MADRID
inter.noise 2019
June 16 - 19
NOISE CONTROL FOR A BETTER ENVIRONMENT

Aircraft pass-by noise on ground modelled with the SAFT-program

Tengzelius, Ulf[1]
CIT - Chalmers Industriteknik
Chalmers Teknikpark 412 88 Gothenburg, Sweden

Åbom, Mats[2]
KTH-Center for Sustainable Aviation
100 44 Stockholm, Sweden

ABSTRACT

SAFT (Simulation of atmosphere and Air traffic For a quieter environmenT) is the name of a simulation tool for aircraft noise propagation that has been developed at CIT, Chalmers and KTH since the end of 2016. It is funded through CSA – Centre for Sustainable Aviation at KTH. Already in its current state SAFT enables aircraft pass-by noise estimations of several kinds. The set of computational approaches stretches from the most complex "full-simulation" ones, involving directivity, time- and frequency dependent individual (jet, fan, flaps, ...) noise sources as well as sound propagation through a refractive atmosphere, down to the more old-fashioned "integrated" computational methods such as given in ECAC doc.29. Special attention has been paid to making the tool user-friendly and fast to run. Even in the case with a refractive atmosphere model SAFT runs at rather short CPU-times thanks to a new concept of a Transmission Loss interpolation matrix. The typical result from SAFT-runs is either a noise-contour map (L_{Amax}, SEL(A) or other metric) or the noise level time history in selected ground points (for simulation computations only). Other features involves possibilities to plot ΔdB-contours from "any possible" model-, parameter- or aircraft procedure variation. E.g. comparison of results such as from ECAC doc.29 vs "full-simulation", aircraft A vs aircraft B, weather condition X vs weather Y, different absorption models, different engine, airframe or procedure modifications etc. In a planned effort noise-source data in SAFT is to be extended with measured aircraft pass-by noise, time-correlated with FDR or/and trajectory data from the Opensky database.

Keywords: sound propagation, aircraft noise simulation
I-INCE Classification of Subject Number: 24,76

[1] urte@kth.se, [2]matsabom@kth.se

1. INTRODUCTION

Aircraft noise mapping has over the last decades traditionally, and due to historical limitations in computer capacity and modelling efficiency, mostly been carried out by so-called “integrated tools” such as INM [1] and methods like ECAC doc.29 [2]. These methods, including the INM successor AEDT [3], are fulfilling the main purpose of computing long-term (typically a year) noise maps for areas around airports apparently well. However, they are lacking possibilities to model new aircraft, changed approach procedures, other configurations than “full” or weather conditions in any detail. These principal limitations, compared with more complete “simulation models” are well known facts and is also expressed within the ECAC doc.29 document itself (at least since 2005, but probably much longer back in time):

a) *“integrated models represent current best practice”* [referring to long time noise level estimates]
b) *“This situation* [i.e., that simulation methods are used also for long-term noise mapping] *may change at some point in the future: 'simulation' models have greater potential and it is only a shortage of the comprehensive data they require, and their higher demands on computing capacity, that presently restrict them to special applications (including research)."*

I.e. it is anticipated that “simulation models” in the future may be used not only as research tools, but also as replacements for “integrated methods”.

Originally SAFT was intended as a tool for single-event noise mapping (level contours) and time-histories in sample ground positions. But, after penetrating the wide topic of aircraft noise propagation in depth, we have come to the conclusion that “long-time” estimates (typically SEL or L_{Amax} contours representing a year) would be possible to achieve even for a “simulation method” of the SAFT-type. In our opinion neither computer capacity, computational methodology or individual aircraft noise-source data would constitute a principle obstacle for “simulation models” anymore. With regard to what we deem as the weakest link in the above chain, namely the noise-source data, we believe that also this part is possible to handle. With the todays more affordable computerized noise measurement equipment and e.g. the Opensky database [4], [5], covering much of the world’s flight traffic, we are able to establish statistically significant aircraft noise sources representative for different aircraft configurations, thrust settings and masses even within a rather small project budget. This means that the ANP NPD-data [6] could be extended, or in the longer term even replaced, to cover more configurations, and speeds and possibly some more aspects. In SAFT one aim is to establish a limited noise source data base for the most common aircraft types at Arlanda airport. Other trends in the development of simulation methods and extending/replacing NPD-data are found at least in Europe and in the U.S. [7], [8], [9] resp.

For the purpose of comparison, SAFT include, beside the full simulation computational paths, also an ECAC doc.29 implementation.

2. SAFT – CURRENT IMPLEMENTATION

2.1 Overview

SAFT enables a versatile toolbox for aircraft ground noise simulation. The most common application are prediction of noise contours or noise histories for aircraft passing over an area or specific observer/microphone positions. A typical run follows the path:

a) The user gives the general definition of the input data including choice of computational models, i.e. defining the sound source and noise propagation model + selection of data for atmosphere and absorption.

b) Definition and input of aircraft type, flight trajectory and ground grid (or/and specific ground points).

