ADS-B Coverage Design in Mountainous Terrain

K. Wangchuk, Sangay, J. Naganawa, D. Adhikari, and K. Gayley

Abstract This paper describes an approach to the ADS-B coverage design being undertaken for the mountainous terrains of Bhutan. Existing ADS-B implementation studies have mostly focused on coverage design based on interference criteria. There is a lack of ADS-B coverage design studies in challenging terrain like in the Himalayan kingdom, where about 98% of the land cover is mountains. To account for the unique environment, a physical optics-based deterministic channel modeling methodology is adopted. A radio siting algorithm developed to determine the best location of additional ADS-B receivers is outlined. The effectiveness of the algorithm is demonstrated by applying it to determine the location of additional ADS-B receiver at PARO control zone to improve coverage in areas critical to flight operations. This study will be augmented by analysis of opportunistic ADS-B signal measurements being carried out before the ADS-B receiver network is implemented for use in air traffic management purpose.

Keywords Surveillance · ADS-B · Mountainous terrain · Coverage design · ATM · Physical optics

K. Wangchuk (✉) · K. Gayley
Air Navigation Services Section, Bhutan Civil Aviation Authority (BCAA), Paro, Bhutan
e-mail: kwangchuk@bcaa.gov.bt

K. Gayley
e-mail: kgaley@bcaa.gov.bt

Sangay
Department of Air Transport (DoAT), Communication Navigation Surveillance Section, Paro, Bhutan
e-mail: sangay@doat.gov.bt

J. Naganawa
Surveillance and Communications Department, Electronic Navigation Research Institute (ENRI), National Institute of Maritime, Port and Aviation Technology (MPAT), Tokyo, Japan
e-mail: naganawa@mpat.go.jp

D. Adhikari
Department of Communication Engineering, Vellore Institute of Technology, Vellore, India
e-mail: dadhikari@doat.gov.bt

© Springer Nature Singapore Pte Ltd. 2021

Air Traffic Management and Systems IV, Lecture Notes in Electrical Engineering 731,
https://doi.org/10.1007/978-981-33-4669-7_19

1 Introduction

More than 98% of Bhutan is mountains [1]. With elevation ranging from 97 meters to 7570 m and average elevation of 3280 m above sea level—located in the eastern end of the Himalayan mountain range—it is one of the most mountainous country in the world. Figure 1 is the obstacles chart showing the contour lines of high terrain on approach to runway 33 of Paro International Aerodrome. Due to the terrain, implementation of conventional radar-based surveillance system is only feasible for the en route phase, but not cost-effective given the low density of traffic in the airspace. On the other hand, ADS-B is an attractive and a viable solution for both En –route and Terminal Area (TMA) surveillance. The representative cost of implementing ADS-B in a TMA is lower by a factor of almost 16 compared to implementing Mode S radar for the same purpose [2]. Existing ADS-B implementation studies have mostly focused on coverage design based on interference criteria. Studies have shown that the main factor to be considered in coverage design and conversely the siting of terrestrial ADS-B receivers is interference from existing systems using the 1090 MHz frequency [3]. As such, there were no publicly available studies conducted on ADS-B coverage design in areas, where there are no existing 1090 MHz terrestrial systems, and coverage is affected primarily by the location of the receivers. In such areas, the existing 1090 MHz propagation models used are not suitable. A more robust propagation modeling methodology using terrain information for prediction of the coverage area is necessary.

This study presents an approach to ADS-B coverage design using 1090 MHz propagation channels simulated with Physical Optics (PO) based method and a radio siting algorithm developed for the purpose. Using existing communication and navigation aid station locations as initial state, the radio siting algorithm determines the best location of additional ADS-B receivers to improve coverage in the required coverage area.

The rest of the paper is organized as follows; Sect. 2 describes the coverage design requirements, and Sect. 3 discusses PO-based simulation results. The radio siting algorithm is outlined in Sect. 5, and the results of application of the algorithm is discussed in Sect. 6. The summary and future work are presented in Sect. 7.

