DL_f and DL_2 Application Notes
for prediction using *CATT-Acoustic* v9

1. Introduction

This application note concerns *CATT-Acoustic* v9 prediction of the DL_f and DL_2 measures for open-plan offices, some discussion about other measures, and the effect of screen diffraction.

2. What are DL_f and DL_2 and what are they for ?

DL_f and DL_2 are two measures defined in the [ISO 14257] standard released in 2001 for use in workrooms regarding noise control (i.e. factories since "machines" are mentioned in the text). These DL-measures can be described as the average (or more detailed) excess of SPL with respect to a free field (DL_f), and the SPL decay per distance-doubling (DL_2). The implementation in *CATT-Acoustic* v9 attempts to fully follow this standard in a way that gives partly new analysis options, options that also indicate the potential problems and pitfalls associated with the use of these measures especially in open-plan offices.

Since the ISO 14257 release the two DL-measures have been suggested for use also in open-plan offices to estimate undesired speech propagation and it has lead to the [ISO 3382-3 draft] where recommendations are given on how to apply ISO 14257. Interesting to note is that ISO 14257 explicitly states that:

- it "does not deal with the acoustical quality with respect to speech communication or other psychological factors" and yet that is a main part of the goal of the ISO 3382-3 draft;
- the measurement path shall be "along a free line of sight" (any large reflecting object at least 1.5 m to the sides of the path), and yet the ISO 3382-3 draft states that the path shall pass right through workstations as well as screens (> 0.5 m from tables).

I.e. while ISO 14257 concerns the overall spatial decay along an unblocked path from the source, the draft ISO 3382-3 concerns spatial decay along a potentially very blocked path (mainly screens but also desks, cupboards, shelves etc.) and it does not necessarily seem feasible to use a straight line regression for SPL vs log(r) as per ISO 14257. The spatial decay may be very nonlinear with an increase before a screen and substantial decrease behind. The draft indicates that different parts of a path may be treated separately (due to e.g. a markedly different absorption or furniture/object/screen density) but it means that it is up to the consultant to decide the paths and the DL_2 and DL_f results with screen may vary substantially depending on the choice. Due to these apparent problems the *CATT-Acoustic* v9 implementation is made so that a creative use of the DL-measures is encouraged where they can rather be used as design tools than only to give "single number quantities" attempting to condense what may be a quite complex acoustic situation into something that appears simple enough to be described by one or two numbers based on linear regression.

A report with measurements in five open-plan offices, of which two have before/after refurbishment measurements, can be downloaded [NT-2010] and gives a background to the suggested use of ISO

14257 in open-plan offices and to the ISO 3382-3 draft work and also includes references to further measurements. Since the ISO 3382-3 standard is still in draft only basic recommendations (subject to future changes) will be discussed here. It is recommended that the user reads this measurement report and an example from it will also be discussed below.

The ISO 3382-3 draft is a subset of ISO 14257 but with some alterations and with some additions regarding further measurements such as of STI:

- the sound source should emit a certain given speech spectrum. In measurement practise pink noise is used that later is filtered with this speech spectrum. Most of the reports seen so far, such as [NT-2010] seem to have been using pink noise only. *CATT-A note: the user has to select the desired spectrum*, *ISO 14257 recommends pink noise but allows for other spectra*;
- the sound source remains omni-directional even if it considers speech propagation. *CATT-A note: the predefined Omni source must be used, and only one source can be used at a time when the Map measures prediction of the DL-measures is used*;
- the sound source is to be placed at a height of 1.2 m, i.e. a sitting talker. *CATT-A note: the user has to select the desired height, ISO 14752 allows for other heights*;
- the microphones are to be placed at a height of 1.2 m, i.e. a sitting listener. *CATT-A note: the user must select an Audience area mapping Map height of 1.2 m, ISO 14752 allows for other heights, the implementation in TUCT Map measures requires both source and receivers to be at the same height*;
- the microphones are to be placed > 0.5 m from tables and > 2 m from walls and other reflecting surfaces (is not a table also a reflecting surface…?). ISO 14752 indicates > 1.5 m from walls and large reflecting surfaces*;*
- the microphones are typically to be placed between 2 and 16 m (case dependent) in a line from the source. ISO 3382-3 draft also allows for non-straight lines through workstation but no example have been seen so far and it is not said how the distance will then be calculated and likely to violate the condition of being > 0.5 m from tables, it seems a too big deviation from ISO 14752 and will not be supported. ISO 14752 describes three distance ranges “near”, “middle” and “far” where a d_1 determines the end of the near region and d_2 determines the end of the middle region. *CATT-A note: in TUCT Map measures these variable ranges are implemented and for open-plan office prediction the middle region can be used as the single variable region with d_1 and d_2 set according to the ISO 3382-3 draft;*
- the measured SPL values should be A-weighted. *CATT-A note: in TUCT Map measures results view Band: sum and check sum(A) but it allows also for 1/1-octave analysis as per ISO 14257*.