(- the simulation starts -)

c) Appropriate aircraft and atmosphere data is read.

d) Sound source(s) data is established as a function of time and frequency.

e) From the discrete points along the flight trajectory: sound is propagated down to the ground points. Depending on choices made by the user accounting for refraction, geometric spreading, absorption, air density (specific acoustic impedance), ground reflexion and receiver height.

f) Noise levels in each grid point is given as a function of time and frequency together with individual TL (Transmission Loss) contributions in dB of the sound intensity from source to ground given by mechanisms above.

g) Computation of noise contours and presentation of those on a map and/or plots of aircraft pass-by noise events as a function of time (and frequency if wanted. Here one may also plot the individual TL contributions as well as source directivity impact, behind the final ground noise).

h) Saving ground grid noise levels for use in later comparisons, e.g. computation of differences in noise levels, ΔdB, on ground with regard to changes of flight procedures, descent profiles, aircraft configuration and engine state during approach or modified or completely different aircraft flying the same route. The ΔdB functionality could alternatively be used do compare the noise pattern between different weather conditions, propagation or atmosphere models.

When developing SAFT, special emphasis has been placed on making the program easy and fast to use. This means that even beginners that are non-experts in aironautics or noise propagation may run standard cases such as shown in the outlined path above, and reach results and getting feedback in the order of minutes. By this user-friendly implementation of a high-end tool we think we have established a platform with the potential to bridge the gap between different disciplines and type of users.

In the current SAFT implementation the code workflow is as outlined in figure 1 below (as of SAFT 2018 version):

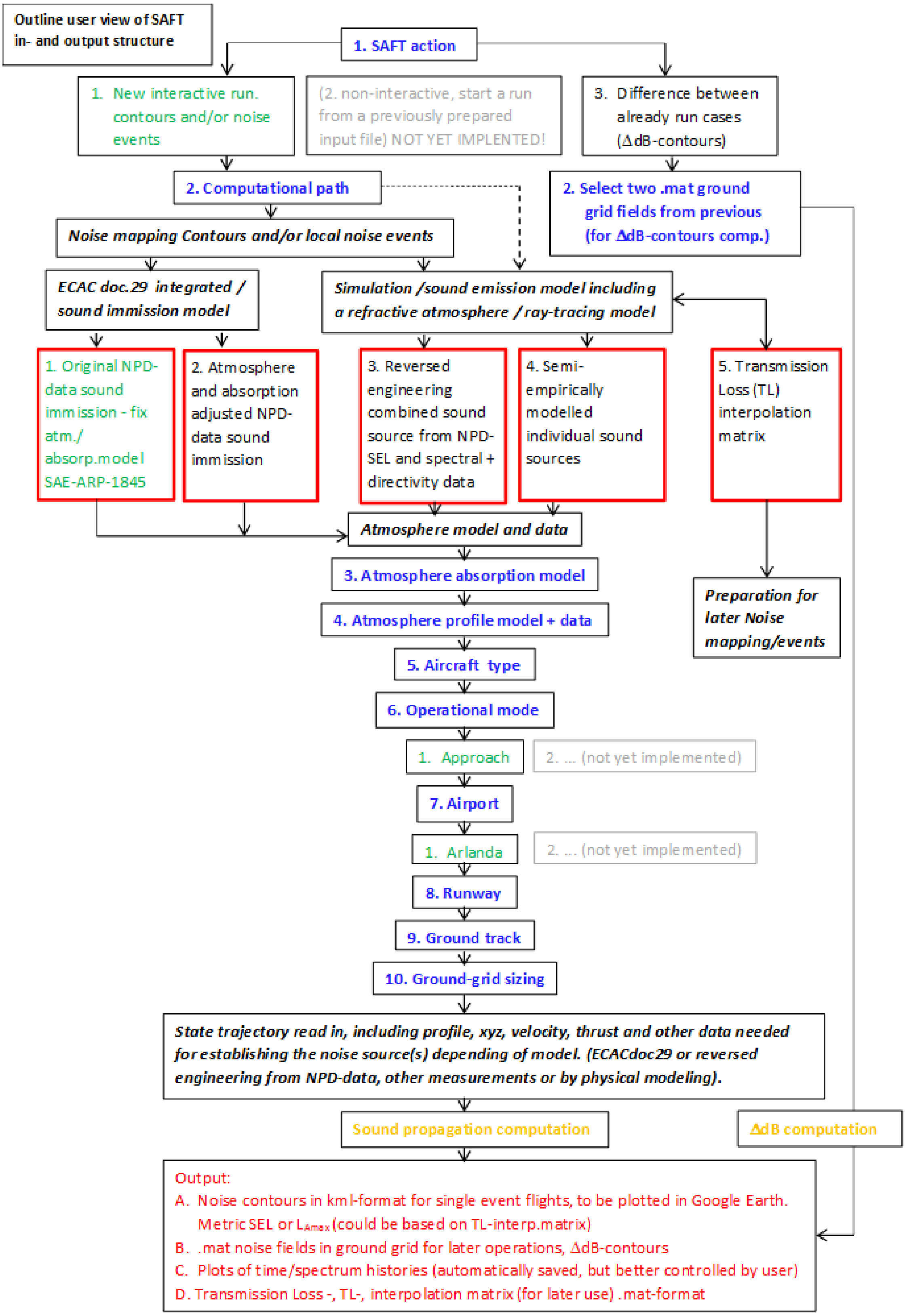


Figure 1. Outline of typical interactive SAFT run logics (as of 2018 version of SAFT)