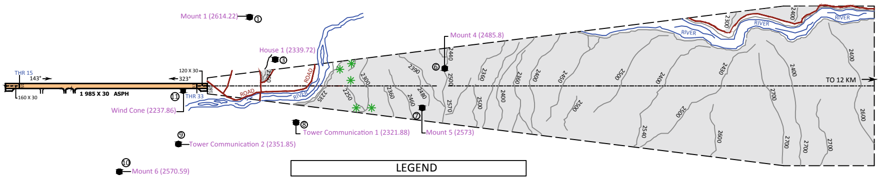

Fig. 1. Part of aerodrome obstacle chart—ICAO Type A, for areas within the PARO CTR (Reproduced with permission from department of air transport—Bhutan)

2 Coverage Design Requirements

It will take an impractically large number of ADS-B receiver stations, on the ground, to provide coverage in all the valleys in the country. This study will only target to design ADS-B coverage on the published Air Traffic Services (ATS) routes, both domestic and international, and around the aerodromes; containing the final approach phase of a flight. Figure 2 shows the Control Zones (CTR) around the four aerodromes in the country. Paro (ICAO: VQPR, PARO CTR) is the only international aerodrome. Bumthang (ICAO: VQBT, BUMT CTR), Yongphula (ICAO: VQTY, YONG CTR) and Gelephu (ICAO: VQGP, GELP CTR) are the three domestic aerodromes. Currently, the CTRs are not formally designated; it is proposed to be established soon. For this study, a volume of cylindrical airspace with a 10 NM radius from the Aerodrome Reference Point (ARP) and extending till 16,000 feet Above Ground level (AGL) is defined as the CTR. The ARP of each aerodrome is also indicated in the figure. Of the four CTRs, the ARP of three CTRs; PARO, BUMT, and YONG are at an altitude of 2580.2 m (8465.2 ft) Mean Sea Level (MSL), 2244.5 m (7363.8 ft) MSL, 2562 m (8405 ft) MSL respectively, and only GELP CTR is at 300.9 m (987.2 ft) MSL. The figure also shows the published ATS routes [4]. Bhutan has only two international routes connecting to the PRO VOR waypoint from BOGOP and SUBSU designated as routes R598 and G348, respectively. There are six RNAV 5 domestic routes (Y_1, Y_2, Y_3, Y_4, Y_5, and Y_6) connecting the various aerodromes within the country. The upper and lower limits on the international routes are 16,000 feet till Flight Level (FL) 460. For domestic routes, the upper and lower limits are defined from 18,000 feet till FL 290.

For coverage design, we set out the following requirements:

i. All areas in the CTRs containing final approach and departure path should have 100% coverage;

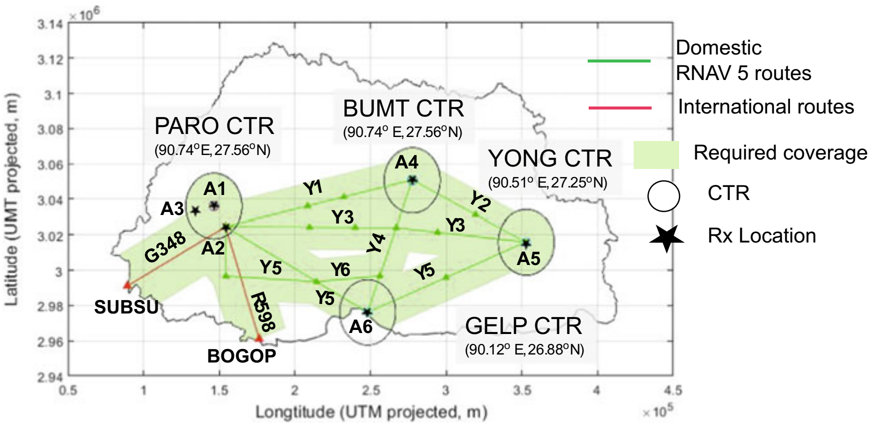

Fig. 2. Required coverage area (shaded) and ADS-B receiver locations

ii. International routes should have coverage from 16,000 feet MSL till FL 460 vertically and 10 NM on either side from the center line of the ATS track;
iii. Domestic routes should have coverage from 18,000 feet MSL till FL 290 vertically and 7 NM on either side from the center line of the ATS track.

The design problem can therefore be stated as maximizing coverage within the required coverage areas, indicated by the shaded region in Fig. 2, utilizing minimum number of receivers.

