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Accuracy of wave based calculation methods compared to ISO 9613-2

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ABSTRACT

Ray-tracing software, which uses ISO 9613-2 to compute outdoor propagation, is practical, and has been used successfully for design. However, serious doubts exist regarding the accuracy of some of the various empirical algorithms used, such as algorithms for ground effects and reflections, source height, reflections by objects, and ground cover. Further, 9613-2 has no algorithms for turbulence, phase, and wave length (except barrier diffraction). New wave-based image-source software (Olive Tree Lab-Terrain by PEMARD) uses theoretically accurate 3-dimensional algorithms that agree more closely with measurements than 9613. It takes into account reflections from finite impedance surfaces and finite-sized objects, applying Fresnel zone corrections as well as diffractions of unlimited orders from edges. The new software also calculates constructive and destructive interferences that are not possible with simpler algorithms, including 9613-2. Full-wave solutions (such as Greens Function-Parabolic Equation), which can also calculate wave-length effects, are usually too computation-intensive for design. The new software is computationally practical for the very large number of sources and sub-sources that are typically modeled during design. This paper compares results of calculations using selected advanced calculation algorithms from OTL-Terrain with measurements and those from 9613-2 both as a function of frequency and distance.

1. INTRODUCTION

ISO 9613-2[1], a simple and practical empirical method to calculate outdoor propagation of sound from a point source to a receiver, has been around since the year 1996 and has served the acoustical engineering community very well. Other methods dealing with outdoor sound propagation are VDI 2714[2], CONCAWE[3], Nord2000[4] and Harmonoise[5] among others. Nord 2000 and Harmonoise are considered more advanced calculation methods, since they apply more sophisticated propagation models (algorithms) based on physics, which give acceptable runtimes for engineering applications. All these methods can be described as 2.5 dimensional (more than 2, but less than a full 3 dimensional), calculating for each plane containing a ray between a source and a receiver. In 2011, P.E. Mediterranean Acoustics Research & Development (PEMARD) introduced Olive Tree Lab-Terrain[6], a wave-based geometrical acoustics software application that calculates (models) outdoor sound propagation in true three-dimensions. In contrast to the rest of the methodologies (except full-wave solutions), OTL-Terrain is based on physics using sound ray modeling to calculate wave phenomena from a source to a receiver to from 1 or 100 kHz, and any frequency resolution. The software also includes advanced image-source technology to compute for each ray from source to receiver in 3 dimensions.

2. ISO 9613-2 BACKGROUND

It is well known that this standard is based on empirical methods. Thus, one should offer criticism bearing this fact in mind. The authors consider the ISO 9613-2 standard (and other similar methods of the time[2,3]), as true innovation in acoustical engineering, since it encapsulates the essence of outdoor sound propagation and it offers engineers the possibilities of calculating complicated scenarios in a spreadsheet format. Later, 9613-2 was implemented in various ray-tracing software packages to make larger, more sophisticated, and more accurate models are possible.

Long before the 1970s there were theoretical models and methods to calculate atmospheric sound propagation, nevertheless, these models were and still are computationally intensive. Therefore, it made sense at the time to provide the community with a simple standard with simple equations. Such models and methods are described in detail in the relevant literature [1,4,**Error! Reference source not found.**].

In the authors' opinion, the weakest parts of this method are its vagueness, and doubts about its accuracy. A lot of modelling input parameters is based on the user's judgment rather than a standardized procedure. This weakness could be an argument against the method to be considered as a standard. For example, the user decides, material reflection properties, how to use foliage, site and housing attenuation factors, and whether ground reflections for vertical diffraction paths are important or not. The other weakest part of 9613-2 is doubts about its accuracy. Uneven ground cannot be properly modelled, calculations are carried out in 1/1 octave center frequencies, barrier diffraction is very approximate, and summing of multiple sound rays removes interference effects, just to mention a few. Further, the calculated levels are a long-term downwind average (say, one year) for conditions favorable to propagation. Calculations for a specific atmospheric condition are not possible. A more extensive critique of the standard is also found in Attenborough et al[7], and Brittain and Hale[8] and Brittain[9].

Bearing this in mind and that today's technology offers faster computers, it is inevitable that more sophisticated and accurate algorithms will be applied in practice, and that new methodologies based on physics will be implemented in software applications. This has already been already done in acoustics using a user-friendly interface, which allows the user to have a limited knowledge of the sophisticated mathematics and physical concepts.

3. OLIVE TREE LAB-TERRAIN, THEORETICAL BACKGROUND

OTL-Terrain is a software application that simulates and predicts sound propagation from a source to a receiver using wave based geometrical acoustics. It utilizes image source sound ray modelling in a proper 3D space that solves Helmholtz's sound wave equation, and thus calculates wave phenomena such as phase changes upon reflection due to finite reflector size and impedance, edge diffraction effects, turbulence, in resolutions down to 0.001Hz, between 1 to 100kHz. With a unique PEMARD methodology to detect all valid reflections and diffracted paths on inclined and non-parallel surfaces and from edges, OTL-Terrain frees the user from limitations inherent in various other methodologies. Lam[10] demonstrates that three dimensional spherical wave sound propagation, as implemented by wave-based geometrical acoustics, provides as accurate results as boundary element method (BEM) in room acoustics. The OTL-Terrain engine is based on a general geometrical acoustics ray model based on analytical solutions for various wave phenomena and can simulate sound propagation in arbitrary geometries.

The software application calculation engine is based on the work of Salomons[11] who applies a ray model using analytical solutions; spherical wave diffraction coefficients given by Hadden and Pierce[12]; spherical wave reflection coefficients based on the work of Chessel[13], and complex ground impedance based on the Delany and Bazley[14] model. Finite-size reflectors' Fresnel zones contribution is taken into account by applying the work of Clay et al[15]. The atmospheric turbulence model used is based on Harmonoise[5] and atmospheric attenuation is based on ISO 9613-1[16]. The Sound Path Explorer (SPE), a module in OTL-Terrain, is an algorithm developed in-house to detect valid diffraction and reflection sound paths from source to receiver in a proper 3D[17]. Sound path detection is based on the image-source method and the geometrical theory of diffraction according to Keller[18].

Economou et al[19] provides more information on the equations used by OTL-Terrain. The limitations of OTL-Terrain, for the time being, include: (a) noise sources do not have directivity properties, (b) no atmospheric refraction, and (c) only multiple point and line sources. It is expected that OTL-Terrain will give accurate results for long distances in a neutral atmosphere, and distances less 200 m in typical atmospheres. Finally, OTL-Terrain also includes the 9613-2 calculation method as an option for those who need to comply with regulations and for comparison purposes.

