one manually developed from an engineer's drawing of the compound.

This study was completed while the author was deployed in support of NTM-A, and therefore a timely resolution and recommendation was required.

Results: All of the theorems were found to severely overestimate the upper bound of the estimated minimum number of cameras required to monitor the compound as compared to the estimate developed from the drawing. The estimate developed from the drawing was provided to DCOM-P as insight into the decision to be made.

Significance: This study compared six theorems to a manual method of estimating the number of camera positions for an exterior compound. The theorems were insufficient in their stated capability to account for a mix of guard types, could not effectively include curved edges and provided very high upper bounds for the estimated minimum number of cameras.

Future plans: The manually derived estimate was presented to the Director Training Operations, DCOM-P and no further work was expected from this study.

Sommaire

Estimating the Number of Security Cameras at the Afghan National Police Academy: An Application of the Terrain Guarding Problem

Gerald Woodill; RDDC CARO TM 2013-237 ; R & D pour la défense Canada – CARO; décembre 2013 .

Introduction ou contexte : En 2012, l'Académie de Police Nationale Afghane a demandé à la Mission de formation de l'OTAN en Afghanistan (MFO-A) les fonds pour fournir et installer des caméras de sécurité au camp de Kaboul. Le commandant adjoint – Police ne disposait pas des bases lui permettant d'estimer les coûts liés à l'acceptation d'une telle requête et une étude a été réalisée dans le but de fournir une estimation du nombre de caméras nécessaires. Cette requête était semblable à un problème de surveillance de musée ou à sa variante, le problème de surveillance de milieu. Sept estimations ont été développées selon le théorème de Chvàtal, cinq autres ont été identifiées par celui de Ghosh et une a été compilée de façon manuelle à partir des dessins d'un technicien du complexe.

Cette étude a été complétée alors que l'auteur était en déploiement en appui à la MFO-A, une résolution et une recommandation rapides étaient nécessaires.

Résultats : En comparaison avec l'estimation développée en utilisant les dessins, tous les théorèmes se sont avérés surestimer largement la limite supérieure du nombre minimum de caméras requises pour surveiller le complexe. Les estimations obtenues à partir des dessins ont été fournies au commandant adjoint – Police comme aperçu pour la décision à prendre

Importance : Cette étude a comparé six théorèmes à une méthode manuelle d'estimation du nombre de positions de caméras dans un complexe extérieur. Les théorèmes se sont avérés insuffisants dans leur capacité à justifier les divers types de points vitaux nécessaires, ne pouvaient pas efficacement prendre en compte les bords recourbés et surestimaient de beaucoup la limite supérieure du nombre minimum de caméras requises.

Plans futurs : L'estimation de la méthode manuelle a été présentée au directeur — Opérations d'instruction, commandant adjoint – Police, et aucun autre travail n'était attendu de cette étude.

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Acknowledgements

The author wishes to acknowledge the patience and sacrifice of his wife, children and extended family who had to "stand and wait" while he was deployed to Afghanistan in the service of Canada. While they received no medals nor sat under the threat of enemy fire, they too displayed courage, the best kind, the quiet kind, that endures through hardship and fear to emerge on the other side. This is for you, Joan, this is why I was there.

1 Introduction and Background

1.1 Introduction

1. In Afghanistan, the Assistant Commanding General – Police Training Group (ACG-PTG) was under Deputy Commanding General – Police (DCOM-P) which was part of the NATO Training Mission – Afghanistan (NTM-A). The objective of NTM-A was to build and train the Afghan National Security Forces to the point where they provided the security that the people of Afghanistan need to progress and the Government of the Islamic Republic of Afghanistan required to survive in the midst of a tough and persistent insurgency.

2. One of the challenges asked of the operational analyst supporting the mission was to provide an estimate of the surveillance requirements of the Afghan National Police Academy (ANPA).

1.2 Background

3. The ANPA was first established in 1948 and was the site for training officers of the Afghan National Police. It was located in Kabul on a site that totals 109,050 square meters. The overall site was best described as having an irregular polygonal shape. The facility was housed in 12 large buildings of rectangular, square, "L" and irregular polygonal shapes plus 30 smaller structures. The site had numerous evergreen and deciduous trees of different heights and density as well as open areas such as a soccer field, pool area, parade grounds, roadways and parking lots. Security was provided by a variable height wall surrounding the complex which also had 11 guard towers along the perimeter to provide over watch of the immediate surroundings and into the compound. Figure 1 provides a Google Maps© aerial view of the ANPA compound with the outer wall highlighted in red. The white building, located in the gap, enclosed the main entrance to the compound. The photo was dated 2009 but was thought to be much older than that. The trees that are visible are evergreens and there are many large deciduous trees on the property. It was believed the photo was taken during the winter when deciduous trees were bare and did not stand out.

Figure 1: The ANPA compound

4. There were a number of encroachments on the facility. The most concern was caused by a large area of private property to the west, south-west and north-west on which newer, larger houses were soon to be built. Some of these houses were to be within a few feet of the wall. To the northeast was a bazaar. Also to the northeast was some more private property which was also at a higher elevation and therefore had the ability to look down into the compound. This encroachment created dead ground[1] and could afford shelter for anyone intent on approaching and or attacking the compound. The irregular shape of the walls also created external dead ground for the guards in the towers. Due to the sizes, shapes and distribution of the buildings and trees the site had a large amount of dead ground inside the compound which were not visible to the guards in the towers. These afforded opportunities for unauthorized personnel to hide or for unauthorised activity to occur.