3. Implementation of DL_f and DL_2 in *TUCT* v1.0h

The DL_f and DL_2 measures do not fit well with other measures since they are not calculated for each receiver or map point but is based on post-processing predicted SPLs for several receiver positions along a line, the ISO 3382-3 draft suggest to use 6 to 10 positions but it can not be an error, but rather a benefit, to use more (as in the *TUCT* implementation) since the SPL can sometimes vary considerably from position to position, especially with one or more screens in between source and receiver. An example of this big variation can be seen in [NT-2010] Figure 54 on page 67 (office plan view on page 59) where the SPLs differ up to 9 dB between points immediately before and after a screen (a 1 m point distance). That a linear regression is used even if the SPLs may vary this much raises the question of the method validity in some cases. This is the reason why in *TUCT* map points with the line regression coefficient magnitude below a given value can be chosen to not be displayed and that in a separate display regression coefficients are shown. However, the use of equally, or almost equally, spaced points will due to the log(r) make the line regression more affected by the biggest r values (the log(r) points will be denser), this problem is neither addressed in ISO 14257 nor in the ISO 3382-3 draft and can have a bigger impact in offices where the SPL(r) can be expected to have a larger spread.

Using *TUCT* v1.0h there are two ways to calculate DL_f and DL_2: post-processing of predicted SPLs from *Predict SxR* and via *Map measures*.

3.1 Predicting DL_f and DL_2 via Predict SxR

This requires some post-processing of a spread-sheet export but since anyone using DL_f and DL_2 should also be able to measure SPL(r) and apply the ISO 14752 equations it simply means to instead use predicted SPL values in a similar spreadsheet. With *CATT-A* v9.0b there is a new receiver-file function called `recline()` that may be useful to generate receivers in a line. With this use there are no checks performed on source and receiver placement, source type or source spectrum but all necessary information will be contained in a spreadsheet export of *Predict SxR* results, except the source-receiver distances that are exported at the end of the export files. This way of predicting would mainly be used when comparing to a direct measurements in the same points, the *Map measures* way below gives many more options for analysis and also for understanding of the properties and problems of the DL-measures.

3.2 Predicting DL_f and DL_2 via Map measures

Show 3D: Audience mapping Measure Results has three selections *DLf*, *DL2* and *DL lines* that when selected also checks if the calculation of these measures is possible (source and map height the same, omni source). It can be a good idea to first make a quick calculation to check that the DL-measures are possible before starting a longer calculation. Do not use a too small map step, 1 m is recommended. The implementations allows for the behaviour along many paths to be investigated and not just one or two.

Basic DL-measure displays using a room with no screens

Fig. 1 shows an example of a DL_2 map in a room without screens or objects to make it simpler to explain how the prediction is made and the principles of the DL-measures. The room is 35 x 20 x 3 m^3 with hard walls and floor and a ceiling absorber. As usual with maps, holding down the SHIFT key and moving the mouse over the map will show map values below the 3D-window.

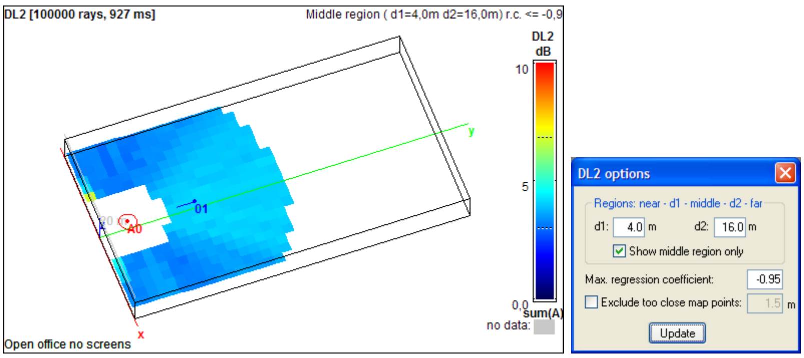

Fig. 1. Sample prediction of DL_2 showing middle region only.

In spite of the DL-measures not being receiver-specific, but rather room- and region-specific (except DL_f that has a point by point option in the standard as well as in *TUCT*), one value per map point is shown, how can that be? This is how: the line from a least-square straight line fit of SPL vs log(r) is calculated for every map point using the map points closest to a line from source through the map point, from the beginning to the end of each region as illustrated in Fig. 2 for the middle region.