4. COMPARING OTL-TERRAIN WITH OTHER METHODOLOGIES

OTL-Terrain is briefly compared below with other mythologies to compute outdoor propagation for use in modeling. Please note that these descriptions are overly simplistic, and each software package has differences. Ray-tracing software (CadnaA, SoundPLAN, and Predictor-LimA) typically uses 9613-2 to calculate outdoor propagation from a point source to a receiver. The software provides point, line, area (horizontal or vertical), and volume (equipment and buildings) sources from which to model a facility, as well as barriers, buildings that are not sources. Ray-tracing software also automatically breaks (partitions) finite-sized sources into a series of point sources as needed to maintain user specified accuracy. All software described here also provides modeling tools, display of models in 3 dimensions, database functions, calculating SPL at receivers, and drawing contours. The software calculates all frequencies at from one source, and sums to get an A-weighted level. Then the contributions from all sources are summed. Brittain[20] has described some of the issues in modeling a power plant, and Hale and Brittain[21] compare accuracies of various types and sophistication of models. For further information on ray-tracing software, various suppliers should be consulted.

There is little consensus for names of various types of software for predicting outdoor propagation of community noise from various facilities. In most cases, software provides other functions as described above for ray-tracing software. The following terminology is suggested.

A. Ray-Tracing With Simple Outdoor Propagation Methodology

This includes 9613-2, VDI 2714, and CONCAWE. These have relatively simple algorithms for calculating outdoor propagation from a point source to a receiver. However, each source can have multiple paths to a receiver. Each reflection and diffraction occurs in a single plane, which can be neither horizontal nor vertical. All calculations assume a long-term (say, one year) downwind average under conditions favorable to propagation. Thus, 9613-2 implicitly assumes all receivers (even on opposite sides of a facility) are downwind. This gives what can be considered near-worst case calculated levels, and is convenient for design.

B. Ray-Tracing With More Sophisticated Outdoor Propagation Methodology

This includes Nord2000 and Harmonoise. The algorithms used are more sophisticated and accurate However, calculations are done for a specific atmospheric condition, including downwind (downwind) and upward diffracting (upwind) atmospheres. Such calculations are difficult to use for designing facility to meet a not-to-exceed community noise limit[22,9]. Ground effects, reflections, and diffractions are more accurate than using 9613-2. However, there are no wavelength effects, except for edge diffractions. Thus, constructive and destructive interferences cannot be calculated. Unlike OTL-Terrain, constructive and destructive interferences and other wave-based (length) effects cannot be accurately calculated, or even calculated at all. This limits the geometries that can be accurately calculated. (See next paragraph.)

C. Wave-Based Methods

This includes OTL-Terrain, parabolic equation (PE), and Greens function-parabolic equation (GF-PE), which are described by Sparrow et al[23]. (Finite and boundary element software are usually not used to calculate outdoor sound propagation, and are beyond the scope of this paper.) GF-PE solves the wave equation on a grid, has limitations (such as no backward propagation), and has user unfriendly interfaces. While GF-PE can calculate wave-length effects and atmospheric diffraction, it is usually too computation-intensive for design. On the other hand, OTL-Terrain uses solutions to the wave equation (see references) for each ray. This is much faster. OTL-Terrain can accurately calculate many (most?) wave-length effects. For example, Figures 7a, b, and c from Brittain and Hale[8] show geometries with propagation dimension that are on the order of a wavelength (at some frequencies OTL-Terrain can accurately calculate wave-based effects in each of these three cases. These configurations come from actual cases where the then available and practical software could not accurately perform these wavelength calculations (FEM and BEM were not considered practical.

The only known geometries where OTL-Terrain cannot accurately calculate wave-based effects are narrow slits (through which sound can propagate), and small holes or cavities. It is doubtful that OTL-Terrain can accurately calculate reflections from the extraordinarily complex equipment surfaces (heat recovery steam generator and huge pipe rack) shown in Figures 6 and 8 in Brittain and Hale[8]. Further, OTL-Terrain can accurately calculate reflections from ribbed metal panels on plant wall. These panels have both a specular reflection, and diffraction by edges of the ribs. However, at higher frequencies, more modeling detail is needed, because smaller objects can diffract sound. It is suggested that wave-based calculations be tested before relying on calculations.

5. COMPARISON WITH PUBLISHED DATA

Isei et al[24] compares results calculated using 9613-2 and OTL-Terrain with published data in terms of excess attenuation. In this paper, comparison is done in terms of sound pressure level (SPL or Lp, in dB) in octave bands, broadband A-weighted and linear levels, and narrow bands. Results using OTL-Terrain are calculated with high-frequency resolution, which are then logarithmically added within the corresponding octave bands, in contrast to the 9613-2 methodology, which calculates only at the octave-band center frequencies.

Due to limited space, the purpose of the comparison is to highlight the differences in results between OTL-Terrain and 9613-2 methodologies, in the following cases: (a) effect of barrier on ground at normal incidence; (b) effect of barrier on ground at oblique incidence; (c) hard and porous ground effects between source and receiver in terms of distance and frequency, up to 200m where atmospheric refraction may be neglected Salomons[25], and (d) an example case study. Any comparison among published data, OTL-Terrain and 9613-2 methodologies is done here for the sole purpose of validating the methods in terms of Excess Attenuation. In all other cases, comparison is conducted between OTL-Terrain and 9613-2 in terms of SPL. In all cases, there is a point source, a receiver, and ground of finite impedance, no atmospheric effects, with or without a semi-infinite noise barrier.

6. COMPARISON OF RESULTS

Calculations done with OTL-Terrain, which includes PEMARD methodology for calculating rays in 3 dimensions, are compared below with results calculated using 9613-2. The 9313-2 results were calculated using an optional provision in OTL-Terrain for calculations using only 9613-2 methodology. In the figures, the term PEMARD is used instead of the more accurate OTL-Terrain, and similarly ISO instead of 9613-2. As indicated previously, all results are for a neutral atmosphere – no wind, no atmospheric refraction (rays are straight with no bending upward or downward), and no turbulence.

