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EDITORIAL

Reviews and Responses for Modelling ADS-B Reception Probability Using OpenSky Data

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Reviewers: Vincent Lenders and Matthias Schafer

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1. Original paper

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2. Review - round 1

2.1 Reviewer 1

This paper analyzes the reception probability of ADS-B. The authors propose several models and then go on to evaluate those models using real-world ADS-B data from the OpenSky Network. While abundant research on wireless reception probability is available, it often relies on mathematical models and simulations only, while this work focuses modeling the reception probability using real world data. It thus provides an interesting avenue on the reception behavior in real-world systems. Using an extensive dataset provided by OpenSky, they manage to characterize the reception probability from 23 selected OpenSky receivers. The considered models include effects such as distance, number of aircraft, or number of airports. While the work is interesting, I have a few comments and concerns that require being addressed before acceptance Detailed feedback:

- a new figure would help at visualizing the geometry and variables from Equation 1 and 2.
- In Equation 1, alpha is not defined/described.
- The representation of Equation 5 could be improved. Some brackets are not needed and the order of the terms with A and S are not consistent over the four lines.
- The title of Section 3.2 should be revised. The model in this section is also an existing model as in Section 3.1
- In Equation 7: the Perimeter is not defined/explained
- The sensor coverage filtering in 4.1 is questionable and requires more discussion. Since you filter drastically the sensors that have "optimal" coverage, one could argue that your model is not general and over fitted. The question is on the impact of this filtering? Will the models and results of this work based on coverage filtering also generalize to other sensors as well.? You should address or at least discuss this point in the paper.
- Figure 5 needs improvement. The units of the horizontal and third dimension are missing and need to be included.

- In Fig 7, It is not clear how you compute the number of airports. This is not obvious and a definition/ more explanation needs to be provided.
- Figure 8a: It is not clear how you calibrated the models. It even seems that you did not calibrate the models as Chung's model seems to have an offset/bias. I think the results will be much better if you calibrate the models properly.
- For figure 8, it would also be good if you can elaborate on the error vs. distance. It would be interesting to have another plot showing the relation of the model error versus the distance between aircraft and sensor.
- Some aspect that is completely missing is the impact of the receiver type on the reception probability. In OpenSky, there are different receivers connected to the network (dump1030, SBS-3, Radarcape). It would be interesting to see if different receivers show different behaviors/reception probabilities. I would expect so and a probability model should therefore not ignore the receiver type entirely.
- The description of the open data at the end of the paper is minimalist. I would have expected a detailed description so that the results are easily reproducible.

2.2 Reviewer 2

This paper explores the estimation of ADS-B reception probability using data from the OpenSky network, addressing an important challenge in aviation surveillance: frequency congestion. The authors propose a model that incorporates distance and traffic density as key variables, and they validate their approach against an existing model, showing improved accuracy. The work is clear, well-structured, and enjoyable to read. While the topic is not new, it remains highly relevant given ongoing issues with frequency congestion.

The use of crowdsourced network data presents unique challenges, and the authors have handled data preprocessing in an understandable and effective way. Their methodology is well-documented, providing transparency and a foundation for future work. However, there are some aspects that could benefit from further consideration:

Limited Literature Review

The paper could engage more deeply with prior research on this well-established topic. Frequency congestion and its implications have been studied, particularly in Europe and for space-based receivers. Referencing additional works, such as [a] and [b], would provide valuable context and strengthen the foundation of the study.

Choice of Factors

The authors focus on distance and the number of aircraft as proxies for signal and interference levels, which are indeed critical variables. However, these are indirect measures of the true underlying factors which are more complex than that. Interference also depends on elements such as the number of ground-based interrogators in vicinity and their configuration (which btw do not necessarily correlate with the number of airports). Transmission rates of individual aircraft in the airspace vary significantly by region and altitude, so using the number of aircraft in range alone as a indicator for interference is not sufficient and incorporating these nuances would enhance the model's accuracy and generalizability.

Receiver Dependence

The results are likely to be specific to the set of receivers used in this study. Detection performance is strongly influenced by the degarbling capabilities of the different receiver implementations. The ADS-B specification already defines multiple degarbling performance classes (e.g. A3 for airborne equipment). For broader applicability, the model should account for this important receiver-dependent factor. Without this, the model's predictive accuracy will degrade when applied to different sets of receivers.

Overall, the paper is a meaningful contribution to understanding ADS-B reception dynamics and highlights the potential of crowdsourced data for tackling aviation challenges. Addressing the issues outlined above would further solidify the work and expand its applicability to a wider range of scenarios.