2.2 The TL-interpolant matrix and its approximations

Among the computational SAFT features that should be emphasized are the possibility to establish TL-interpolant matrices (TLipmat) for direct use in the ongoing SAFT run or to apply in later computations. This TLipmat concept involves, for the selected atmosphere model and data (for a given hour), establishing of an invariant 4D TL-matrix as a discrete function of source altitude, radial distance(r) out from an aircraft ground track position, propagation direction (θ) and frequency. The TLipmat is computed by ray-tracing which also allows us to keep track of the emission angle related to radial propagation distances, which in turn are directly coupled to the directivity as a function of frequency for the aircraft noise source of concern. In the same way the incident angle at ground is a direct function of r and θ (assuming a flat ground), which together with ground properties/impedance gives us the reflection coefficient. This means that we 1) keep the TLipmat invariant along the aircraft flightpath we study, 2) make use of the simplification that the ground altitude is kept constant (i.e. assumed flat ground set to either the runway threshold or an "Arlanda" value) and 3) include only one ray-bounce on ground . All these assumptions are believed to introduce comparably insignificant errors in the Arlanda TMA case. (Here the ground altitude typically does not vary more than around +/-40 m from the RW thresholds at distances >50 km and gets smaller closer to the airport. Max sound level errors introduced by TLipmat because altitude simplifications would around Arlanda then become of the order +/-0.2 dB, i.e. negligible with regard to other uncertainties. The single ground reflection/ray-bounce is also assumed applicable without any significant level errors introduced, as long as the aircraft is found at an altitude "high enough". This question, and the related uncertainty with buildings on ground, is not yet quantified or addressed in detail. Though: if found needed future implementations in SAFT could very well include propagation computations down to a boundary in free space above a built-up, or topographically complex, area where another code, or future SAFT-modules, take over with more detailed sound propagation methods.

2.3 Examples from SAFT runs with comments

Results from some sample SAFT runs with an Airbus A321-232 are shown in figure 2 – 12 below. (Figure 2 is there only to give an idea of the example trajectory.)

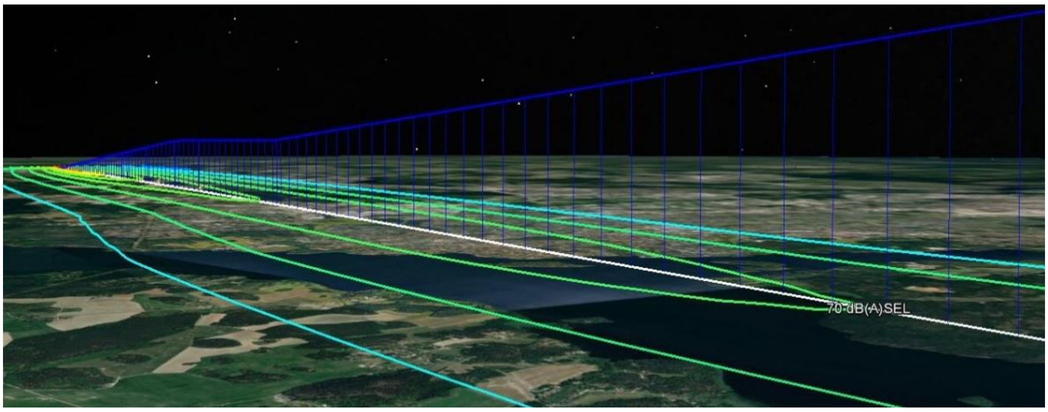


Figure 2. Sample SAFT run A321-232 ANP- standard trajectory landing at Arlanda RW01L. Last 18 nm straight flight, descent from ca 5000ft, level flight from ca 13 to 9 nm before landing. Dark blue = trajectory, white = ground track (light blue,green = Noise contours as of SAFT ECAC doc.29 implementation)