A. Effect of barrier at normal sound incidence

The following terminology is used the proceeding figures. Hs=source height, Hr=receiver height, Dsr=Source-Receiver distance, Hb=barrier height, GFR=ground flow resistivity, HG=hard ground, PG/(SG)=porous, (soft) ground. The complex impedance is calculated from the flow resistivity using the Delany and Bazley methodology.[14]

1. Validation of OTL-Terrain results with published data

The following geometry, is found in Isei et al[24] and reproduced by Hadden and Pierce's[12], model, compare the accuracy of OTL-Terrain calculations. More validation projects[26] by PEMARD are available on the Internet. Figure 1 shows the geometry modeled and ground parameters. Figure 2(a) shows the insertion loss, and 2(b) excess attenuation. Superimposed on Pierce's[12] graph are OTL-Terrain's results displayed in colored dashed lines, which are almost indistinguishable. Thus, the lines from Pierce and OTL-Terrain are plotted as the same dashed lines. The incoherent results are the sum of the five possible diffraction paths, four of which include ground reflections, taking amplitude and phase of each path into account. The variations (fluctuations) show constructive and destructive interferences, which result from including phase in the summations. These also show the effects of hard and soft ground. The colored solid lines and markers show the 9613-2 results, which were calculated by subtracting the final spectrum at the receiver from the power spectrum of the source. These lines are the log sum of amplitudes of each propagation path. Since this sum ignores phase, there are no constructive or destructive interferences. (It should be noted that in most cases, turbulence and other effects would significantly reduce the destructive interferences – local minimums.) OTL-Terrain results match to the last detail the calculations by Attenborough et al[7]. As expected, 9613-2 deviates substantially from wave-based results. Here, the source is on the left side of the barrier, and the receiver is on the right side.

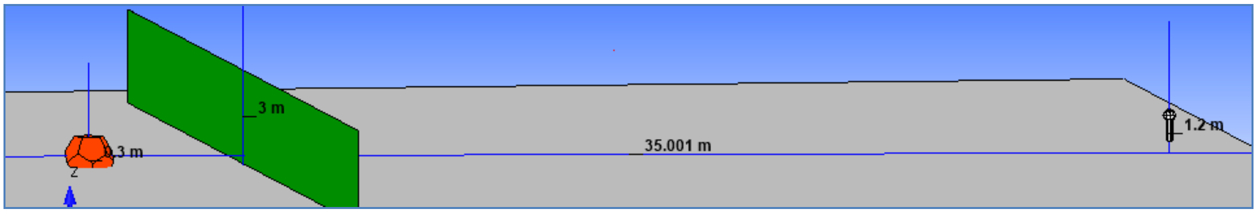
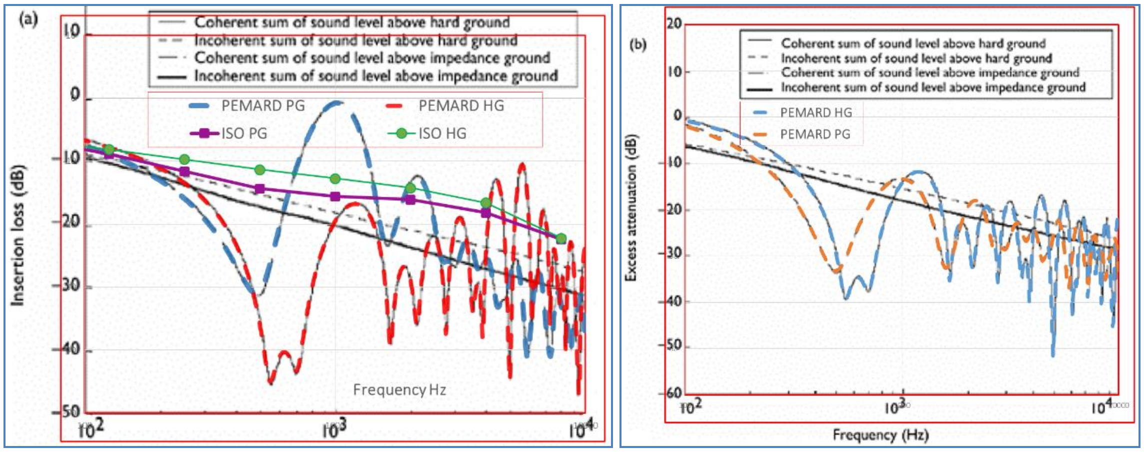


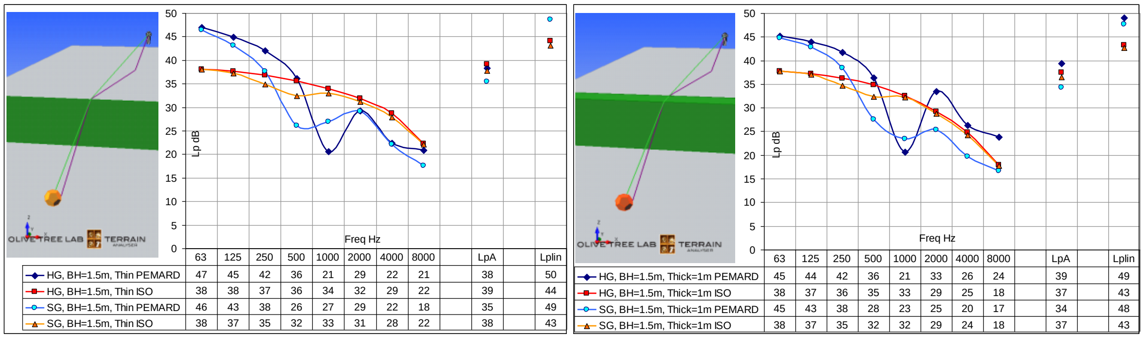
Figure 1: Geometry of set up in Terrain from Isei, Hs=0.3m, Hr=1.2m, Hb=3m, Dsr=variable in Fig 1(a) and 1(b), HG=GFR=20 MNs/m^4, PG=GFR=300 kNs/m^4



(a) (b)

Figure 2: Validation of results from Isei's geometry. Calculations are superimposed on graph courtesy of Attenborough et al. (a) Insertion loss of barrier with hard and porous ground effects. In colored dashed lines, OTL-Terrain results are almost indistinguishable from the original graphs Solid lines and markers show the 9613-2 results. (b) Excess attenuation with barrier in place, colored dashed lines show OTL-Terrain results.

Figures 3 to 5 show the effect on calculated SPL by varying the height and width of an infinite horizontal barrier in Isei's set up. Source-receiver-ground geometry is fixed, while the effect of hard versus porous ground is also investigated. All figures also show 9613-2 and OTL-Terrain results. The diffraction by the top of the barrier has four paths (all are shown) – one with no ground reflections, two with one reflection each, and one with two ground reflections.