3 Physical Optics-Based Simulation

A stochastic channel model is generally preferred for use in designing mobile systems; as it captures all possible channel states. However, for a fixed terrestrial ADS-B receiver network, a deterministic channel modeling methodology that utilizes the terrain information will be more accurate. In this study, the 1090 MHz ADS-B signal propagation channel is simulated using a Physical Optics (PO) based method utilizing a 90 m resolution NASA Shuttle Radar Topographic Mission (SRTM) Digital Elevation Model (DEM).

Installing ADS-B receiver (Rx) ground stations at the existing Communication and Navigation (Com/Nav) system stations is most practical and cost-effective from implementation point of view. As an initial state, seven receiver locations coinciding with existing communication and navigation aid stations and aerodrome control towers are chosen. These Rx locations are labeled as A_1 to A_7 in Fig. 2. The coordinates of these locations are obtained from the current Aeronautical Information Publication (AIP) of Bhutan [4]. For receivers co-located with VHF radio antennas at the aerodrome control tower, an antenna height of 15 m is used. For receivers that are located at remote Com/Nav stations, antenna height of 10 m is used in the simulation. A model of a 1090 MHz vertically polarized, 9 dBi gain, omnidirectional antenna is used for simulation.

The infovista mentum planet wireless access network planning and optimization software [5], a popular simulation platform with mobile RF planners, is used to carry out the simulations. The simulator supports various access technologies and wireless propagations models; however, the most suitable propagation model supported for our purpose is the predict air model [6] that is based on physical optics and therefore deterministic in nature. It is highly dependent on the terrain information or the DEM. The simulator environment and simulation parameters used are summarized in Table 1.

In the actual simulation, the reciprocity of propagation channels is exploited. Simulation is carried out by positioning transmitter antennas at the Rx locations and calculating the received signal strength at gridded locations, of 50 m resolution. According to ICAO Annex 10 volume IV chapter 5, Table 5-1 [7], the minimum power at antenna feed for an airborne system should be 51 dBm; however, in this study, only 40 dBm power at antenna feed is used mainly to account for losses in

Table 1 Simulation environment and parameters

Simulator	Infovista mentum planet 6.3.0
Propagation model	Physical optics-based predict air
Receiver antenna coordinates	Co-located with Com/Nav antenna as per AIP Bhutan, second edition
Antenna height	10 m (Com/Nav stations), 15 m (Aerodrome control tower)
Antenna	9 dBi Omni antenna (Vertically Polarized)
Output power at antenna feed	40 dBm
Com/Nav system site coordinate and altitude	A_1 = (27.40 N, 89.42 E, 2590 m) A_2 = (27.30 N, 89.51 E, 3469 m) A_3 = (27.38 N, 89.33 E, 4095 m) A_4 = (27.57 N, 90.78 E, 3447 m) A_5 = (27.25 N, 91.51 E, 2528 m) A_6 = (26.88 N, 90.46 E, 310 m) A_7 = (27.56 N, 90.74 E, 2595 m)

signal path leading to the antenna feed. This is a very pessimistic but a practical assumption given that we expect the ADS-B antennas to be positioned at significant distances from the stations—for optimal coverage.

4 Simulation Results and Discussion

From an altitude of 16,000 feet to FL 490 on the international routes and from 18,000 feet till FL 290 on the domestic routes, the seven ADS-B receivers located at existing Com/Nav stations and aerodrome control towers provide adequate coverage on these routes. No additional ADS-B receivers are required. However, with only the seven receivers, coverage at lower altitudes is patchy and not adequate; does not cover whole of approach and departure paths. This is particularly severe within PARO CTR, where areas along the published RNP-AR approach paths does not have ADS-B coverage.

For determining coverage in the lower altitude areas in the CTR, areas with terrain higher than the altitude at which the coverage is being determined should be excluded from the coverage calculation. For instance, Fig. 1 shows the terrain on the approach path to runway 33 at Paro International Airport, within the PARO CTR. It is clear that even at an altitude of 8500 feet (2591 m) MSL, there are many areas where terrain is higher than this altitude. Therefore, for determining the area over which coverage is required at a particular altitude, areas with terrain higher than that altitude should be excluded. At 8500 feet, these areas in all the CTRs are indicated by black shaded region in Fig. 3.