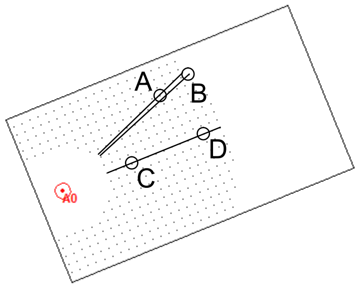

Fig. 2. Illustration of how map point DL-measures are derived within a region, middle region shown.

In the case of points C and D the lines analyzed for A0-C and A0-D will be the same and the DL-values will thus be the same for all map points along the line since the same SPL-values are taken into account in the line regressions. In the case of points A and B the lines analyzed for A0-A and A0-B will be slightly different taking slightly different map points along the lines into account in the line regression, this case can be seen in Fig. 1 but the difference is typically only a fraction of a dB.

Fig. 3 shows all three regions with the same regression coefficient magnitude limit (0.95) and it can be seen that the far region line regressions are not successful, i.e. the SPL vs log(r) values are not on a straight-enough line to give a regression coefficient in the range -0.95…-1.0. In Fig. 4 the results with a limit of -0.3 are shown.

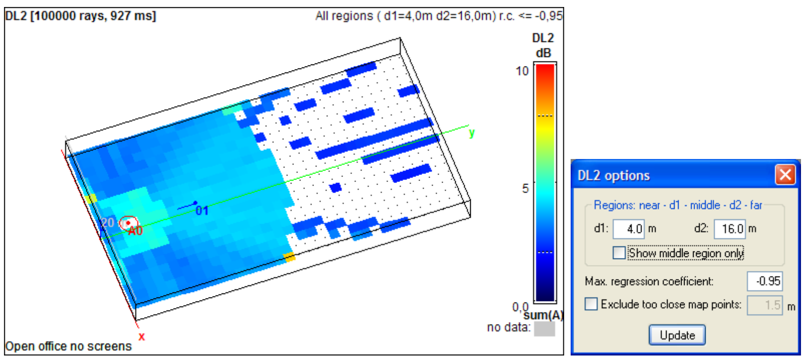

Fig 3. As Fig. 1, but showing all three ranges using the same regression coefficient magnitude limit. Dots indicate points where the regression coefficient limit is not reached.

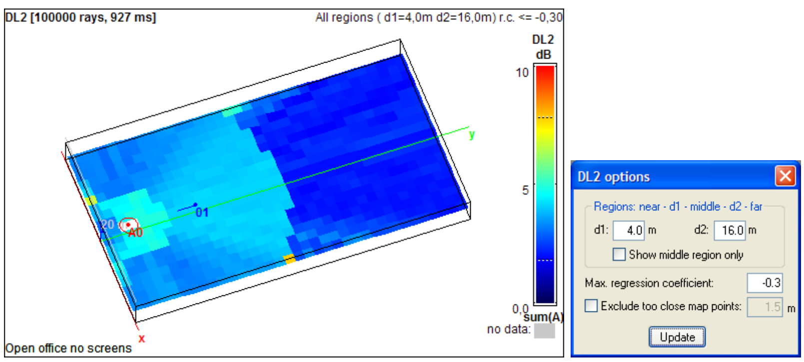

Fig. 4. As Fig. 3, but using a lower regression coefficient limit (-0.3).

A regression coefficient of -1.0 means that points are perfectly aligned on a downwards sloped straight line, a lower magnitude negative value (e.g. -0.3) means that the estimated line is still downwards but the points do not follow the line very well. A coefficient > 0 means that the estimated line points upwards. Fig. 5 shows examples of line regressions along the y-axis as displayed by the *Show 3D: Audience mapping Measure Results: DL lines*.

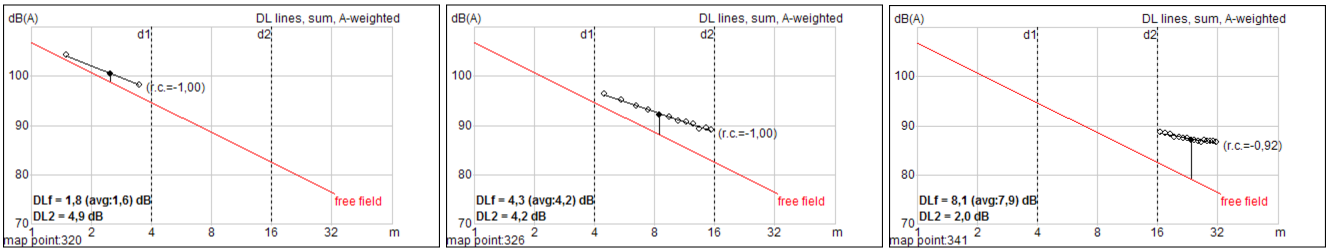

Fig. 5. Example line regressions for the close, middle and far regions.