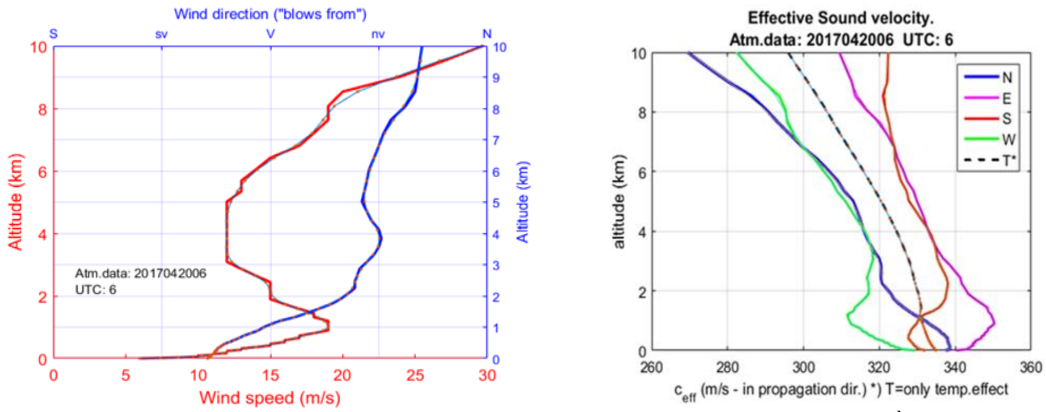
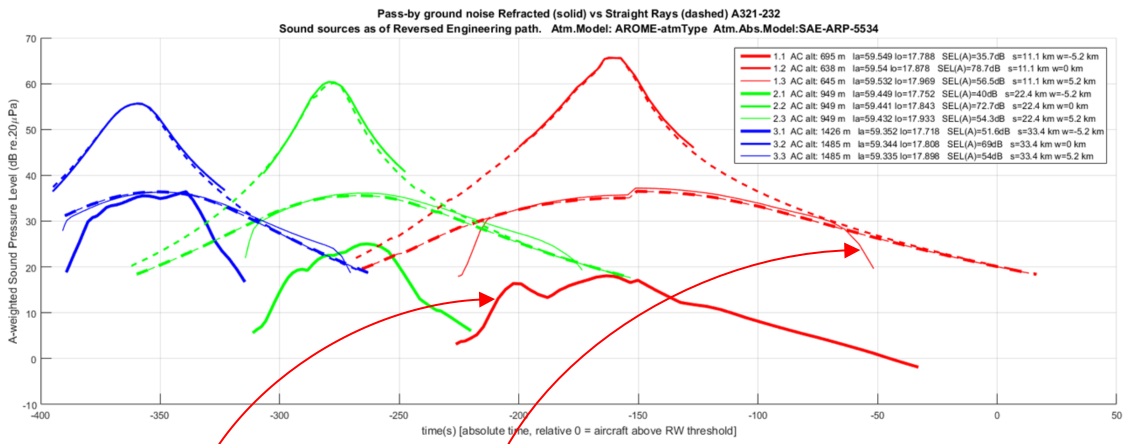


Figure 3a and b. Sample atmospheric profiles ("spring", UTC 06 20th April 2017)



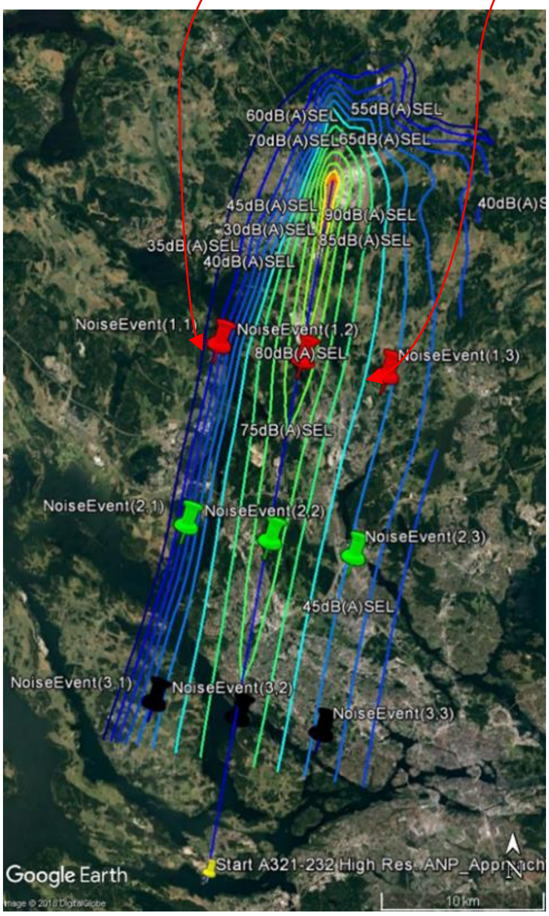


Figure 4a and b. Side wind case pass-by noise, $L_A(t)$, for a A321-232 computed by SAFT with straight (dashed curves in figure 3a) respectively refracted rays (solid curves in fig.4a). Noise contours (A-weighted SEL, Sound Exposure Levels) in fig.3b. [Note the asymmetries in fig.a and b!]