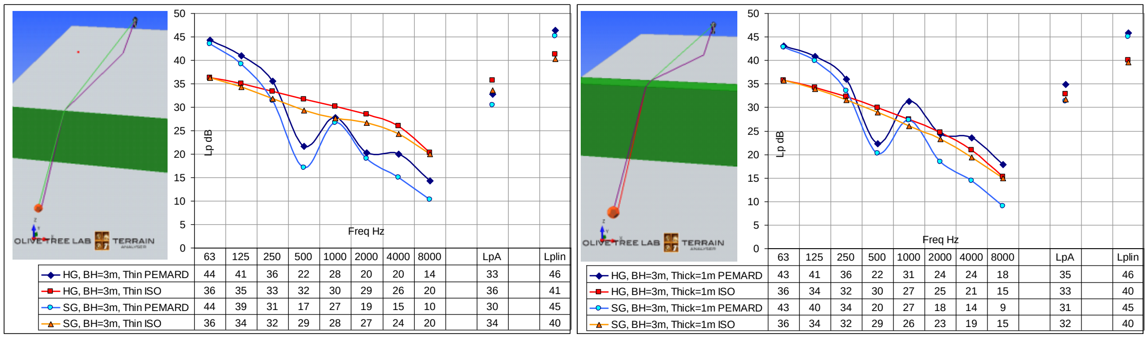


	63	125	250	500	1000	2000	4000	8000		LpA		Lplin
HG, BH=1.5m, Thin PEMARD	47	45	42	36	21	29	22	21		38		50
HG, BH=1.5m, Thin ISO	38	38	37	36	34	32	29	22		39		44
SG, BH=1.5m, Thin PEMARD	46	43	38	26	27	29	22	18		35		49
SG, BH=1.5m, Thin ISO	38	37	35	32	33	31	28	22		38		43

	63	125	250	500	1000	2000	4000	8000		LpA		Lplin
HG, BH=1.5m, Thick=1m PEMARD	45	44	42	36	21	33	26	24		39		49
HG, BH=1.5m, Thick=1m ISO	38	37	36	35	33	29	25	18		37		43
SG, BH=1.5m, Thick=1m PEMARD	45	43	38	28	23	25	20	17		34		48
SG, BH=1.5m, Thick=1m ISO	38	37	35	32	32	29	24	18		37		43

(a) (b)

Figure 3: Isei's geometry, barrier height 1.5m, thin & wide, and hard vs. porous ground. SPL spectra, L_{pA} and L_p values based on Isei's geometry, HG=GFR=20 MNs/m^4, PG (SG)=GFR=300 kNs/m^4 (a) Hs=0.3m, Hr=1.2m, Hb=1.5m, Dsr=35m, (b) Hs=0.3m, Hr=1.2m, Hb=1.5m, 1m thick barrier, Dsr=35m.

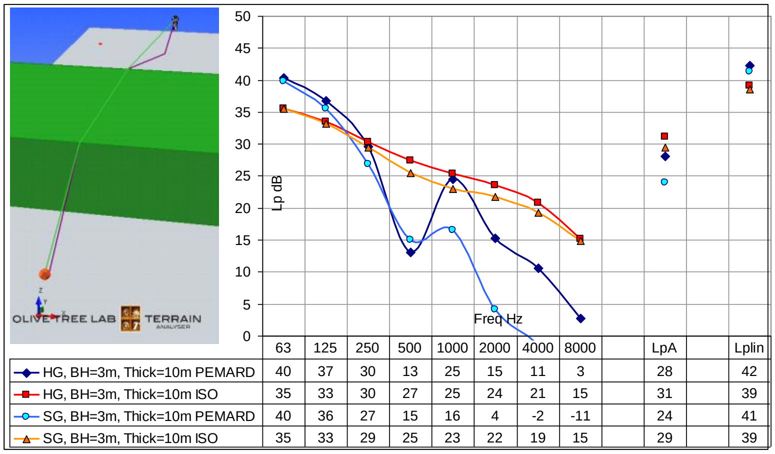


	63	125	250	500	1000	2000	4000	8000		LpA		Lplin
HG, BH=3m, Thin PEMARD	44	41	36	22	28	20	20	14		33		46
HG, BH=3m, Thin ISO	36	35	33	32	30	29	26	20		36		41
SG, BH=3m, Thin PEMARD	44	39	31	17	27	19	15	10		30		45
SG, BH=3m, Thin ISO	36	34	32	29	28	27	24	20		34		40

	63	125	250	500	1000	2000	4000	8000		LpA		Lplin
HG, BH=3m, Thick=1m PEMARD	43	41	36	22	31	24	24	18		35		46
HG, BH=3m, Thick=1m ISO	36	34	32	30	27	25	21	15		33		40
SG, BH=3m, Thick=1m PEMARD	43	40	34	20	27	18	14	9		31		45
SG, BH=3m, Thick=1m ISO	36	34	32	29	26	23	19	15		32		40

(a) (b)

Figure 4: Isei's geometry, barrier height 3m, thin & wide, and hard vs. porous ground. SPL spectra, L_{pA} and L_p values based on Isei's geometry, HG=GFR=20 MNs/m^4, PG (SG)=GFR=300 kNs/m^4 (a) Hs=0.3m, Hr=1.2m, Hb=3.0m, Dsr=35m, (b) Hs=0.3m, Hr=1.2m, Hb=1.5m, 1m thick barrier, Dsr=35m**.**



	63	125	250	500	1000	2000	4000	8000		LpA		Lplin
◆ HG, BH=3m, Thick=10m PEMARD	40	37	30	13	25	15	11	3		28		42
■ HG, BH=3m, Thick=10m ISO	35	33	30	27	25	24	21	15		31		39
○ SG, BH=3m, Thick=10m PEMARD	40	36	27	15	16	4	-2	-11		24		41
▲ SG, BH=3m, Thick=10m ISO	35	33	29	25	23	22	19	15		29		39

Figure 5: Isei's geometry, barrier height 3m, 10m thick, and hard vs. porous ground. SPL spectra, L_{pA} and L_p values based on Isei's geometry, HG=GFR=20 MNs/m^4, PG (SG)=GFR=300 kNs/m^4, Hs=0.3m, Hr=1.2m, Hb=1.5m, 10m thick barrier, Dsr=35m.