This display will be further explained below. The reasons for low regression coefficient magnitudes can be several:

- an actual very varying SPL over distance, this can be seen e.g. in Fig. 54 in [NT-2010] and in the next example with screens;
- too few rays in relation to the map step;
- the line direction (as can be seen with the next example with screens, different directions will give different results and will have different SPL(r) behavior, another issue to keep in mind;
- a too short line or a too short region with too much SPL(r) variation (too few points in the line regression);
- a 1/1-octave display is used, using *sum* or *sum(A)* (as suggested in ISO 3382-3 draft) the lines will be smoother and the regression coefficient magnitudes will typically become higher.

DL_f has the same options as DL_2 but also offers a region average (according to ISO 14257 eq. (7)) and individual map point DL_2 values as shown in Figs 6-8. *Individual re line* means the difference between the estimated SPL line and the free-field line (called DL'_f in ISO 14257) while *Individual re points* means the difference between the actual estimated SPL at the map point and the free-field line (or simply the map SPL normalized with the free-field value).

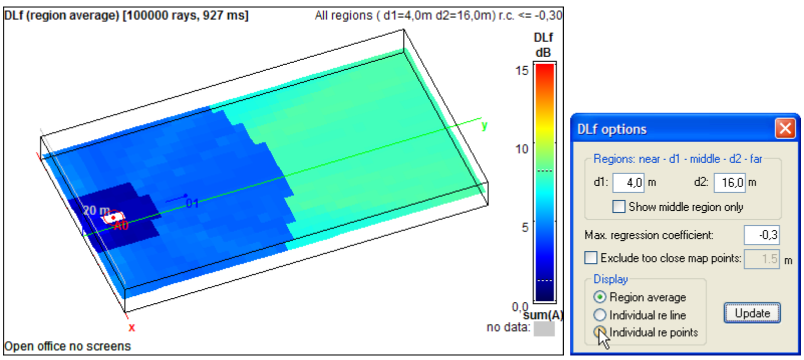

Fig. 6. Sample prediction of DL_f region averages (all regions).

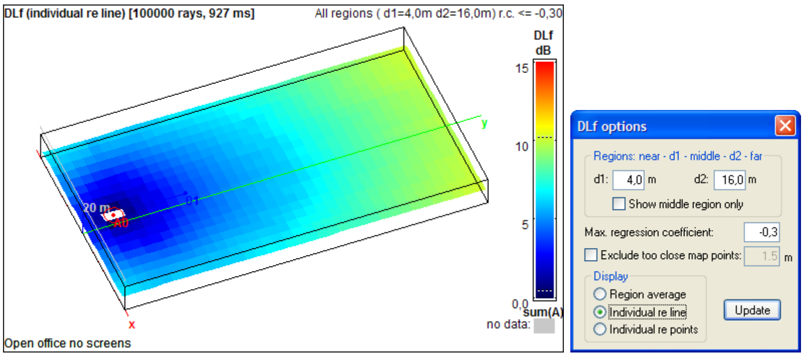

Fig. 7. Sample prediction of individual map point DL_f re line (all regions).

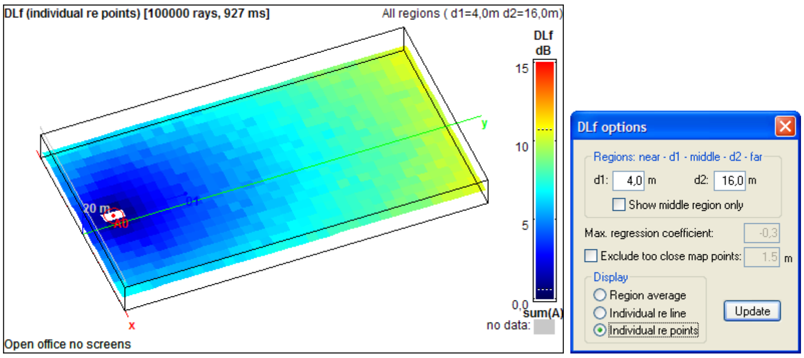

Fig. 8. Sample prediction of individual map point DL_f (all regions), Fig. 7 is essentially a smoothed version of this.

As for other maps the *Statistics* button is active but does not necessarily show useful information for the DL-measures.

The 3rd display option *DL Lines* offers mouse-over much like the *Echograms* option where the regression lines and all measures are displayed as the mouse is moved over the map while holding down the SHIFT key, see Fig. 9.