5. The wall enclosing the compound was considered inadequate as in some places it was easily scaled from outside and provided no protection from sniper fire. Existing towers were being renovated to increase their height and a new one was under construction. The current towers were to remain as rest areas for the guards.

[1] "Dead ground" is ground that cannot be observed from a specific location due to changes in elevation, blocking terrain or structures.

6. ANPA proposed to install security cameras (likely Pan-Tilt-Zoom (PTZ) with infrared capability) that would allow the guards to see into and monitor the dead ground within and outside of the compound as well as to continuously monitor the ingress and egress points for the compound. The number and type of monitors as well as their location had not been determined. Monitors could be located in a central control room, in the towers, at the gates or a combination of all three. Recording facilities for the camera feeds were also required. An English version of the request is presented at Annex A.

7. Unfortunately, the original request was not entirely clear. Were the cameras intended to only survey the exterior, the interior or both? The lowest cost option would seem to be to scan the exterior of the compound however the more effective security gained from additional coverage of those areas inside the compound that the guards could not already see might be worth the additional cost. Were an intruder to breach the walls, they would find many locations within the compound in which to remain unobserved from the guards in the towers. Security cameras within the compound could greatly assist security forces trying to find unauthorized persons in order to limit the damage they could perpetrate.

8. There were four questions to be answered before the request could be satisfactorily considered. How many cameras were required to provide:

   a. 100% coverage of the areas immediately adjacent to the external walls?

   b. 100% coverage of the interior of the ANPA Compound?

   c. Coverage of only the choke points or important areas of the interior of the compound?

   d. Coverage of only the areas around the building entrances?

9. The expected order of expense from highest to lowest was:

   a. 100% coverage of both interior and adjacent exterior ground (Q a. and b.)

   b. 100% coverage of interior ground (Q b.)

10. The order of expense for the remaining three options (adjacent exterior, internal choke points, building entrances) was unknown. Answering all four questions would provide five levels of budget and allow the optimization of coverage within anticipated budget constraints.

11. There had been no prior independent analysis to estimate the number and placement of the cameras. Such information would be useful to inform the budget for the project and the actual construction of the camera network. Estimating the number of cameras required before funds are committed would also allow the planners to know if the "all cameras" proposal was affordable or if some other resolution to the problem should be pursued. The purpose of this study was to provide an estimate to DCOM-P of the number of cameras required and offer suggestions to be considered if the number of cameras required caused the project to become too expensive.

12. Should the cost of the "all camera – 100% coverage" solution to the first two questions exceed acceptable amounts, other solutions in addition to exploring questions c. and d. could have included:

    a. Setting up cameras that cover only the dead transit routes between areas of dead ground.

    b. Fencing off or applying other area denial methods to locations that cannot be observed, if they serve no useful purpose.

    c. Thinning the trees and other vegetation inside and outside that created dead ground.

    d. Adding windows to existing buildings that would increase the probability of personnel being observed in current dead ground.

    e. Moving or tearing down some of the smaller structures that created dead ground.

    f. Requiring the guards to conduct sporadic foot patrols of the grounds and around the perimeter.

    g. Placing or creating high use facilities in the areas that are currently dead ground to draw authorised personnel into them and thus discourage unauthorised persons or activities.

    h. Some combination of any or all of the above.

2 The Nature of the Problem, Theory and Solutions

13. The number and placement of security personnel and apparatus within the compound is classically referred to as a "Museum Guard" or "Art Gallery" problem. An extension of this type of study that attempted to respond to more complex, external situations was referred to as a "Terrain Guard Problem". Placing security cameras on a perimeter to monitor the terrain outside of the enclosed area was a relatively straightforward exercise that was included in this report for the sake of completeness.

14. Academia has approached problems of guarding internal space as computational geometry with proposed formulas such as Chvàtal's $\lfloor n/3 \rfloor$ where n is the number of vertices in the perimeter of the area of the museum to be guarded [1]. This theorem provides the upper boundary of the estimate of the minimum number of observation points (i.e. guards or cameras) required to cover all of the area to be guarded. Another way to phrase this is the maximum number of observation points required to completely guard the area.

15. Variations on Chvàtal's theorem include art galleries with holes. These require more guards as indicated by Ghosh [2]. Others in the field of computer science who have attempted to take the problem outside have focused on how to use the speed and accuracy of a computer to solve it [3]. While progress was being made, the effort to develop a fast and accurate method of estimating the number and placement of security cameras (or any sensor network) continued. A website advertising an applet that claimed to be able to solve an art gallery problem was found in [4]. Unfortunately it could not be purchased nor downloaded to the computer network in use for this study.