In figure 4a above and 4b to the left, the red arrows stretching between figure 4a and b connects the upper 4a "noise level as a function of time"- graph with respective geographical position denoted in figure 4b (red Google Earth place mark symbols). As seen in figure 4a these receiving points, symmetrically positioned with regard to the ground track, show two rather different pass-by noise histories for this side wind situation given by a "real" sample atmospheric profile from SMHI [10]: Moderate westerly to north-westerly winds as of figure 3 above. While the receiving position found in the headwind direction with regard to the aircraft route (to the west from ground track) show more or less insignificant levels, (< 20dB(A)), the corresponding receiving point, symmetrically positioned east of the ground track, show levels between 35 and 40dB(A), i.e. clearly audible and possibly annoying, e.g. in bedroom with open window in the evening. These lower levels, from less than 20dB(A) up to ca 40dB(A), at the example positions ca 5 km sideways from the ground track, would not be significant when creating noise maps over accumulated SEL- or max levels over longer times. Neither are these lower levels and non-symmetric contours, traceable with a straight-ray model (or with even more simple models such as the ECAC doc.29). Such rather low noise levels (< 40 dB(A)) may appear as negligible at first sight. However, such reductions of around 20dB, even at these low absolute levels, could represent a significant gain for people if they could be avoided over some time periods. In other words, there is a potential value in understanding such asymmetry-patterns and make use of this knowledge together with population distribution, weather forecasting by the ATC, in the operative routing and in the runway use pattern in order to distribute noise equitable over time and populated areas. This knowledge, would also be good to have already in the design of new routes, even if the noise levels are below restriction levels.

It should be noted that the estimation of sound "leaking" into so called sound shadow zones (up-bending sound propagation due to upwards decreasing effective sound velocity) are rather hard to carry out. This is due both to its complex theoretical nature, including a dependence of random convection and turbulence and to the stochastic nature of the problem. Though, since we know that, typically we get a strong weakening of the noise level, compared with in a sonified region at the same distance. For "medium" frequencies typically of the order of 20dB lower, which makes these levels of less concern and empirical estimates could in many engineering situations be regarded as "good enough".In other words, we do not need to apply probabilistic methods involving repeated runs to get statistically significant results within the shadow zones. While a headwind propagation typically may lead to reduced noise levels several 10:ths of dB:s compared with in a non-refractive medium, the opposite, i.e. a tailwind propagation would in the general case not increase the levels with more than a single or a few dB:s, and this only in minor areas. (Quite surprising: also tailwind propagation leads to limited zones with reduced sound levels). A practical consideration here is how to handle "caustics" or zones where consecutive rays are crossing, or creating infinitely small distances/areas, leading to infinitely high sound power (in contrary to a situation with a homogenous non-refractive media or straight ray model or even with a field model applied to an inhomogeneous media). Though such artificial ray-tracing extremes do not occur in reality, we have to deal with focusing zones and locally increased levels even in reality. One reason for these maxima to be of smaller concern in our aircraft context than for static noise sources is that these concentration zones would have a very short existence time, given a stationary ground position and a fast moving sound source/aircraft. Again, the dominating random character + the in reality distributed sound source + the diffusing effects of possible turbulence would further emphasise this situation. The current implementation in the creation of the TLipmat involves a simple empiric smoothing to avoid this kind of extremes [11],[12].

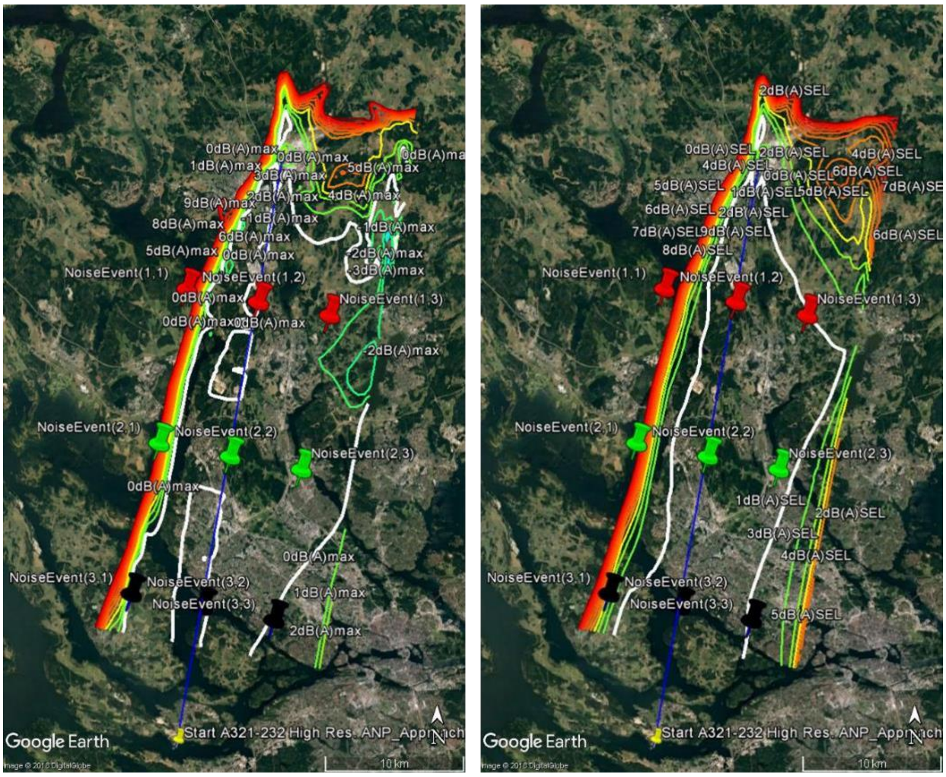


Figure 5a and b. Sample difference between straight vs. refracted rays. ΔdB for a) L_{Amax} and b) SEL(A) respectively (blue= ground track, white lines = 0ΔdB)