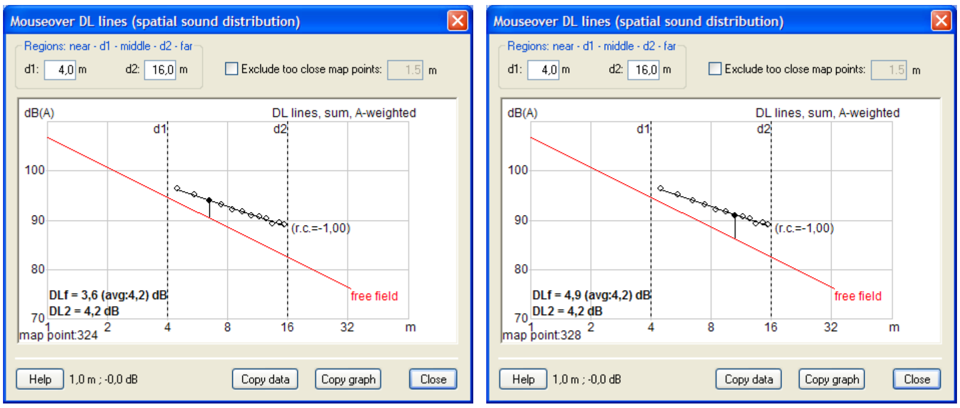

Fig. 9. Sample *DL lines* display when the mouse is pointed at two map points along the same line and the corresponding DL_2, DL_f (individual re line and region average) and the regression coefficient (r.c.). The black dot indicates the map point actually pointed at and the short vertical black line indicates DL_f re line for that map point.

To summarize, the *DL2* and *DLf* displays are good for overview while the *DL lines* display shows more of the background to the values and can be more useful for analysis.

DL-measure displays with screens added

If we now move to a case with 1.8 m high fairly absorbing screens added it can be seen that the SPL vs log(r) curves become much more uneven resulting in lower regression coefficients magnitudes as exemplified in Figs. 10-13 where a limit of -0.3 has been used.

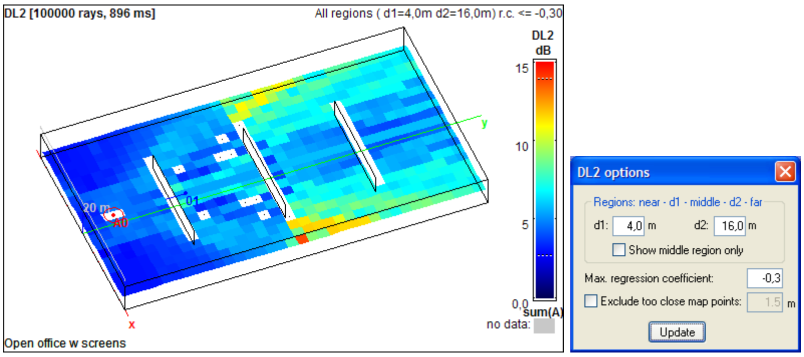

Fig. 10. Sample prediction DL_2 with screens (all regions).

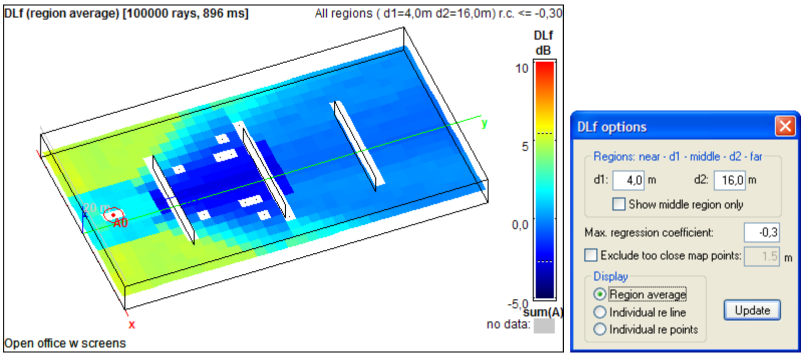

Fig. 11. Sample prediction of DL_f with screens, region average (all regions).

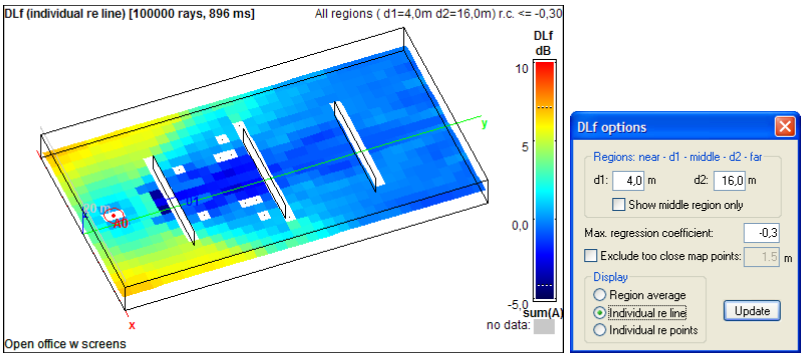

Fig. 12. Sample prediction of DL_f with screens, individual map points re line (all regions).