16. Complicating the problem was that the facility deployed both edge and vertex guards as defined in [2], the addition of cameras could add more edge, vertex or even point guards. [2] Other alternatives that could have been considered were mobile guards. [2]

17. Further complicating the problem were several copses of trees within the compound at varying stages of growth. The trees presented an irregular shape featuring curves or innumerable small vertices depending on the scale and accuracy used to display them. The photograph in Figure 1 depicts far fewer and much smaller trees than were observed within the compound on 29 May 2012. There were also many more trees immediately outside of the walls than can be seen in Figure 1.

18. In [2] Ghosh provided the following theorems:

    a. Any polygon P with n vertices and h holes can always be guarded with $\lfloor (n+2h)/3 \rfloor$ <u>vertex</u> guards.

    b. To guard a polygon P with n vertices and h holes, $\lceil (n+h)/3 \rceil$ <u>point</u> guards are always sufficient and occasionally necessary.

c. To guard an orthogonal polygon with n vertices and h holes, $\lfloor (3n+4h+4)/16 \rfloor$ mobile guards are always sufficient and occasionally necessary.

d. To guard an orthogonal polygon with n vertices, $\lfloor (3n+4)/16 \rfloor$ mobile or edge guards are always sufficient and occasionally necessary.

e. To guard an orthogonal polygon P with n vertices and h holes, $\lfloor n/4 \rfloor$ point guards are always sufficient.

f. To guard a simple polygon with n vertices, $\lfloor n/4 \rfloor$ edge or mobile guards are always sufficient and occasionally necessary. (Note that e. and f. are effectively the same)

19. For comparison purposes the theorems were used to establish upper bounds on the estimate of the minimum number of cameras required. Note that of the five theorems presented in [2], the first three were concerned with the number of holes. The ANPA compound had 42 structures that could be considered "holes" for the purpose of this study as the guards were not required to observe into the buildings. On that basis, Table 1 displays a range of estimates generated by the equations theorized above for a range of hole and vertex counts.

Table 1: Upper bound for the estimated minimum number of guards based on polygon type, guard type, selected n and h.

Theorem	Polygon Type	Guard Type	*n*	180	200	220	240	260	280	300
			h	42	44	46	48	50	52	54
Chvàtal	Any	Vertex		60	67	73	80	87	93	100
Ghosh a	Any	Vertex		88	96	104	112	120	128	136
Ghosh b	Any	Point		74	81	89	96	103	111	118
Ghosh c	Orthogonal	Mobile		45	49	53	57	62	66	70
Ghosh d	Orthogonal	Mobile/Edge		34	38	42	45	49	53	57
Ghosh e	Orthogonal	Point or Mobile		45	50	55	60	65	70	75

20. The ANPA problem did not fit neatly into any of the six theorems. The combination of an irregularly shaped polygon and vertex, edge (and possibly point and/or mobile) guards or cameras, plus curved edges instead of straight lines indicated that any or none of the theorems might apply. Chvàtal proposes only one theorem, Ghosh is silent on how to choose between the various theorems he developed. Another concern was that the theorems were uninformative for placement of point, vertex or edge guards. It was interesting that the mobile and edge guard types estimated fewer required guards than the vertex and point types, with the exception of point types in an orthogonal polygon, which were theorized to be the same as mobile guards.

21. The theorems collectively provide a range of upper bounds for estimates of the minimum number of guards that could be compared to a manually developed estimate. At the low end of the hole and vertex counts the estimate ranged from 34 to 88 cameras while at the high end it was 57 to 136. The estimates were not uniformly distributed, there were two distinct clusters. The lower bounded cluster was derived from the orthogonal-polygon theorems while the higher bounded cluster was derived from the any-polygon theorems.

22. The objective of the study was to provide a baseline estimate for comparing bids to fulfil any contract to provide the cameras. Therefore it was desirable to obtain an estimate of the minimum number of cameras required.

23. For the purpose of this study it would appear that the orthogonal-polygon theorems would provide the more conservative estimates that would benefit a client attempting to decide on a budget for a project. However the range of the estimations within the lower bounded cluster was substantial and there was no clear indication of which was better for the current problem. For the purpose of a complete study any-polygon theorems were included as well.

24. The alternative to calculating the upper bound estimate with any of the above algorithms was for a team of people to physically examine the area or a detailed map, identify the lines of sight (LOS), where they intersect and where they were blocked, then provide an estimate of the best locations for the smallest number of sensors. This manual method was considered expensive and time consuming, with time and expense rising quickly as the size and complexity of the area to be monitored increased.

25. For this application, no computer software capable of tackling the terrain guarding problem was available nor were the necessary digital maps. Therefore the only alternatives for this problem at that time were one or more of the five theorems presented by Ghosh plus Chvàtal's $\lfloor n/3 \rfloor$ or to solve it using a map, straight edge and pencils.

26. Fortunately for this application the area to be monitored was manageable and the ground on which the complex was built was flat for the study's purpose. ANPA was actually located on a slope however the direction of the slope was continuous and therefore the ground itself did not offer any obstruction of the LOS. However to do this required some assumptions[2]:

    a. All buildings, trees and structures blocked the line of sight for the remaining distance within the compound,

    b. That the guards in the towers could not see under or through structures without walls such as canopies,

    c. That the guards in the towers could not see under or through trees and other vegetation that may form a natural canopy[3],

    d. That the guards were capable of looking down to see the base of their own tower and

[2] A walk through of the compound on 29 May 2012 confirmed that all of these assumptions were well founded.