From these figures, it is apparent that all spectra, A-weighted and linear levels, differ between the OTL-Terrain and 9613-2 methodology results for every case examined. Furthermore, there is a consistent tendency for the A-weighted levels calculated using 9613-2 to be higher than the OTL-Terrain levels by a few dB. The opposite tendency appears in the linear broadband levels, with OTL-Terrain calculations to be higher by up to 6dB than the 9613-2 levels. However, deviations in octave bands are much higher. OTL-Terrain results in octave bands are up to 5 dB higher at low frequencies and generally 10 to 20 dB lower above 250 Hz. For designing to meet octave-band community noise limits or prevent annoyance, 9613-2 would be expected to predict the need for far more extensive noise control, and possibly vastly, more expensive than OTL-Terrain.

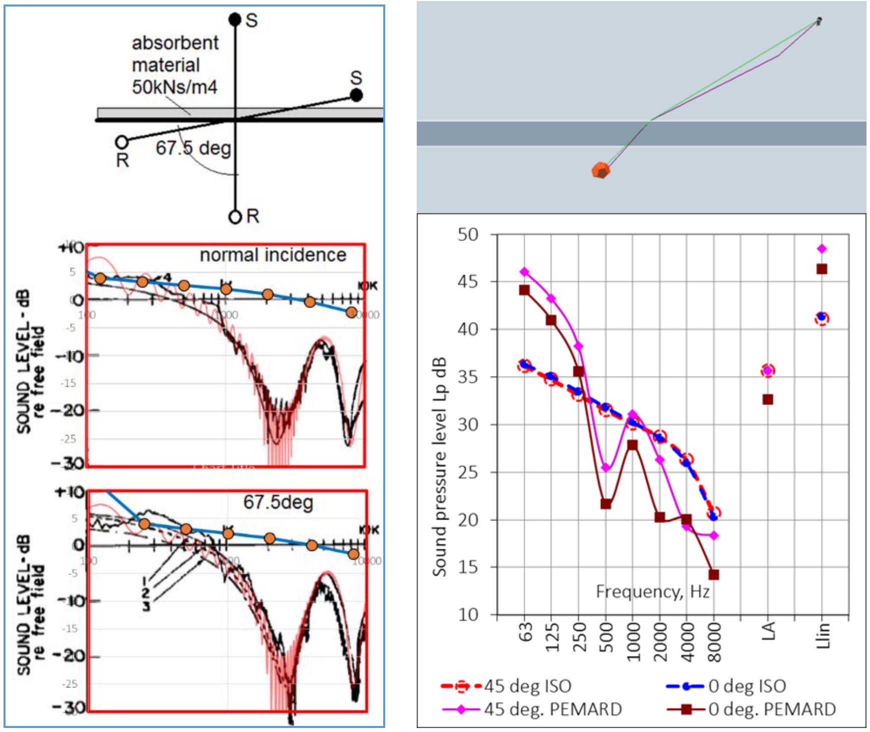
2. Effect of barrier at oblique sound incidence

The effect of a sound wave with both normal and oblique incidence to a barrier placed on a hard ground is shown. This effect was studied experimentally by Isei et al[24]. Figure 6(a) shows this results with OTL-Terrain (labeled as PEMARD) and 9613-2 (labeled as ISO) calculations are superimposed on the graph. Frequencies range from 100 to 10,000 Hz. The oblique ray is 67.5 degrees from the normal. In light red, solid curved and rapidly fluctuating lines are the results from OTL-Terrain. Curves 1, 2, 3 show excess attenuation as predicted by Isei et al. for a reflective barrier, an absorptive barrier (50 cgs) and a perfectly absorptive barrier (0 cgs). The nearly straight thick blue solid lines with markers show the results from 9613-2. Hs=0.125m, Hr=0.125m, Hb=0.26m, Dsr=2.0m are the same for both normal and oblique incidence (kept constant by rotating source and receiver about the center of the barrier). The entire source side was covered by absorbent material with FR=50kNs/m4. The fluctuations in level with frequency must be attributed to diffraction effects around the vertical edges of a finite-width barrier, which was assumed to be 3.6m including the absorbing material.

Wave-based results Figure 6(a) are 10 to 25 dB lower than calculated by 9613-2 above 1000 Hz. However, the general shape of wave-based results above 1000 Hz is similar.

Figure 6(b) shows the standard geometry from Isei (Figure 1) for source and receiver at both at normal incidence and at 45 degrees with the barrier located a fixed Dsr distance of 35m, and over hard ground. OTL-Terrain calculations are plotted in solid lines with markers, while 9613-2 calculations in dashed lines with markers. The two 9613-2 lines are nearly identical.

In Figure 6(b), A-weighted levels increase at the receiver by 3 dB when the source is moved from normal incidence to a 45 degrees incidence, as observed from plan view. Compared to 9613-2, The OTL-Terrain spectra are once again higher at low frequencies, and generally much lower above 250 Hz. These general effects are noticeable in Figure 6(a), too. What is remarkable is that the 9613-2 calculations are insensitive to the direction of sound incidence to the barrier, in contrast to results from OTL-Terrain.



(a) (b)

Figure 6: (a) shows the results from Isei et al for oblique versus normal sound incidence to a barrier. OTL-Terrain (light red curved or fluctuating solid line) and 9613-2 results (blue solid nearly straight line with markers) superimposed on the graph. Geometry and description of the setup is given in the above paragraph. (b) shows the standard geometry from Isei (Figure 1) for source and receiver at both 45 degrees and normal to the barrier at a fixed Dsr distance of 35m over hard ground. OTL-Terrain calculations in solid lines with markers, while 9613-2 calculations in dashed lines with markers.

C. Hard and porous ground effects in terms of distance and frequency

1. *Validation of OTL-Terrain results with measured data and NORD2000*

For the validation of ground effects for road noise, Figure 7 compares measured results[27] for Case 77 with calculations using Nord2000 and OTL-Terrain. Case 77 is used, which models a source and a receiver over finite impedance ground at a distance of 100m without any atmospheric effects (neutral atmosphere). Hs=1.55m, Hr=2.00m, Dsr=100m, PG=GFR=630 kNs/m^4. The measurements were taken during the validation of Nord2000 model[27]. ISO 9613-2 includes octave-band frequencies only down to 63 Hz. (Some suppliers of ray-tracing software include lower frequencies, 1/3 octave bands, and other deviations from 9613-2.)