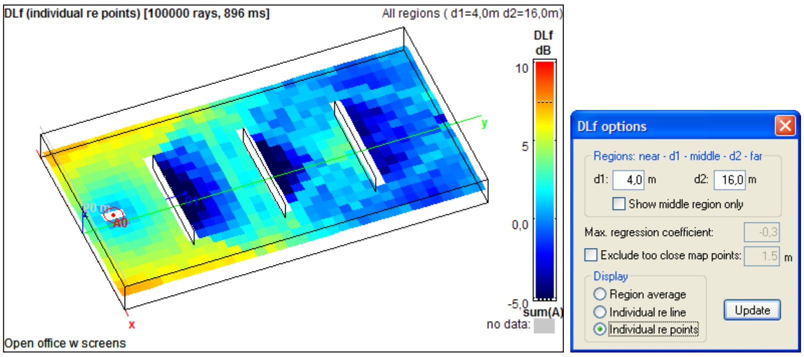

Fig. 13. Sample prediction of DL_f with screens, individual map points, Fig. 12 is essentially a smoothed version of this.

Now the SPL vs log(r) lines look more interesting and are considerably less linear in the regions where the screens are:

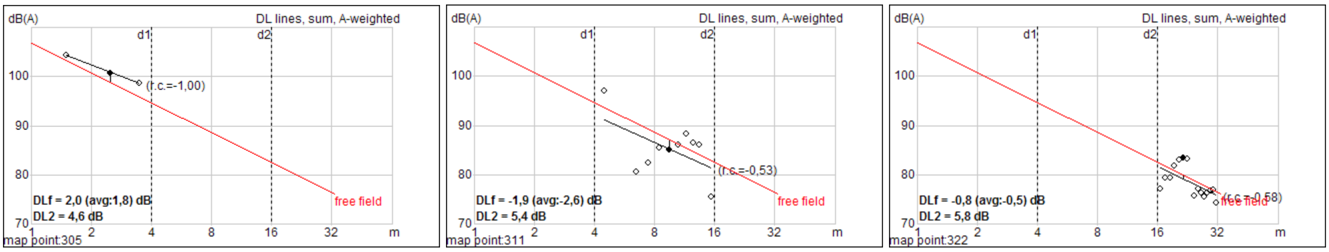

Fig. 14. Example line regressions with screens for the close, middle and far regions along the y-axis.

It can be argued that in the case the middle region was here not well chosen and not according to the ISO 3382-3 draft but it was used to illustrate how very sensitive it can be depending on the choice of d_1 and d_2. To further complicate and illustrate the issue Figs. 15-18 show the same as Figs. 10-13 but now with d_2 = 30 m as suggested in the ISO 3382-3 draft.

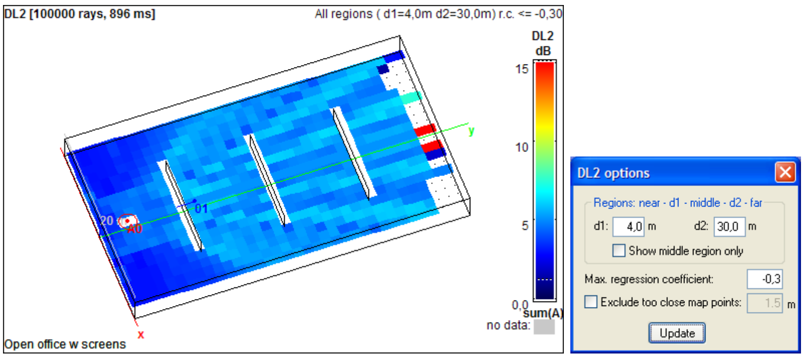

Fig. 15. Sample prediction DL_2 with screens (all regions), d_2 = 30 m.

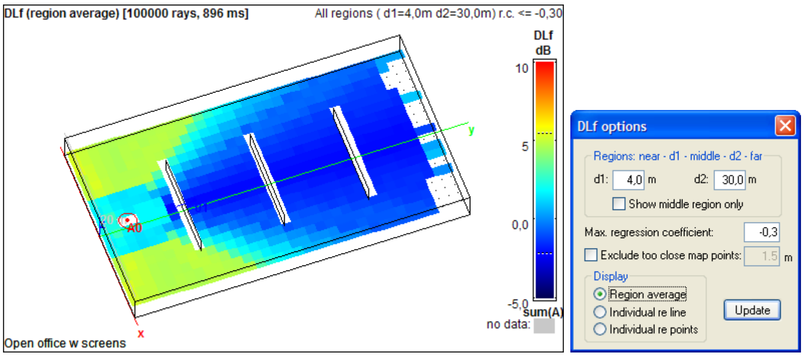

Fig. 16. Sample prediction of DL_f with screens, region average (all regions), d_2 = 30 m.