[a] https://www.ll.mit.edu/sites/default/files/publication/doc/2018-12/Orlando_1995_ATC-229_WW-15318.pdf
[b] https://www.icao.int/safety/acp/ACPWGF/FSMP-WG-F-32/FSMP-WGF32-WP17r1_Analysis%20of%20co-channel%20interference%20to%20satellite-based%20reception%20of%201090ES%20ADS-B.docx

3. Response - round 1

3.1 Response to reviewer 1

The title of Section 3.2 should be revised. The model in this section is also an existing model as in Section 3.1

Response

The naming of the model has been changed to "adapted model"

In Fig 7, It is not clear how you compute the number of airports. This is not obvious and a definition/ more explanation needs to be provided.

Response

This comment has been addressed in the revised Data Processing subsection of the paper. The updated text is as follows:

The airports considered in this research are those of medium and large airports with scheduled service. The number of airports is then determined by considering airports that are within the convex hull of the sensor coverage [a]. With the distance, traffic, and number of airports calculated, and the establishment of minimum data requirement, we can calculate the reception probability for each distance-traffic bin and perform a regression analysis.

[a] Available at https://ourairports.com/data/

The sensor coverage filtering in 4.1 is questionable and requires more discussion. Since you filter drastically the sensors that have "optimal" coverage, one could argue that your model is not general and over fitted. The question is on the impact of this filtering? Will the models and results of this work based on coverage filtering also generalize to other sensors as well.? You should address or at least discuss this point in the paper.

Response

This comment has been addressed in the revised Methods section of the paper. The updated text is as follows:

Although this filtering step reduces the generality of the model, it is essential. Without it, modeling would be nearly impossible due to the open-ended nature of the problem. Sensors with non-circular coverage have varying reception probabilities depending on the direction and distance, making it difficult to establish a consistent model. Additionally, terrain obstructions create unique coverage patterns for each sensor, further complicating generalization. Therefore, we include only sensors with circular coverage in the modeling process, ensuring that the model remains valid for receivers meeting this criterion.

Figure 8a: It is not clear how you calibrated the models. It even seems that you did not calibrate the models as Chung's model seems to have an offset/bias. I think the results will be much better if you calibrate the models properly.

Response

In the original paper, Chung's model was included without any calibration or fitting to the observed data. In the revised version, we now include a *Fitted Chung model*, which has been calibrated using the same observation data for a fair comparison. The adapted model (previously referred to as the proposed model) outperforms Chung's model, likely due to the inclusion of more tunable parameters, providing a higher degree of freedom during the fitting process.

For figure 8, it would also be good if you can elaborate on the error vs. distance. It would be interesting to have another plot showing the relation of the model error versus the distance between aircraft and sensor.

Response

This is a valid point. To address it, we now include Figure 12, which shows the reception probability error as a function of distance.

Some aspect that is completely missing is the impact of the receiver type on the reception probability. In OpenSky, there are different receivers connected to the network (dump1030, SBS-3, Radarcape). It would be interesting to see if different receivers show different behaviors/reception probabilities. I would expect so and a probability model should therefore not ignore the receiver type entirely.

Response

This is a valid point and was not addressed in the original version of the paper. In the revised version, we include Figure 9 to illustrate the effect of receiver type on reception probability. To improve the modeling accuracy, we also perform cross-validation using only data from the same receiver type. The results of this analysis are presented in Figure 11.

Minor suggestions:

- a new figure would help at visualizing the geometry and variables from Equation 1 and 2.
- In Equation 1, alpha is not defined/described.
- The representation of Equation 5 could be improved. Some brackets are not needed and the order of the terms with A and S are not consistent over the four lines.
- In Equation 7: the Perimeter is not defined/explained

- Figure 5 needs improvement. The units of the horizontal and third dimension are missing and need to be included.
- The description of the open data at the end of the paper is minimalist. I would have expected a detailed description so that the results are easily reproducible.

Response

Thank you for the detailed suggestions. We have addressed all comments mentioned above.

3.2 Response to reviewer 2

The paper could engage more deeply with prior research on this well-established topic. Frequency congestion and its implications have been studied, particularly in Europe and for space-based receivers. Referencing additional works, such as [1] and [2], would provide valuable context and strengthen the foundation of the study.

Response

Thank you for the feedback. We have included these works as references in our paper.

The key difference between our study and the cited literature is that our model is based on high-level features that influence ADS-B reception probability, such as range, traffic, and surrounding airports. These features are particularly valuable for developing air traffic management simulations. While Chung's model (as a benchmark) has been widely used for such simulations, it has only been validated at a single point. In contrast, we provide a broader validation using the open data and demonstrate that our model achieves better performance.