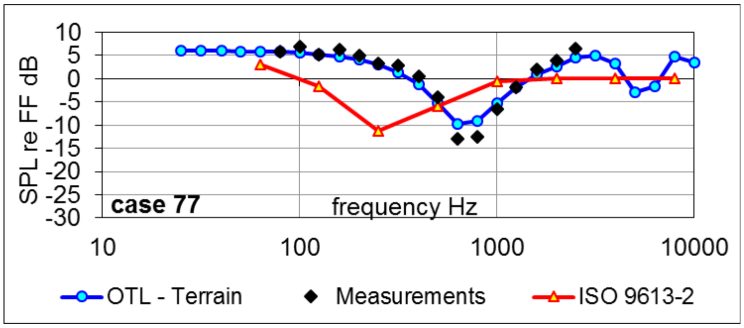
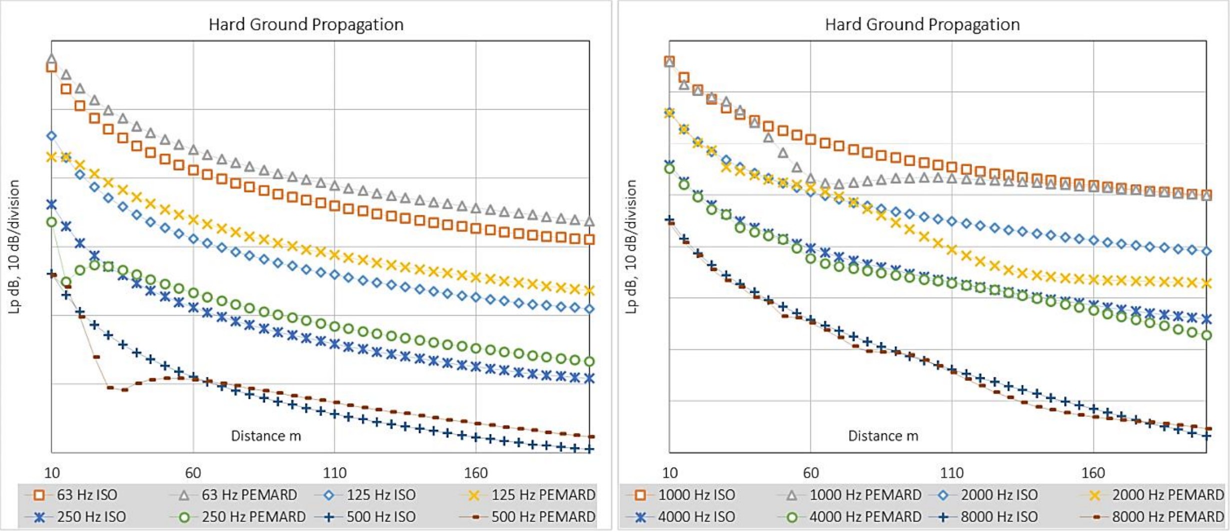


Figure 7: Comparison measured road noise with calculations using OTL-Terrain and Nord2000. Hs=1.55m, Hr=2.00m, Dsr=100m, PG=GFR=630 kNsm^4, from Ref 25

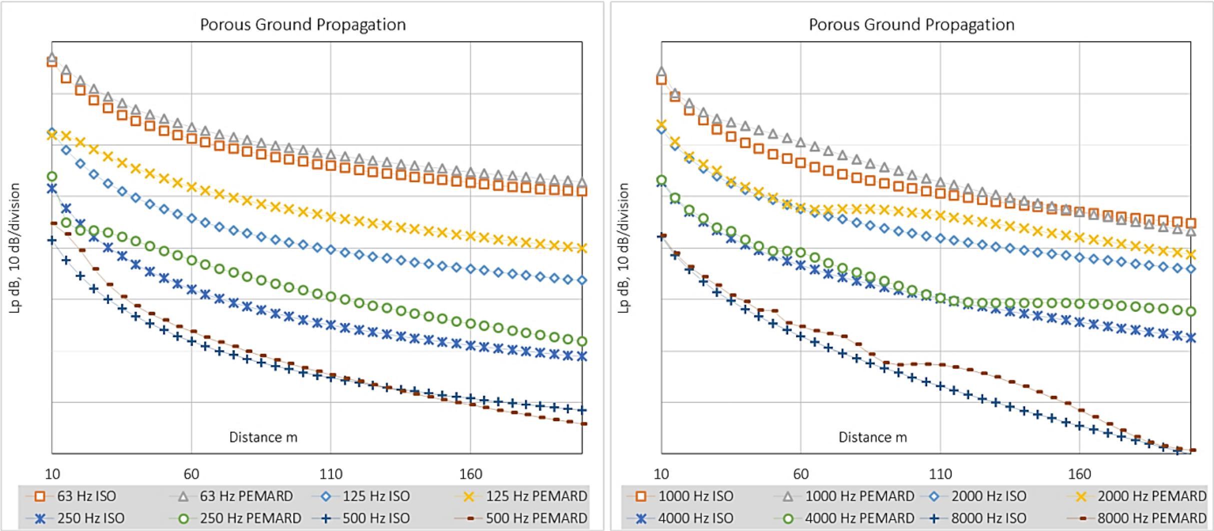
2. *Octave band levels vs distance, Hard vs Porous Ground*

Below sound propagation over hard and porous ground (GFR= 20 MNs/m^4, and 300 kNs/m^4 respectively) is computed with Hs=5m and receivers at Hr=1m every 10m from the source to 200m. Atmospheric refraction is considered to be negligible at distances up to 200m^4. Figures 8 to 9 show octave-band levels against distance, L_{pA}, A-weighted levels and L_p, linear levels against distance respectively, computed using OTL-Terrain and 9613-2. Figures 8 and 9 are for hard and soft ground, respectively. While results from OTL-Terrain and 9613-2 are similar in shape, differences of up to about 6 dB occur.



(a) (b)