[3] Note that assumptions b and c effectively renders the area an *x*-monotone polygonal chain.

e. That the taller towers to be built when the walls are built up are in the same locations as the current towers.

27. With these assumptions and a good map, the application of trigonometric principles could provide an estimate of the number of security cameras required to monitor the dead ground on the compound. This estimate could then be tested by comparing it to the estimates derived from the theorems and by walking the ground to determine the extent of the overestimation of LOS blockage due to the assumptions made earlier.

3 Procedure

3.1.1 Internal

28. There were two possible methods to develop an estimate for the internal cameras given the available resources. The first was to use Chvàtal's and or Ghosh's theorems after counting all of the vertices and holes within the compound. This required an up to date aerial view of the facility in order to properly account for the trees. The estimate, minus the number of towers located at vertices and along the edges provided a relatively quick and easy benchmark to compare with what was obtained by the second method.

29. The second procedure required that we first develop an estimate of the number and size of dead ground areas and began with determining what could and could not be seen from the towers. Once the number, location and size of the dead ground areas were known the next step was to determine how many cameras were required to cover them all. This heuristic was viewed as providing a practical solution to the coverage problem.

3.1.1.1 Identifying Internal Dead Ground

30. A map of sufficient scale to indicate all of the structures within the compound was obtained from an engineering firm that had drawn it in 2008. Each guard tower was marked on it.

    a. Starting with one guard tower, a ruler was used that reached the far side of the image of the compound. One end was held in place at the tower.

    b. The ruler was swung to the furthest right of arc that still crossed part of the compound

    c. Then slowly swung back toward the left. At every point where the ruler touched a structure or tree, a line was drawn along it from the contact to the farthest point in the compound that could be reached – normally (in this case) a similar obstruction or the compound wall.

    d. If the structure or tree line was parallel to the ruler a line was drawn along the structure on the side furthest from the tower

    e. Small arrows were used to indicate which side of the line was blocked from the LOS of the tower.

    f. Steps A through F were repeated for each tower.

    g. After all towers had their LOS plotted, the areas that were enclosed by the lines were the dead ground within the compound.

    h. All lines that did not form the boundary of a blind spot were erased.

31. The result of steps a. through h. is presented in Figure 2. The internal compound areas that were visible from the towers were outlined in bright green. Note that the site plan layout had three major errors; building 28 had not been built since the 2008 drawings were completed, Tower 46-12 was under construction at the North-east corner and the main gate actually features an arch over the roadway that blocks any view from the towers into the compound. The limits of the treed areas were approximate.