Figure 5 shows the same A321-232 case as before but this time the difference in the noise field on ground between a straight ray computation versus a refractive ray-tracing is shown. The $\Delta dB_{straight\text{-}refr.rays}$ contours revealed in figure 5 are equidistant with a 1 dB step, where the white line shows where the straight rays and refracted rays model gives the same result.

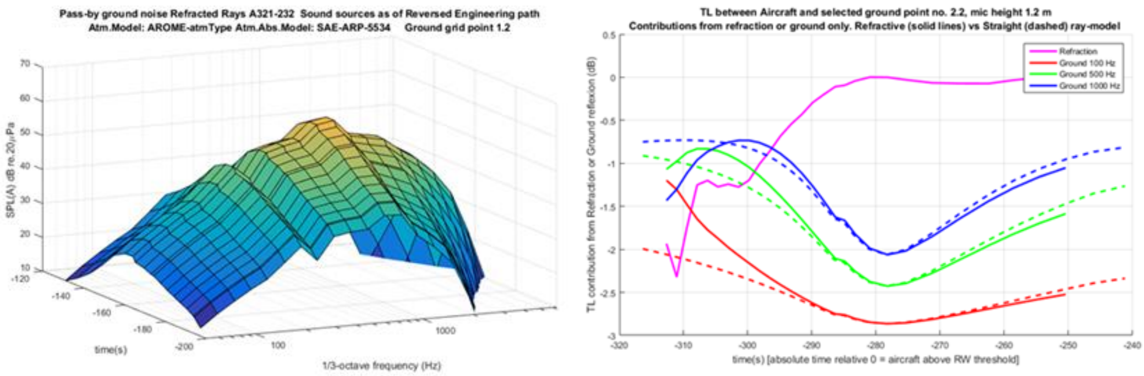


Figure 6. a and b Pass-by noise (1/3-octave spectra) for a A321-232 computed by SAFT a) frequency-time plot of noise in ground point1.2, i.e. on the ground track and b) TL contribution from refraction and ground reflection in ground point 2.2 (Solid lines = refraction included, Dashed lines = straight ray). Point numbers found in legend of fig.4a

In figure 6 b above sample impacts on receiver noise history are given for: 1) Ground reflection, at some frequencies (both refractive and straight ray model), and 2) Refraction, here approximated as frequency independent. For ground reflections has a model accounting for the limited coherence of a reflected wide band source has been applied. [13]. This is, quite naturally, more representative for ground reflections than the usually applied narrowband models, assuming a perfect phase match at certain combinations of receiver height and frequency. when dealing with 1/3 octave band sources.

Below in figure 7 to 10 some samples showing ΔdB for different absorption models [14],[15],[16] and input data are shown. All representing SAFT runs based on ECAC doc.29 method and a ANP data spectrum 202 for approach (a refractive full simulation propagation would have given almost the same results)

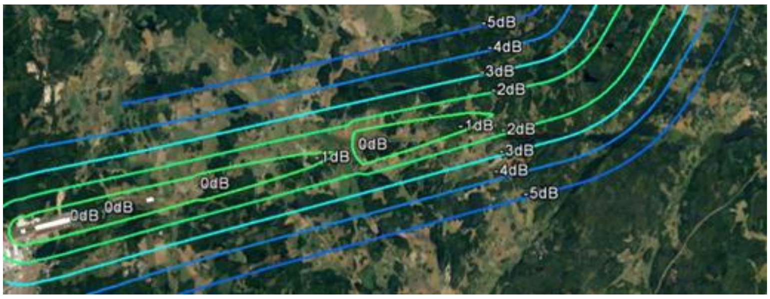


Figure 7. Comparison SAE AIR1845 and ARP866A absorption models $\Delta L_{Amax,\ 1845\text{-}866A}$ dB a sample day atmosphere data over Arlanda airport

Figure 8. Comparison SAE ARP866A and the new ARP5534 absorption models $\Delta L_{Amax,866A\text{–}5534}$ dB sample day atmosphere data over Arlanda airport

Figure 9. Comparison ISA atm and a sample day atm.as of SMHI (both modelled by ARP5534) $\Delta L_{Amax,\ ISA\text{–}SMHI,\text{'spring'}}$ dB sample day atmosphere data