From Fig. 3, we see that in PARO CTR and BUMT CTR, majority of the terrain in the CTR are above 8500 feet. The figure also shows the signal strength of the

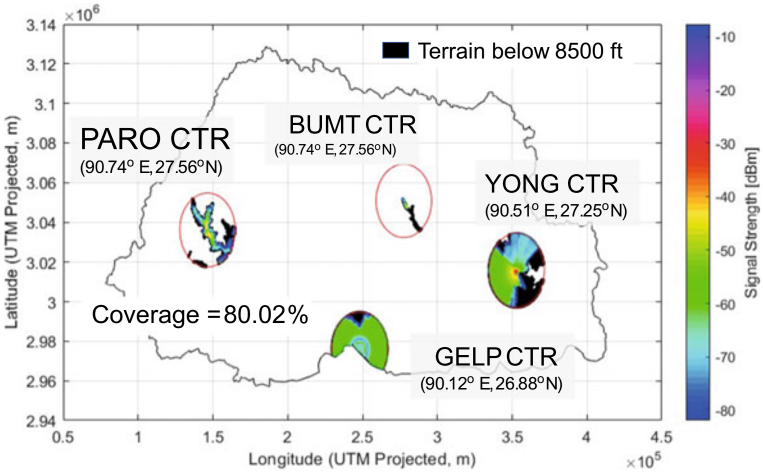

Fig. 3. Simulated signal strength within the CTRs superimposed on coverage required areas

received signal, for transmitters located at various points in the coverage area and receivers located at A_1–A_7, super imposed over the areas that require coverage. The areas appearing shaded in black in the figure are areas that require coverage but does not have coverage.

Coverage percentage P, taking into account the terrain can therefore be expressed as:

$$P = \left[1 - \frac{R}{(A - A')}\right] \times 100 \tag{1}$$

where A is the area in which coverage is required without considering the terrain; A' is the area for which the terrain is higher than the altitude at which the coverage is being determined; and R is the area within the required coverage region for which signal strength value is higher than the threshold value. For this study, −82 dBm is used as the threshold value, which is within the minimum receiver trigger threshold level defined in Annex 10 Volume IV, chapter 5, Table 5-3 [7].

Using the expression in (1), the coverage percentage at 8500 feet in Fig. 3 is found to be only 80.2%. More stations strategically located are required to fill in this coverage gap. Coverage at higher altitudes is much better, with more than 90% coverage at altitudes above 11,000 feet. It is clear that at lower altitudes within CTRs, more strategically located receivers are required to satisfy the coverage requirements.

5 Radio Siting Algorithm

A simple radio siting algorithm to determine the best location of additional ADS-B receivers to improve coverage in the required coverage area is developed. The main component of the algorithm is a ray tracer, where the number of reflections is set to zero, and strength of each rays is weighted not by the total path loss, as in conventional radio propagation ray tracing algorithms, but set to one. The algorithm finds the number of unobstructed rays, unobstructed by triangulated (using Delaunay triangulation) faces obtained from DEM point clouds, originating from the point in space, where coverage is required and directed toward the centroid of triangulated terrain faces. We then determine the centroid of the triangulated terrain face that receives the maximum power. This centroid location is, therefore, the best location for the additional receiver as it has line-of-sight to maximum number of points, where coverage is required. For simplicity of implementation, other propagation mechanisms such as reflection and diffraction are not considered in the algorithm.

Figure 4 (Left) shows the outline of the receiver siting algorithm. The most computationally intensive part of the algorithm is to determine if a ray is obstructed by the triangulated terrain faces. In order to reduce the number of triangulated terrain faces considered for the determination, only the triangulated faces whose centroids are within the cylindrical Region of Interest (RoI) of radius $\boldsymbol{r}$, and with its axis aligned along with the ray is considered. In this study, $r = 80$ m is chosen since the longest distance from vertices of the triangulated faces to their centroid is found to be 78 m.