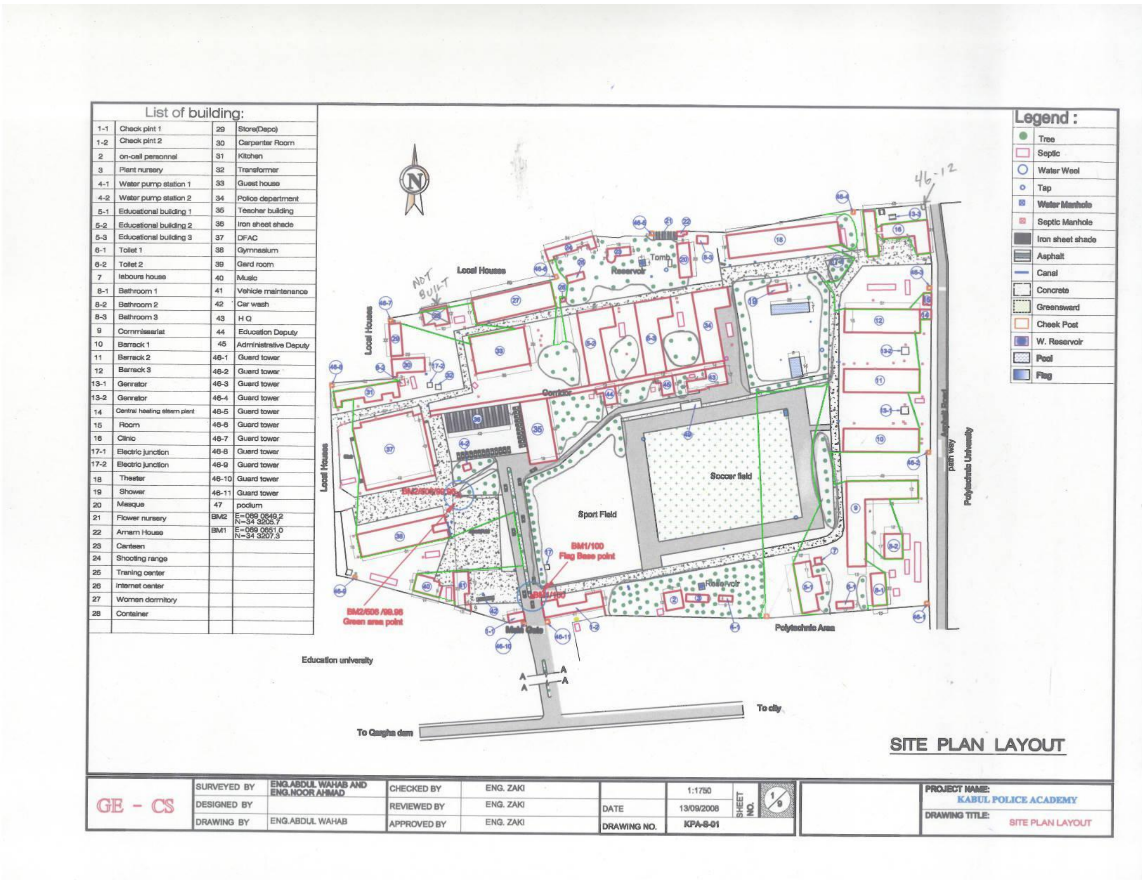

Figure 2: Areas of the ANPA compound that were visible from the towers

3.1.1.2 Estimating the Number of Cameras Required to Cover the Internal Dead Ground

32. Generating an estimate of the number of cameras required to cover the dead ground could have been influenced by the type and capability of the cameras to be installed. The angle of view (AOV) of a camera is defined by the camera's focal length and the dimensions of the sensor [5]. Using fixed-focal-length cameras introduced issues of AOV. Wide angle cameras have a limited range for producing a useful image while telephoto lenses have limited AOV. See Annex B for details on calculating AOV for different focal length and sensor dimensions. As noted above, PTZ cameras were preferred for security work for the reason that they may be remotely controlled to cover more area than a single fixed camera and also

have variable focal lengths and AOV. Another alternative was to program them to pan an area at regular intervals, with the option to direct them if needed. PTZ cameras are also the closest technology to a human guard and would most closely match estimates based on Chvàtal and Ghosh. For the purpose of this study the following procedure was used, based on the assumption that PTZ cameras would be installed.

a. A map with the LOS from the towers marked on it was used, a location on the map was chosen that provided the greatest field of view for the camera over the largest area(s) of dead ground.

b. The remaining dead ground was identified.

c. The next camera was placed such that it covered the most (or largest) remaining area(s) of dead ground.

d. Steps b. and c. were repeated until all areas of dead ground were covered.

3.1.1.3 Comparing the Seven Results

33. The total number of holes and vertices were 37 and 343 respectively. Note that the buildings that shared a wall and copses that shared an edge with the perimeter wall were not considered holes. The vertices created by these features were included in the count for the inside of the perimeter wall. Buildings within copses of trees were not counted. The numerous buildings adjacent to the corridor were counted as separate holes and the corridor was counted as 1 hole with 2 vertices, the 2 eastern vertices having been counted with the adjacent buildings.[4] Twelve stand alone copses were counted as holes; the number of vertices created by each was estimated based on the roughly equivalent polygonal shape.

34. To test the sensitivity of the result to the interpretation of the corridor and surrounding buildings, a second count was conducted in which the “iron sheet shade” (car park shelter - # 36) the corridor and buildings 5-2, 5-3, 34, 35 & 43, 44, 45 plus copses J, K & L were counted as 1 hole and only their 47 external vertices were counted. This resulted in a reduced overall total of 26 holes and 322 vertices referred to as “Count 2”. See Annex C for detailed maps.

35. The site plan layout displayed in Figure 2 served as the starting point for the camera placement. With a total of 35 cameras all dead ground was covered. The cameras were placed along edges, at vertices and on points. Adding the 35 camera positions to the 12 already existing and under construction guard towers produced a total of 47 “guards” to cover the interior of the ANPA compound. Table 2 compares the numbers of estimated guards using Chvàtal, Ghosh and the map.

36. It was readily apparent that the equations proposed by Chvàtal and Ghosh overestimated the number of guards required for an area as complex as the ANPA compound. The closest calculated estimate was 129% of the “Count 2” estimate generated using the map. While the

[4] The “corridor” was merely a covered, open air walkway that allowed people to pass between the 7 buildings adjacent to it without exposure to the sun or precipitation.

equations were (and are) intended to produce an upper limit for an estimate of the minimum number of guards required it is with some concern that the use of them for the purpose of setting a budget would allow for so many more than the actual minimum required. Subject to comparison with the cost of obtaining a more accurate estimate (see paragraph 20), any method that allows a contractor to propose and bid as high as 296% of the actual requirement adds very little value for the user.

Table 2: Comparing the estimated number of guards.

Theorem	Polygon Type	Guard Type		**Count 1**		**Count 2**	
			Vertices	**343**	**%**	**322**	**%**
			Holes	**37**	**Over**	**26**	**Over**
Chvàtal	Any	Vertex		114	243%	107	228%
Ghosh a	Any	Vertex		139	296%	124	264%
Ghosh b	Any	Point		127	270%	116	247%
Ghosh c	Orthogonal	Mobile		73	155%	67	143%
Ghosh d	Orthogonal	Mobile/Edge		64	136%	60	128%
Ghosh e	Orthogonal	Point or Mobile		85	181%	80	170%
Woodill	Complex	Vertex, Edge and Point		47		47	

37. Another potential source of human error was the vertex and hole count. To estimate how much error had to be included in the map method in order to cause the over estimation generated by the equations, the equations were reversed to calculate how many vertices and holes would generate an estimate of 47 guards. These results are displayed in Table 3. This was straightforward for the equations based solely on the number of vertices. There were many combinations of vertex and hole counts that could have produced an estimate of 47 guards. In order to proceed, the ratio of vertices to holes was kept constant. This ratio was 9.27:1 for count 1 and 12.38:1 for count 2.