Figure 10. Comparison two sample days atmosphere data (both modelled by ARP5534 with SMHI data) $\Delta L_{Amax,'spring'-'summer'}$ dB

To note in figures above are: In fig.7 big underestimation of noise levels tend to be the result when applying the since long outdated SAE AIR1845 standard for absorption. This gives a fix absorption in dB per meter as a function of frequency without any possibility to bring in a variation of atmospheric conditions. Moreover, this is the absorption in which ANP NPD-data is given, i.e. clearly emphasising that one should follow the recommendation in ECAC doc.29 to recalculate NPD-data to at least ISA-data with SAE ARP866A instead. In Fig. 8 we see that the latest absorption model recommended in ECAC doc.29, SAE ARP5534, gives in the example even slightly less absorption, i.e. higher noise levels, compared with the previous ARP866A. This is a tendency we have seen indications of also in other cases. Such a seemingly small difference, of the order of 1 dB, might though have a rather significant influence on the area added within a contour line. Consequently, a strict implementation of rules for noise insulation of houses within a certain noise level contour area computed with ECAC doc29, could lead to quite extensive cost increases simply by such a change of applied absorption model. Examples in fig. 9 and 10 shows that even with one and the same absorption model, solely variations in atmospheric data can give variations of a few dB. (In the shown case the SMHI 'summer' atmospheric profile example gave about the same levels as the standard ISA-atmosphere, while the SMHI 'spring' profile example gave 0-2 dB less "total" absorption for the assumed ANP data approach spectrum 202).

The final series of figures, 11 to 13, show comparisons between a standard ECAC doc29. run and a refractive atmosphere simulation for our example A321-232 landing at Arlanda in the same atmospheric conditions but at different runways creating side and headwind respectively. The A321 as a sound source is in the simulation case modelled by reversed engineering from an assumed ANP-data spectra 202 and with a longitudinal directivity (over all frequencies) in one case as "front-heavy", see figure 11, and in the other as flat/non-directive.

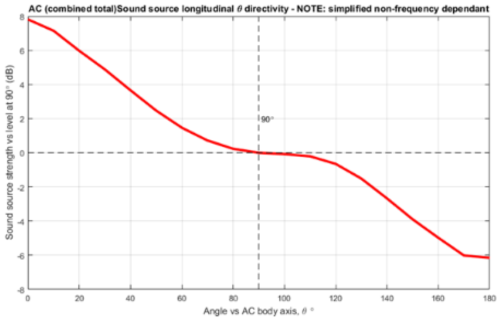


Figure 11. Assumed directivity (representing a more modern high-bypass turbofan)

This directivity is applied for the headwind landing example in figure 12 b while a non-directive assumption is applied in figure 12 a. Except for the very last part before and

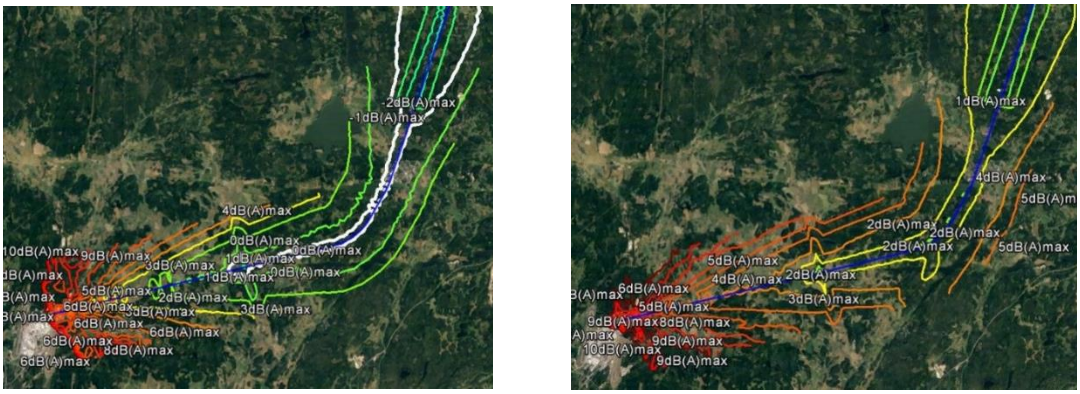
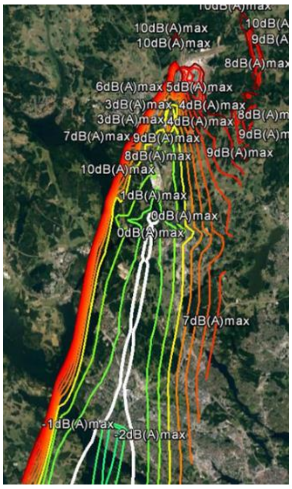


Figure 12 a and b. Difference ECAC doc.29 vs SAFT reversed engineering source ΔdB
a) non-directive, b) directive as of figure 11. (white curve: *ΔdB=0)*



after landing figure 12 a show rather small differences (as expected) while the directivity (12 b) indicate higher ground noise levels for ECAC doc 29 compared with the SAFT-simulation. In the side wind case, figure 13, showing the difference between an ECAC doc29 computation and a simulation with reversed engineering with a non-directive source, we see only a rather small or zero difference close to the ground track but lower levels for the SAFT–simulation at further distances away from the ground track, of course most significant in headwind propagation direction, i.e. to the west. It should be emphasised that the same atmospheric data and absorption model has been used both in the ECAC doc.29 and in the SAFT-simulation case.