The authors focus on distance and the number of aircraft as proxies for signal and interference levels, which are indeed critical variables. However, these are indirect measures of the true underlying factors which are more complex than that. Interference also depends on elements such as the number of ground-based interrogators in vicinity and their configuration (which btw do not necessarily correlate with the number of airports). Transmission rates of individual aircraft in the airspace vary significantly by region and altitude, so using the number of aircraft in range alone as a indicator for interference is not sufficient and incorporating these nuances would enhance the model's accuracy and generalizability.

Response

This is indeed a very important point. We acknowledge that the high-level features, such as range, traffic, and surrounding airport, used in our model, serve only as proxies for the underlying physical factors influencing interference. These proxies do not fully capture complexities such as ground-based interrogator activity or variation in transmission rates by region and altitude. We agree that incorporating such detailed features would likely improve the model's accuracy and generalizability, and we consider this a valuable direction for future work.

The results are likely to be specific to the set of receivers used in this study. Detection performance is strongly influenced by the degarbling capabilities of the different receiver implementations. The ADS-B specification already defines multiple degarbling performance classes (e.g. A3 for airborne equipment). For broader applicability, the model should account for this important receiver-dependent factor. Without this, the model's predictive accuracy will degrade when applied to different sets of receivers.

Response

This is a valid point and was not addressed in the original version of the paper. In the revised version, we include Figure 9 to illustrate the effect of receiver type on reception probability. To improve the modeling accuracy, we also perform cross-validation using only data from the same receiver type. The results of this analysis are presented in Figure 11.

4. Review - round 2

4.1 Reviewer 1

Thanks to the authors for addressing my previous comments. The paper has improved a lot and is now in a much better shape.

Still there are some minor things that should be addressed:

- Figure 1: it is not clear from the picture if the "r" refers to the distance between aircraft and receiver or if it refers to the circle. I think it belongs to the distance between aircraft and receiver. If yes, it would be better to put the "r" above the distance dashed line to avoid confusion.
- Equation (1) does not seem correct. r cannot be the sum of two angles times the radius. Additionally, there is an equal sign missing at the beginning of the second line.
- Figure 2: You should specify for which h_r the plot is. The plot would be more interesting if you draw a few curves for different h_r
- line 120: of position data -> of received position data
- line 121: frequency congestion -> channel congestion
- line 116: It is not correct to say that ADS-B transmitters consistently transmit position messages every 0.5 seconds, since there is a random offset to the transmission update frequency.
- line 132: You write that the pattern is in line with the probability model formulated in Equ 4, but it is not clear how much in line it is. You should quantify the fitting here.
- line 156: consider model -> consider the model
- line 170: It is not clear why it is sufficient to model 1 to 5 mode A/C overlaps. You should provide an argument or a reference for this choice.
- line 180: you refer to technical specifications without saying which technical specifications you mean. You should cite the technical specifications here.
- line 253: You define circularity in Equ 7 without providing a reference. If this is a common definition of circularity, you should provide a citation.
- line 330: validate its the -> validate the
- line 384: will correcting -> will be correcting
- line 425: the the two model an Chung -> the two models and a Chung

5. Response - round 2

5.1 Response to Reviewer 1

Figure 1: It is not clear from the picture if the "r" refers to the distance between the aircraft and the receiver or if it refers to the circle. I think it belongs to the distance between aircraft and receiver. If yes, it would be better to put the "r" above the distance dashed line to avoid confusion.

Equation (1) does not seem correct. r cannot be the sum of two angles times the radius. Additionally, there is an equal sign missing at the beginning of the second line.

Response

We thank the reviewer for these helpful observations.

Regarding Figure 1, the symbol r denotes the maximum line-of-sight distance between the aircraft and the receiver, consistent with Figure 1.1 in [1]. To eliminate ambiguity, we revised the figure by renaming the label from "d" (as used in the literature) to "r" and by adding an arrow to explicitly indicate the corresponding line.

Concerning Equation (1), we reverified both mathematically and against the literature, and we confirm that the formulation is correct. To improve clarity, we have added an explicit explanation noting that both angles, α_t and α_r, are expressed in radians. We have also corrected the alignment of the equal sign in the second line of the equation to address the reviewer's formatting concern.

Figure 2: You should specify for which h_r the plot is. The plot would be more interesting if you draw a few curves for different h_r

Response

The figure has been updated to show multiple curves corresponding to different values of h_r. We also added an explanation highlighting how the receiver height affects the minimum detection altitude of the aircraft.

line 116: It is not correct to say that ADS-B transmitters consistently transmit position messages every 0.5 seconds, since there is a random offset to the transmission update frequency.

Response

We have revised the sentence to clarify that ADS-B transponders nominally transmit position messages with a period of 0.5 seconds; however, a random offset (jitter) is applied, causing the actual transmission intervals to deviate around this nominal value.

line 132: You write that the pattern is in line with the probability model formulated in Equ 4, but it is not clear how much in line it is. You should quantify the fitting here.