Table 3: Vertex and hole counts that produce estimates of 47 guards.

Theorem	Equation	Count 1		Count 2	
		Vertices *n*	**Holes *h***	**Vertices *n***	**Holes *h***
Woodill	**Map Count**	**343**	**37**	**322**	**26**
Chvàtal	$\lfloor n/3 \rfloor$	141	n/a	141	n/a
Ghosh a	$\lfloor (n+2h)/3 \rfloor$	116	13	121	10
Ghosh b	$\lceil (n+h)/3 \rceil$	127	14	130	11
Ghosh c	$\lfloor (3n+4h+4)/16 \rfloor$	218	24	225	18
Ghosh d	$\lfloor (3n+4)/16 \rfloor$	249	n/a	249	n/a
Ghosh e	$\lfloor n/4 \rfloor$	188	n/a	188	n/a

38. The vertex and hole count would have to have been subject to major errors for that to explain the degree of overestimation of the number of guards as calculated by Chvàtal and Ghosh. In addition, the assumptions made about the number of vertices produced by the copses reduced the vertex count from what could have been a much higher number. A higher vertex count would have caused the Chvàtal and Ghosh equations to further overestimate the upper bound on the estimate of the minimum number of guards required.

39. Chvàtal and Ghosh overestimate the minimum number of guards. The performance of those algorithms for the purpose of developing a project budget was poor.

40. There has been a considerable amount of effort directed at the museum guarding problem and its related terrain guarding problem in which the focus appears to be, wisely, on the development of efficient algorithms which would use digital maps to mimic what was done in this study with a paper map, pencils and a ruler. While the world awaits that development and subject to the cost of manually developing an estimate, it would be wise to avoid depending on any one of the algorithms applied in this study to estimate the number of guards required for the purpose of developing a project budget. Given the shape of the space to be guarded, it is possible to obtain solutions using far fewer observers than the calculated upper bounds.

3.1.2 External Dead Ground

41. The external dead ground adjacent to the walls was readily identified by observation. They were documented through a series of photographs and notes that were recorded during a walking tour of the perimeter that took place on 29 May 2012.

42. Due to the fact that the land outside of the compound was owned by private citizens and organizations, the primary external area of interest was adjacent to the walls as far out as the structures and vegetation allowed the cameras or guards to see.

43. External dead ground was created by the vertices in the perimeter wall and vegetation or buildings that lie immediately adjacent to the exterior of the wall. While it was desirable to see anyone approaching the wall, it was critical to be able to see anyone within contact of it. Therefore the main area of interest was the space immediately outside (within meters of) the perimeter wall. The term immediately could not be defined more precisely due to the highly varied distances that could be observed outward from the wall.

44. It was preferable that the exterior cameras be fixed in place and focal length as it was necessary to observe all areas of interest all the time due to some very short distances from cover to the wall. Therefore fixed focal length and fixed AOV were preferred as they were less expensive than PTZ cameras.

45. There were 27 external vertices built into the exterior of the perimeter wall. Nine of them were less than 180 degrees (inside corners) when seen from the exterior. One low building outside of the compound but directly adjacent to the wall plus a copse of trees some distance along the wall away from the low building combined to create an additional blind spot that could not be observed from any of the towers.

46. Assuming the use of fixed focal length cameras with a 90 degree AOV plus one wide angle camera per position produced an estimate of either 15 positions deploying 49 cameras or 16 positions deploying 53 cameras. A position deployed either 3 or 4 cameras as depicted in Figure 3. In Figure 3 the stars mark the location of the camera cluster. Green, red and yellow areas are the fields of view for cameras 1, 2 and 3 while the shaded triangle and the shaded ¾ circle are the fields of view for the downward looking camera. The one wide angle camera for each position points downward to provide a view of the ground immediately around the position[5]. This area would otherwise be overlooked by the fixed outward looking cameras. For an along-the-wall camera position, three cameras would suffice two 90 degree AOV plus one wide angle.

[5] How wide an AOV is required depends on how high above the ground the camera position is mounted.