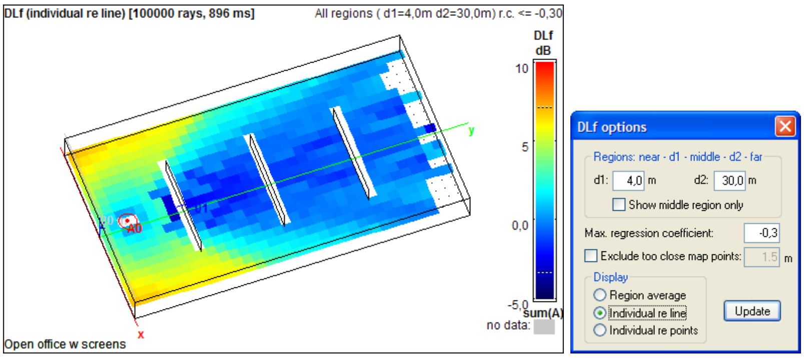

Fig. 17. Sample prediction of DL_f with screens, individual map points re line (all regions), d_2 = 30 m.

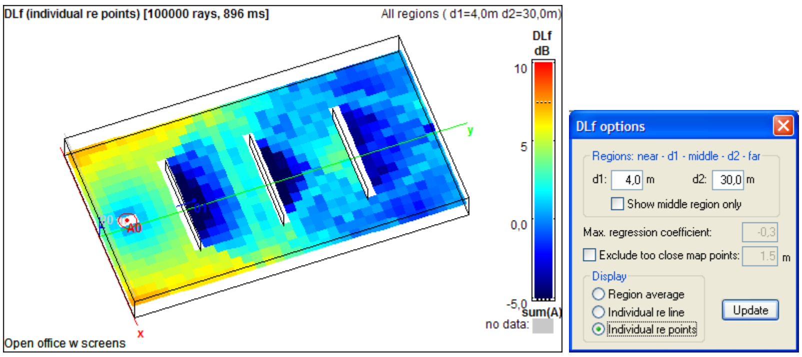

Fig. 18. Sample prediction of DL_f with screens, individual map points (all regions), d_2 = 30 m.

Fig. 19 shows the corresponding SPL vs log(r) paths and regressions where the abrupt SPL change before/after a screen can be clearly seen.

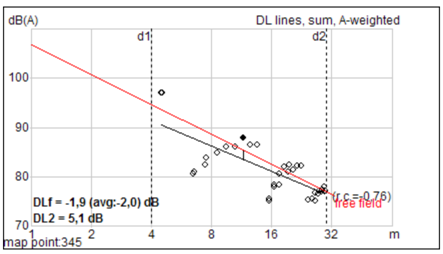

Fig. 19. Example line regressions for the middle region 4-30 m.

Looking at Figs. 15-19 the individual map point DL_f seems to clearly be the most useful for analysis since it e.g. indicates where the screens are most efficient, in Figs.15-18 it appears as if the screens are equally effective also on regions that have been reached by side wall reflections. The individual map point DL_f is not included in the standard (it would require many points to be measured) but is based on the same principle as DL_f re line (i.e. DL'_f) but can give more detailed and useful information.

4. A note on diffraction, especially in relation to DL_f and DL_2

So far *CATT-Acoustic* v9 does not include diffraction calculations. Using simple screen formulas that may solve the office-with-screen case has been decided against but to rather attempt to make a proper full diffraction implementation that with *TUCT Predict SxR* is feasible due to the directly created impulse responses (in contrast, with v8 a full implementation would have been near impossible). One reason for this decision is that diffraction does not only cause sound to reach the shadow zone behind a screen but will also interfere with the sound on the illuminated side. A full implementation will also, among other things, help modelling curved surfaces in a better way. Many screen formulas do not include diffraction into full space but only in the shadow zone and often without the phase component (that is of little interest in e.g. traffic noise prediction where these formulas mainly come from) and therefore cannot model this interference.

Screens in offices is one of the cases where prediction of diffraction has been claimed to be crucial, but as with most topics in acoustics it depends and the DL-measures calculated as proposed in ISO 3382-3 draft is an example where it does not seem crucial at all. The [NT-2010] report includes a set of figures that give a very good background for discussing the potential importance of diffraction in an office with screens, it can be practical to print out pages 59, 69 and 70 for easy reference. First turn to page 59 and Figure 45 where an open- plan office drawing is shown and where path B can be seen to cross two screens and Figure 54 on page 67 indicates that the sound distribution curve drops 15 dB behind the first screen, why does diffraction not appear to lower the effect of the screen? There are three reasons:

1. from Figure 59 on page 70 the sound distribution curves for individual octave-bands are shown and it can be seen that it is mainly in the 125 Hz band, and somewhat in the 250 Hz band, that diffraction has an effect rendering the screen inefficient at those frequencies;
2. these 1/1-octave curves are then A-weighted (-16.1 dB at 125 Hz and -8.6 dB at 250 Hz) to create the curve in Figure 54, while the mid-frequency bands are essentially unaffected;
3. these measurements were made with pink noise while the ISO 3382-3 draft indicates that a special type of speech spectrum should be used that for the 125 Hz band means a further suppression of -3 dB relative 1 kHz giving a total suppression of about -19 dB as compared to 1 kHz.