Response

Additional explanation has been included to quantify how closely the observed reception probability matches the formulated model, as written below.

To estimate the reception probability, we assume that the jitter causes the transmission times to deviate within the interval 0.25 to 0.75 seconds. Under this assumption, each bump in the histogram spans a fixed 0.5-second window. The reception probability is then obtained by evaluating the area of the first bump relative to the total area of the histogram. In the example of Figure **??**, this first bump constitutes 69.23% of the total, followed by the second bump at 21.3%.

For subsequent bumps, deviations become more apparent: the third bump is observed at 6.55% while the model predicts 3.80%, and the fourth at 2.02% compared to 3.39%. Similarly, the fifth and sixth bumps appear at 0.62% and 0.19% in the observation, while the theoretical values are 0.92% and 1.20%, respectively. Overall, the observation can be modeled using the geometric formulation, with good agreement in the first two bumps. Beyond the second bump, however, deviations emerge as the model underestimates the probability mass in the middle tail and slightly overestimates it in the far tail. Nonetheless, the formulation remains sufficiently accurate as an approximation of the reception probability.

line 170: It is not clear why it is sufficient to model 1 to 5 mode A/C overlaps. You should provide an argument or a reference for this choice.

Response

For line 170, the assumption to model overlaps from 1 to 5 Mode A/C follows the approach adopted in the Chung's model literature [2]. We have clarified this in the text and added an explicit explanation to make the reasoning transparent.

The first term, $d(0) \cdot P(0|m_A) \cdot P(0|m_S)$, represents the probability of message reception without interference. The second term, $\sum_{x=1}^{5} d_A(x) \cdot P(x|m_A) \cdot P(0|m_S)$, accounts for 1 to 5 Mode A/C overlaps with no Mode S interference. The third term, $d_S(1) \cdot P(1|m_S) \cdot P(0|m_A)$, considers 1 Mode S overlap without Mode A/C interference, and the final term, $\sum_{x=1}^{5} d_A(x) \cdot P(x|m_A) \cdot d_S(1) \cdot P(1|m_S)$, captures simultaneous Mode A/C and Mode S interference. **This formulation follows the assumption used in [2], and is therefore adopted here without modification.**

line 180: you refer to technical specifications without saying which technical specifications you mean. You should cite the technical specifications here.

Response

For line 180, we now cite the relevant technical specification referenced in the literature, so that the source of the assumption is clearly identified.

A key limitation of this model is that the model relies on fixed parameter values derived from technical specifications [3] and controlled test conditions rather than real-world observational data. In particular, it assumes a constant value of the reception decay exponent in the range-dependent detect/decode probability function ($d(0)$, $d_A(x)$, and $d_S(1)$), which governs how rapidly reception probability deteriorates with distance. This assumption may not hold across varying receiver types, or traffic densities. Therefore, in this paper, we treat the exponent as a free parameter and fit it empirically using large-scale data from the OpenSky network. This allows us to more accurately capture the effect of distance on reception probability based on observational data. In this paper, we call this model as Fitted-Chung Model and referring the original one as Chung Model.

line 253: You define circularity in Equ 7 without providing a reference. If this is a common definition of circularity, you should provide a citation.

Response

We have added citation for the definition of circularity which is derived from the isoperimetric inequality [4].

line 120: of position data -> of received position data

line 121: frequency congestion -> channel congestion

line 156: consider model -> consider the model

line 330: validate its the -> validate the

line 384: will correcting -> will be correcting

line 425: the the two model an Chung -> the two models and a Chung

Response

Thank you for the detailed suggestions. We have addressed all comments mentioned above.

References

[1] Junzi Sun. *The 1090 Megahertz Riddle: A Guide to Decoding Mode S and ADS-B Signals.* 2nd ed. TU Delft OPEN Publishing, 2021. ISBN: 978-94-6366-402-8. DOI: 10.34641/mg.11.

[2] William Chung and Ronald Staab. "A 1090 extended squitter automatic dependent surveillance-Broadcast (ADS-B) reception model for air-traffic-management simulations". In: *AIAA modeling and simulation technologies conference and exhibit.* 2006, p. 6614.

[3] RTCA. *Minimum Operational Performance Standards (MOPS) for 1090 MHz Extended Squitter Automatic Dependent Surveillance-Broadcast (ADS-B) and Traffic Information Services-Broadcast (TIS-B).* Tech. rep. DO-260A. RTCA, Inc., Apr. 2003.

[4] Marcel Berger. *Geometry revealed: a Jacob's ladder to modern higher geometry.* eng. Heidelberg New York: Springer, 2010. ISBN: 978-3-540-70997-8.