The overall runtime of the algorithm is directly proportional to the number of rays being considered. On carefully observing the location of approach paths and departure paths from each aerodrome, particularly PARO CTR and BUMT CTR, it is seen that flights approach and departs from the aerodrome along the valley in which the runway is located. At lower altitudes coverage in valleys other than that in which the runway is located, even if the valley is situated within the CTR, is not necessary. For these aerodromes, we assume that only those triangulated terrain faces that are facing toward the valley could be the next ADS-B receiver location. In Fig. 4 (Middle and Right), the curved line segment LM is the trace of the floor of the valley, where the runway is located. Only those triangulate faces are retained, whose face

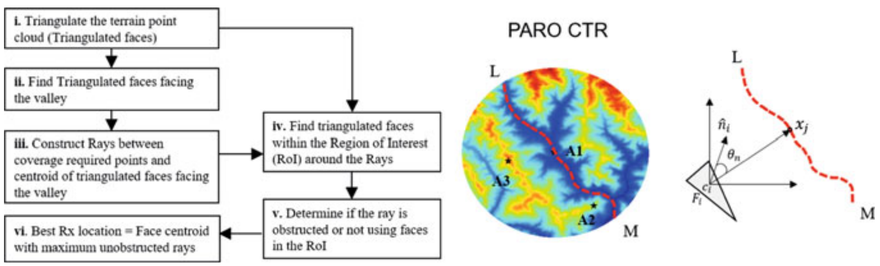

Fig. 4. (Left) Outline of the radio siting algorithm developed. (Middle) Trace of the valley in which the runway is located. (Right) Illustration of a triangulated face facing the valley

normal projected on to the XY-plane (Longitude—Latitude plane) makes an angle $\theta_n < \theta_{\text{min}}$ with the all the vectors originating at the centroid and terminating at any point on the curved line segment LM. For instance, in Fig. 4 (Right), the triangulated terrain face F_i will be retained if the angle θ_n between the vectors $\hat{\boldsymbol{n}}_i$ and $\overrightarrow{\boldsymbol{c}_i \boldsymbol{x}_j}$ is less than θ_{min} $\forall j$ and x_j located on LM; where $\boldsymbol{c_i}$ is the face centroid, $\hat{\boldsymbol{n}}_i$ is the face normal vector projected onto XY- plane, and x_j is a point on LM. This is a reasonably safe assumption as the triangulated faces with face normal facing away from the valley are located on the other side of the ridges. $\theta_{\text{min}} = 60^{\circ}$ is heuristically chosen.

To determine if the rays are obstructed by the triangular faces, whose centroid are located within the RoI, the Möller–Trumbore algorithm [8] is implemented in Matlab™. To make the algorithm runtime practical for running on a desktop computer, the number of rays is further reduced by resampling the coverage required points in space and also removing adjacent triangulated faces. The algorithm is then run separately for each CTR.

6 Coverage Improvement with Additional ADS-B Receiver Locations

For PARO CTR, additional ADS-B receiver location is necessary to cover the final phase of approach path on both ends of the runway; RWY 15 and RWY 33. These regions are marked as R1 and R2 in Fig. 5. This is also observed in the test measure-

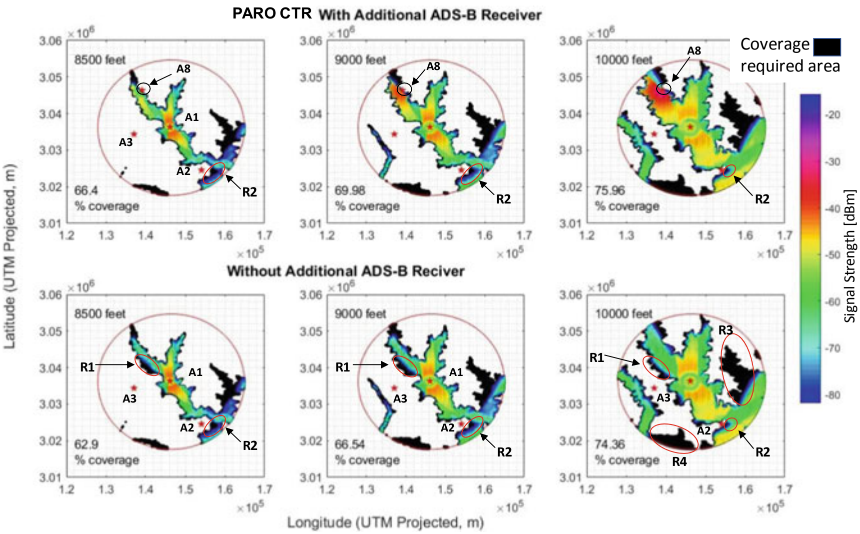

Fig. 5. Comparison of ADS-B coverage with and without additional ADS-B receiver (additional receiver location obtained from radio siting algorithm)

ments taken with ADS-B receivers implemented on a software-defined radio platform and with antennas located at A_1 and A_2 [9].