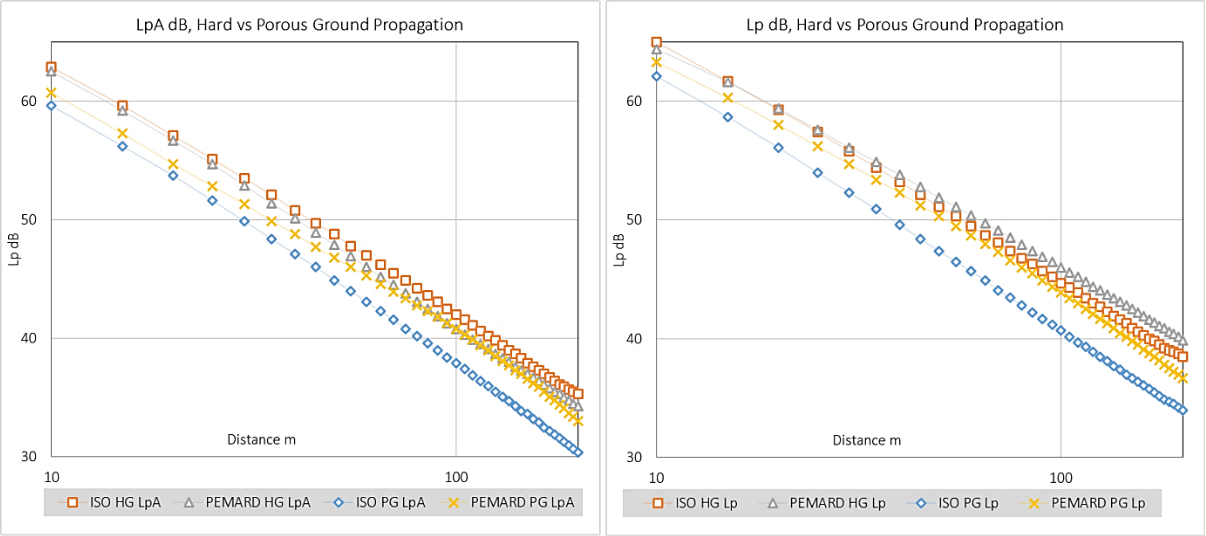
Figure 8: Sound propagation over hard ground in relative levels (10 dB/division), (a) in octave bands between 63 and 500 Hz and (b) from 1000 and 8000 Hz. HG=GFR= 20 MNs/m^4, and PG=GFR=300 kNs/m^4, with Hs=5m and receivers at Hr=1m every 10m from the source to 200m.



(a) (b)

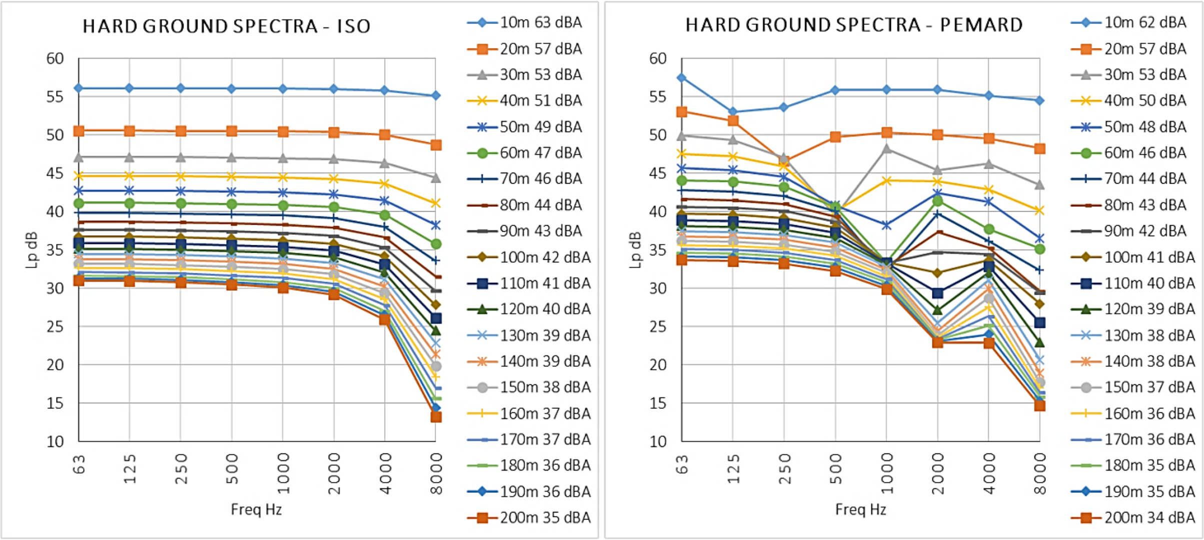
Figure 9: Sound propagation over porous ground in relative levels (10 dB/division), (a) in octave bands between 63 and 500 Hz and (b) from 1000 and 8000 Hz. HG=GFR= 20 MNs/m^4, and PG=GFR=300 kNs/m^4, with Hs=5m and receivers at Hr=1m every 10m from the source up to 200m.

Figure 10 shows how A-weighted levels vary with distance calculated from 10 to 200m using 9613-2 and OTL-Terrain. Source height Hs=5m and receivers at Hr=1m height every 10m from the source to 200m over hard and porous ground, GFR= 20 MNs/m4, and 300 kNs/m4 respectively. Figure 10 shows the results of OTL-Terrain and 9613-2 methodologies show consistent small differences with distance. However, they conceal ground interference effects that can be very dramatic at certain frequencies and at certain distances. Figures 11 and 12 show the shape of the spectra at various distances from the source with hard and porous (soft) ground respectively. The configurations are identical to those of Figure 10 including the ground.



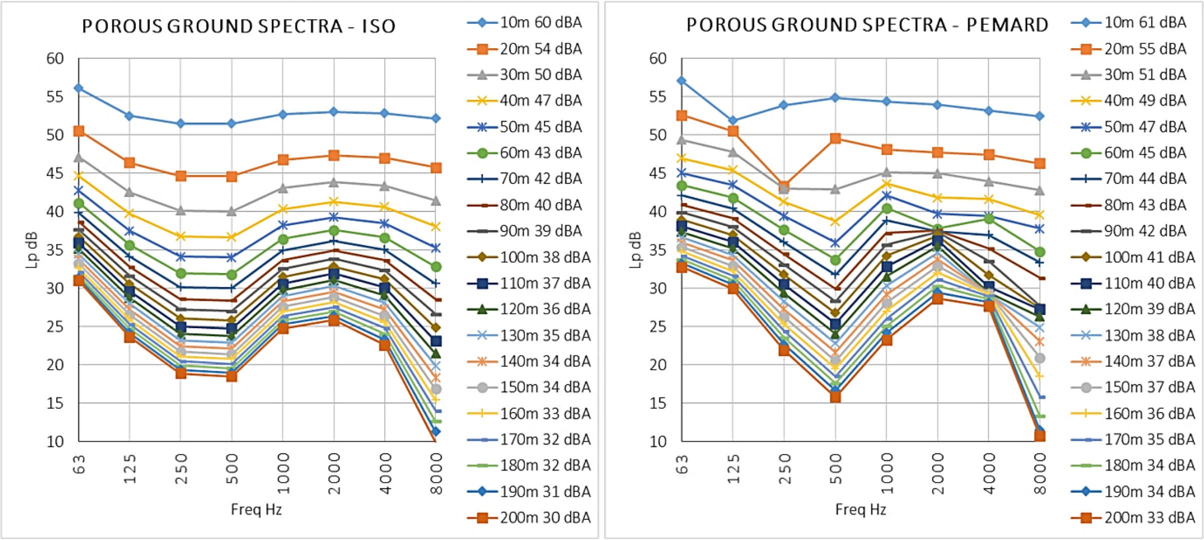
(a) (b)

Figure 10: Sound propagation over hard vs. porous ground in absolute levels, (a) A-weighted levels in dBA. (b) Linear levels in dB. HG=GFR= 20 MNs/m^4, and PG=GFR=300 kNs/m^4, with Hs=5m and receivers at Hr=1m every 10m from the source up to 200m.