Figure 13. Difference ECAC doc.29 vs SAFT reversed engineering source ΔdB
Side wind case as of fig. 3. (white curve: *ΔdB=0)*

3. PLANNED FUTURE IMPLEMENTATIONS

- Configuration dependent source estimation from noise-measurements [17] + meteorological + trajectory data (Opensky or/and FDR) + SAFT estimation (trimming directivity/source strength) and statistical methods
- Methods for configuration and mass identification without FDR-data
- Modularised trajectory builder
- Going from single event to air traffic scenarios
- New gridding methods covering complete TMA, e.g. Stockholm TMA, with a hierarchical sub-grid technique
- Enable batch runs from files (today only interactive input)

4. CONCLUSIONS

SAFT has already in its current state (February 2019) shown to be useful in producing results that could explain complex relations and thereby help finding ways to reduce aircraft noise impacts.

5. ACKNOWLEDGEMENTS

We acknowledge gratefully the Swedish Transport Administration (TRV 2016/92229) for the funding and support of this work.

6. REFERENCES

1. Integrated Noise Model (INM) https://www.faa.gov/about/office_org/headquarters_offices/apl/research/models/inm_model/ (last viewed on 26/02/2019)

2. ECAC. Doc.29: "*Report on Standard Method of Computing Noise Contours around Civil Airports*", Volume 2: Technical Guide. 4th ed. Neuilly-sur-Seine, France: European Civil Aviation Conference (ECAC); 2016 7.12.2016. Available from: https://www.ecac-ceac.org/ecac-docs (last viewed on 26/02/2019)

3. AEDT- Aviation Environmental Design Tool, FAA Federal Aviation Administration https://aedt.faa.gov/ (viewed 26/02/2019)

4. The OpenSky Network, https://opensky-network.org

5. M. Schäfer et.al. "*Bringing Up OpenSky: A Large-scale ADS-B Sensor Network for Research*".In Proceedings of the 13th IEEE/ACM International Symposium on Information Processing in Sensor Networks (IPSN), pages 83-94, April 2014.

6. The Aircraft Noise and Performance (ANP) Database Eurocontrol Experimental centre https://www.aircraftnoisemodel.org/

7. P. Houtave and J-P. Clairbois "*Single aircraft pass-by: Modelling relevant noise at ground*" Euronoise 2018. (viewed 26/02/2019) http://www.euronoise2018.eu/docs/papers/27_Euronoise2018.pdf

8. Cristoph Zellman *"Development of an Aircraft Noise Emission Model Accounting for Flight Parameters"* Dr.Thesis Technischen Universität Berlin 2017

9. D.Mavris et.al. Georgia Institute of Technology /FAA Project 043 *"Noise Power Distance Re-Evaluation "* https://ascent.aero/project/noise-power-distance-re-evaluation/ + https://ascent.aero/documents/2018/06/ascent-043-2017-annual-report.pdf/ (viewed 26/02/2019)

10. www.smhi.se. Meteorologiska modeller. (viewed o26/02/2019) http://www.smhi.se/kunskapsbanken/meteorologi/meteorologiska-modeller-1.5932.

11. Keith Attenborough "Chapt 4. Sound Propagation in the atmosphere", Springer Handbook of Acoustics (viewed 26/02/2019) https://www.researchgate.net/publication/302545876_Sound_ Propagation_in_the_Atmosphere

12. Lam, Y. W. "*An analytical model for turbulence scattered rays in the shadow zone for outdoor sound propagation calculation."* Acoustical Society of America, 2009, J. Acoust. Soc. Am., Vol. 125(3).

13. Chessell, C. *"Propagation of noise along a finite impedance boundary,"* Journal of the Acoustical Society of America, 62(4), pp. 825–834 1977

14. Society of Automotive Engineers: *Procedure for the Calculation of Aircraft Noise in the Vicinity of Airports.* SAE AIR-1845 (1986).

15. Society of Automotive Engineers: Standard values of atmospheric absorption as a function of temperature and humidity. SAE ARP 866A (1975).

16. Society of Automotive Engineers: Aerospace Recommended Practice, Application of pure-tone atmospheric absorption losses to one-third octave-band level. SAE-ARP-5534 (2013).

17. CSA ULLA-project https://www.kth.se/polopoly_fs/1.874098.1550154409!/CSA%20workshop%202018%20ULLA%20A%20johansson.pptm (viewed 26/02/2019)