Applying the radio siting algorithm described above to PARO CTR, site A_8 was determined to be the best location for an additional ADS-B receiver in terms of line-of-sight to areas, where coverage is required. As described in Sect. 5, for simplicity of implementation, the algorithm does not take into account other propagation mechanisms such as reflection and diffraction. Figure 5 shows the improvement in coverage with the added ADS-B receiver location at various altitude for PARO CTR. At 8500 feet, there is a 3.5% improvement in coverage, 3.4% improvement at 9000 feet, and 1.6% improvement at 10,000 feet. At altitudes higher than 10,000 feet, the coverage without the additional ADS-B receiver is already more than 90%, the additional receiver improved the coverage by less than 1%. Although the percentage improvement is not significant, with the additional receiver the critical region, marked R_1 in Fig. 5, which contains the final approach phase of the flight toward runway 15 at Paro International Aerodrome, is now covered. However, there is no improvement in another critical region, marked R_2 and containing the final approach phase of flight toward runway 33 at the aerodrome. Repositioning the antenna at receiver location A_2 might be able to improve coverage in region R_2. Although the regions R_3 and R_4 contain large areas without coverage, they are not critical for actual flight operations to and from Paro International Aerodrome as these regions are located on the other side of the ridges that form the valley within which the aerodrome is located.

For BUMT and YONG CTRs, additional ADS-B receiver location is not warranted given the low number of flights currently handled and forecasted in the future. The coverage with receivers located at existing Com/Nav stations is adequate. There are also no set approach procedures for these aerodromes. Locally repositioning the antennas could be explored to improve coverage, if needed. GELP CTR will not require any additional ADS-B receiver locations; the coverage with the receiver located on the aerodrome control tower is adequate.

7 Summary and Future Work

In this paper, an approach to ADS-B coverage design using physical optics-based simulation of the 1090 MHz ADS-B frequency, and a radio siting algorithm that uses the local terrain information was presented. The approach has been developed specifically for ADS-B coverage design in the mountainous terrains of Bhutan. Using simulated 1090 MHz propagation channel and the developed radio siting algorithm, improved coverage in critical regions of flight operation has been demonstrated.

As future work, the results from this study will be compared with the results from analysis of opportunistic ADS-B measurements to improve and validate the simulated coverage. The measurement campaign using ADS-B receivers implemented on an SDR platform is already underway. The improved coverage prediction thus obtained will be used for implementation of ADS-B network in the Bhutanese airspace for ATM purposes

Acknowledgements The authors would like to acknowledge the generous support received from the Ministry of Land, Infrastructure, Transport, and Tourism—Japan to conduct a part of this study at the ENRI.

This work is also supported by JSPS KAKENHI Grant (No. 17K14688).

References

1. L. Semernya A. Ramola, B. Alfthan, Giacovelli, Waste management outlook for mountain regions: Sources and solutions. Waste Manage. Res. **35**(9), 935–939
2. ICAO, *Guidance Material on Comparison of Surveillance Technologies (GMST)*, 1st edn (ICAO 2007)
3. E. Boci, *RF Coverage Analysis Methodology as Applied to ADS-B design.* in 2009 IEEE Aerospace conference (Big Sky, MT, 2009), pp. 1–7
4. DoAT, *Aeronautical Information Publication of Bhutan*, 2nd edn (2018)
5. InfoVista Mentum Planet, https://www.infovista.com/planet/rf-planning-software
6. J.H. Whitteker, Physical optics and field-strength prediction for wireless systems. IEEE J. Selected Areas Commun. **20**(3) (2002)
7. ICAO, *Aeronautical Telecommunications Volume IV Surveillance and Collision Avoidance System,* 4th edn (2007)
8. T. Moller, B. Trumbore, fast, minimum storage ray/triangle intersection. J. Graphics Tools (1998)
9. J. Naganawa et. al., *Measurement of Opportunistic Aircraft Signals and Verification of a Propagation Prediction Tool in Mountainous Region*, submitted to EUCAP 2020