These three points explain why in Figure 54 no clear effect of diffraction is seen and will thus not affect the DL-measures in a significant way. Then also consider that even *if* diffraction were included at 125 Hz there may still be modal behavior (lowest wavelength within the 125 Hz band is 3.8 m) that would not be taken into account unless a full wave treatment (FEM e.g.) were used and it is unlikely a direction that anyone will take for acoustic predictions in offices since it also requires using much more complex input data not likely to be available.

So, to conclude, while diffraction would be necessary (but not necessarily sufficient due to modes) to calculate octave-band measures at positions behind the screen at 125 Hz and 250 Hz, it is unlikely that it will matter when it comes to prediction of DL_f and DL_2 using A-weighted speech (or A-weighted pink noise) signals as suggested in the ISO 3382-3 draft.

5. Using further measures in offices with screens

In the [NT-2010] report several other measures have been tested and two of them, D_{50}/C_{50} and EDT, deserves special mentioning. These measures essentially assume a direct sound to be present for them to be meaningful and they then behave in a predictable and understandable way. These measures (and several others such as T_s, C_{80}) are supposed to start their calculation at the time of direct sound arrival (time zero) which is the reference and the anchor and if without direct sound the first arriving sound, which might be a diffracted sound, instead is used to decide time zero it gives three problems:

1. for these measures to be meaningful it is, in one way or another, assumed that it is useful sound as compared to not useful sound and the first arriving sound with the direct sound blocked, such as weak diffraction, cannot be seen as useful being affected by interference and/or frequency dependent absorption and scattering. The measures then rather compares early not useful sound to late not useful sound. In [ISO 3382-1] where these numbers are defined the case of a missing direct sound is not even discussed. The most problematic one is probably EDT where in addition to the assumptions above, and problems in the point below, is that it is based on a straight line fit to the first 10 dB after time zero while these 10 dB of very early decay may be far from linear. It can also happen that EDT, due to the weak first sound behind a screen, becomes longer than T_{20} which is very unusual for EDT used in the way it is intended. This can be seen in some of the examples in [NT-2010] e.g. Table 8-9 page 43 where EDT increases after refurbishment while T_{20} decreases. T_{20} will behave in a more meaningful and useful way so that with added absorption it will decrease;
2. the measurement/evaluation without a clear direct sound (or clear first arrival) will be very sensitive, i.e. what time zero is decided to be. Already with a direct sound EDT can be differently evaluated by different impulse response evaluation procedures and without direct sound it will become worse;
3. in many cases the measurement along a path in a room may have positions both with direct sound and without and the values are then not really comparable, the reasons for their values are very different such as a close position but behind a screen vs a far position with line of sight.

In *CATT-A* all such measures are calculated starting time zero at the time the direct sound would have arrived had it not been blocked, this can not be consider correct either but these measures are simply not well defined without a direct sound. There is likely to be some useful information in these measures also without direct sound but they cannot be interpreted the same way as in e.g. an auditorium.

Another measure used in open-plan offices is STI that is also suggested in the ISO 3382-3 draft. STI does not have an apparent problem with lack of direct sound, since it does not need to know zero time but only analyzes the modulation, but it ought to have similar issues as the other measures and was, as far as I know, never validated for cases without direct sound such as behind a screen. Just like the time zero based measures it is likely to be useful also without direct sound but cannot be interpreted and treated exactly the same way as in e.g. an auditorium.

6. References

[ISO 14257] ISO 14257 (1st ed. 2001-10-15), "Acoustics – Measurement and parametric description of spatial sound distribution curves in workrooms for evaluation of their acoustical performance"

[ISO 3382-1] ISO 3382-1, "Acoustics - Measurement of room acoustic parameters - Part 1: Performance spaces"

[ISO 3382-3] ISO 3382-3 (in draft), "Acoustics - Measurement of room acoustic parameters - Part 3: Open plan spaces"

[NT-2010] NT Technical Report, Erling Nilsson, Björn Hellström , "Acoustic design of open-plan offices", July 2010. http://www.nordicinnovation.net/nordtestfiler/rep619.pdf