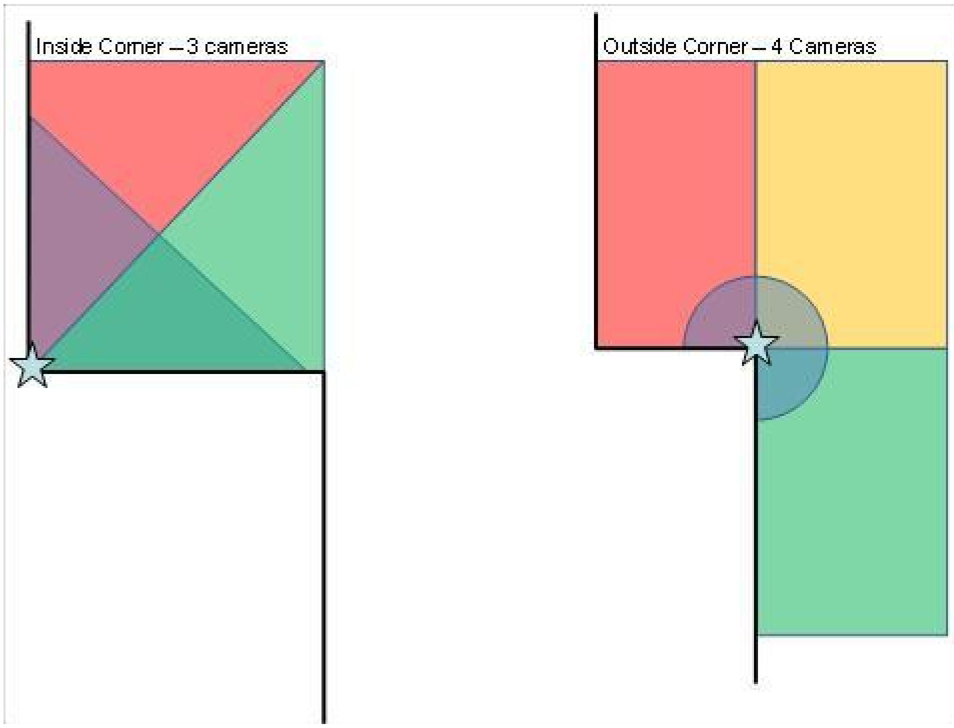

Figure 3: Camera arrangement for inside and outside corners

3.1.3 Total Cameras

47. Based on this analysis the following estimates may be used to inform the decision to proceed with the project.

48. 100% coverage of the areas immediately adjacent to the external walls may be achieved by installation of between 49 and 53 fixed cameras at 15 or 16 locations around the perimeter. Each position should have either 3 or 4 cameras depending on the field of view to be covered. A 180 degrees (or less) field of view requires 3 cameras while a greater than 180 degrees field of view (up to 270) requires 4 cameras. The cameras should have a 90 degree AOV with one wide angle[6] camera per position looking down to observe the areas beneath and outside of the AOV of the other 2 or 3.

49. 100% scheduled coverage of the interior of the ANPA Compound may be achieved by the installation of 35 PTZ cameras installed at key points within the compound. The use of PTZ cameras minimises the number of cameras and monitors while allowing a controller to view all areas on a regular basis and focus on specific areas during emergent situations.

[6] How wide an angle of view depends on the required height above ground of the camera mounts

4 Recommendations

50. Based on this study the results should be utilized as a guide for the purpose of choosing a course of action in response to the ANPA request for surveillance cameras.

51. An estimate can be developed for 100% surveillance of only the adjacent external ground, or 100% surveillance of both external and interior ground.

52. For the wider scientific audience it is recommended that where feasible, for the purpose of developing project budgets, Chvàtal's and Ghosh's theorems be tested by comparing them to an estimate derived either using a manual method as described here or computer software and digitized maps developed for the same purpose.

53. Where it is infeasible or too expensive to develop a map based estimate, the Orthogonal Polygon Type algorithms (Ghosh C, D and E) are recommended due to their production of upper bound estimates that had the least overestimation of the minimum as developed manually.

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[5] Wikipedia, http://en.wikipedia.org/wiki/Angle_of_view accessed 28 June 2012.

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Annex A The Request for Cameras

54. An English Translation of the request for cameras for the ANPA compound is presented below. The translation was provided by one of the interpreters working for DCOM-P.

Ministry of Interior Affairs
Deputy Directorate of ANPTGC
ANP-A General Department of Staff

Request	Date	Orders
To: General Department of Communication Taking care of security condition for ANP-A is very important because of training the raising of homeland children (Students). Higher rank LT General Bolger from Department of NTM-A has come to ANP-A some days ago to review the ANP-A security condition and he promised to install cameras around the ANP-A in security towers. Per the requested of the chain of command, ANP-A has prepared a request letter for the security cameras and sent this letter to the related department by their representative. LTCOL Schulman has been informed of this letter and a copy of this letter has been provided to him reference the installation of the security cameras in ANP-A. Responsible section has to order to follow up and solve the security problem based on above issue, which has been mentioned. **Sincerely** **BG Nawrooz (Khaliq)** **Commander of ANP-A**	**10/06/2012**	

Annex B Calculating Angle of View

B.1 Rectilinear Image Cameras

55. The basic equation for calculating the horizontal angle of view (AOV) in degrees for rectilinear cameras is depicted as Equation B1, Table B1 displays the results.

$$\alpha = (180/\pi) \times 2 \times \arctan(d/2f) \qquad \text{(B.1)}$$

Where:

$\pi = PI$ *(3.14159...)*

d = the horizontal length of the sensor plate (for a digital camera) or the film in mm

f = the focal length of the lens in mm

Table B.1: Angle of view (degrees) based on focal length and sensor width.

Focal Length (mm)	Horizontal Dimension (mm)				
	24	36	44	56	70
12	90.0	112.6	122.8	133.6	142.2
14	81.2	104.3	115.1	126.9	136.4
15	77.3	100.4	111.4	123.6	133.6
16	73.7	96.7	107.9	120.5	130.9
20	61.9	84.0	95.5	108.9	120.5
24	53.1	73.7	85.0	98.8	111.1
28	46.4	65.5	76.3	90.0	102.7
31	42.3	60.3	70.7	84.2	96.9
35	37.8	54.4	64.3	77.3	90.0
45	29.9	43.6	52.1	63.8	75.7
50	27.0	39.6	47.5	58.5	70.0
55	24.6	36.2	43.6	54.0	64.9
75	18.2	27.0	32.7	40.9	50.0
85	16.1	23.9	29.0	36.5	44.8
100	13.7	20.4	24.8	31.3	38.6
105	13.0	19.5	23.7	29.9	36.9
120	11.4	17.1	20.8	26.3	32.5
135	10.2	15.2	18.5	23.4	29.1
150	9.1	13.7	16.7	21.1	26.3
200	6.9	10.3	12.6	15.9	19.9
300	4.6	6.9	8.4	10.7	13.3
400	3.4	5.2	6.3	8.0	10.0
500	2.7	4.1	5.0	6.4	8.0
600	2.3	3.4	4.2	5.3	6.7
800	1.7	2.6	3.2	4.0	5.0

56. Equation B1 can be approximated for any focal length greater than 50 mm by:

$$\alpha = (180d) / (\pi f) \qquad \text{(B.2)}$$

Annex C ANPA Compound Images

57. Annex C is a separate publication. Access to Annex C is restricted to Department of National Defence only.

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List of symbols/abbreviations/acronyms/initialisms

ACG-PTG	Assistant Commanding General - Police Training Group
ANPA	Afghan National Police Academy
ANP-TGC	Afghan National Police - Training General Command
AOV	Angle of view
CORA	Center for Operational Research & Analysis
DCOM-P	Deputy Commander - Police
DND	Department of National Defence
DRDC	Defence Research & Development Canada
DRDKIM	Director Research and Development Knowledge and Information Management
LOS	Line of Sight
NTM-A	NATO Training Mission - Afghanistan
PTZ	Pan Tilt Zoom

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In 2012 the Afghan National Police Academy (ANPA) requested of the NATO Training Mission – Afghanistan (NTM-A) the funds to provide and install security cameras for the Kabul campus. The Deputy Commander – Police (DCOM-P) had no basis on which to estimate the cost of granting such a request and a study was conducted to provide an estimate of the required number of cameras. This request was similar to a museum guarding problem or its variant the Terrain guarding problem. Seven estimates were developed using Chvàtal's theorem, five others identified by Ghosh, and one manually compiled from an engineer's drawing of the compound. Two problems were identified for Chvàtal's and Ghosh's theorems. None of them were identified as useful for a combination of vertex, edge and point guards and they did not consider the effects of curved edges instead of straight lines and vertices. While the theorems were intended to provide an upper bound on the estimate of the minimum number of cameras required to monitor the compound, when compared to the estimate developed using a manual procedure applied to an engineer's drawing they were found to be overestimating by a minimum of 29% and a maximum of 196%. These were considered undesirable for the purpose of estimating the potential cost of a contract. The estimate developed using the manual method was provided to DCOM-P as insight into the decision to be made.

En 2012, l'Académie de Police Nationale Afghane a demandé à la Mission de formation de l'OTAN en Afghanistan (MFO-A) les fonds pour fournir et installer des caméras de sécurité au camp de Kaboul. Le commandant adjoint – Police ne disposait pas des bases lui permettant d'estimer les coûts liés à l'acceptation d'une telle requête et une étude a été réalisée dans le but de fournir une estimation du nombre de caméras nécessaires. Cette requête était semblable à un problème de surveillance de musée ou à sa variante, le problème de surveillance de milieu. Sept estimations ont été élaborées selon le théorème de Chvàtal, cinq autres ont été indiquées par celui de Ghosh et une a été compilée de façon manuelle à partir des dessins d'un technicien du complexe. Deux problèmes ont été cernés dans les théorèmes de Chvàtal et de Ghosh. Aucun d'eux ne s'est avéré utile à cause d'une combinaison de sommets, d'arêtes et de points vitaux et du fait qu'ils n'envisageaient pas les effets des bords recourbés au lieu de lignes droites et de sommets. En comparaison avec l'estimation développée en utilisant la méthode manuelle appliquée aux dessins d'un technicien, on a découvert que ces théorèmes surestimaient d'au minimum 29 % et d'au maximum 196 % le nombre minimum de caméras requises pour surveiller le complexe alors qu'ils visaient à en donner une limite supérieure. Ces théorèmes ont donc été jugés inappropriés en vue de l'estimation des coûts potentiels d'un contrat. L'estimation obtenue à partir de la méthode manuelle a été fournie au commandant adjoint – Police comme aperçu pour la décision à prendre.

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Operational Analysis, Support to Operations, Test of Chvàtal and Ghosh, Terrain Guarding Problem, Museum Guard Problem, Application of Chvàtal's and Ghosh's theorems, Estimating the minimum number of guards,