(a) (b)

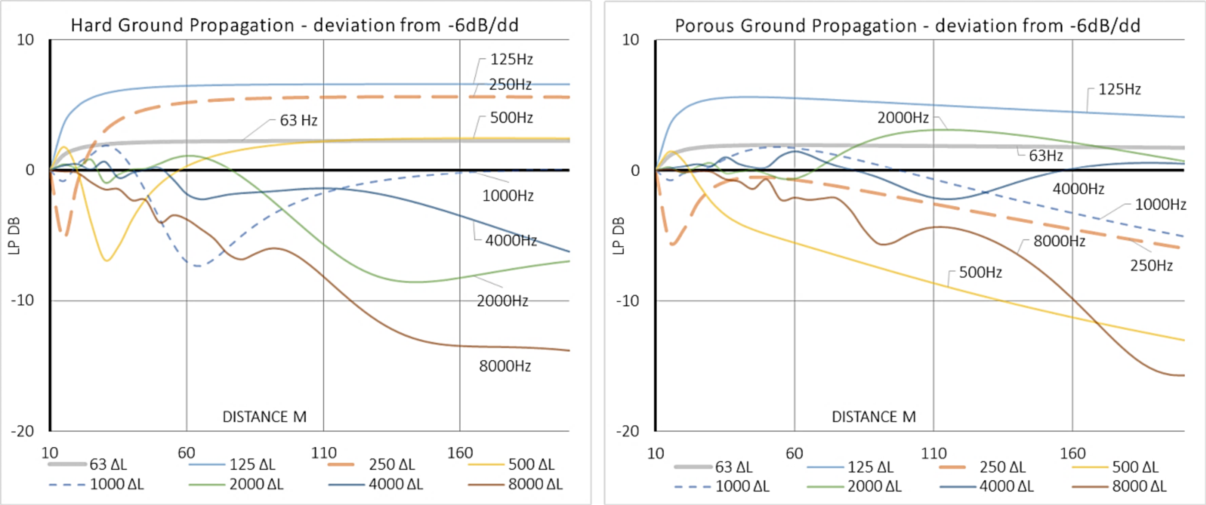
Figure 11: Sound spectra at various distances from the source over hard ground. The legend includes A-weighted levels in dB at each distance from the source, (a) 9613-2 results, (b) OTL-Terrain results. HG=GFR= 20 MNs/m^4, and PG=GFR=300 kNs/m^4, with Hs=5m and receivers at Hr=1m every 10m from the source up to 200m.



(a) (b)

Figure 12: Sound spectra at various distances from the source over porous ground. The legend includes dBA levels at each distance from the source, (a) 9613-2 results, (b) OTL-Terrain results. HG=GFR= 20 MNs/m^4, and PG=GFR=300 kNs/m^4, with Hs=5m and receivers at Hr=1m every 10m from the source up to 200m.

Figures 13 (a) and (b) show geometrical attenuation (with atmospheric absorption) calculated using OTL-Terrain deviates from the -6dB/dd for spherical spreading over hard and porous ground, respectively. ISO 9613-2 uses spherical spreading in all cases. A reference SPL at 10m is assumed. Zero values indicate -6dB/dd. For example, at 10m the level is 100 dB, while at 15m it is 98.2 dB. The -6dB/dd rule is calculate according to 100-20log(15m/10m)=96.5 dB, therefore the difference between the OTL-Terrain results (98.2 dB) minus the -6dB/dd rule (96.5 dB), (1.7 dB at 15m) are plotted below against distance. Any deviation from zero indicates that the spherical spreading rule does not apply even in a neutral atmosphere. Deviations of up to +6 to -12 dB were calculated.

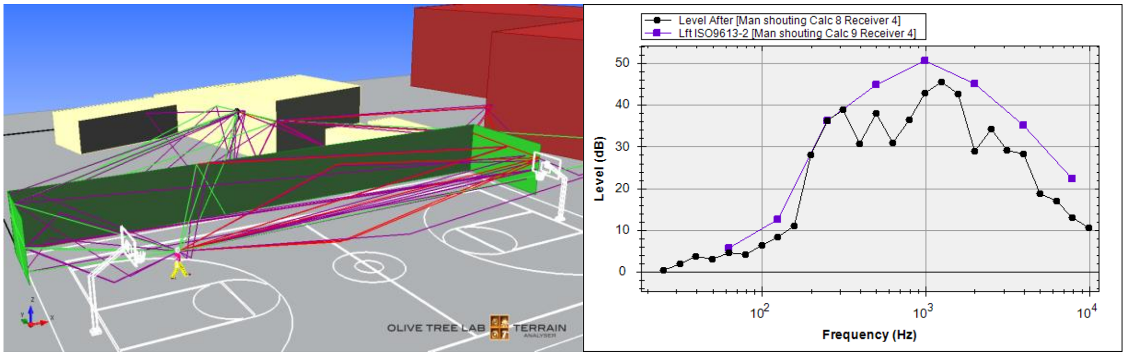


(a) (b)

Figure 13: Geometrical attenuation as a function of distance calculated using OTL-Terrain for octave-band center frequencies. Fig 13(a) over porous ground and (b) over hard ground. The horizontal line at 0 dB represents spherical spreading with of -6dB/dd, which is used by 9613-2.

D. Case study – basketball court affecting neighbors with people shouting

Finally, an example demonstrates in practice the differences between OTL-Terrain and 9613-2 calculation results. A basketball court in a neighborhood affects nearby residences with human activity especially, with shouting. Figure 14(a) shows the 3D model with the many reflected and diffracted sound paths from a man shouting toward a neighbor's façade. Figure 14 (b) shows the spectra at the façade, in 1/1 octave bands, for the 9613-2 calculation results, and in 1/3 octave bands for the OTL-Terrain calculations. OTL-Terrain values are lower since they are in narrower 1/3 octave bands.



(a) b)

Figure 14: Figure 14(a) shows the 3D model and the sound paths from a man shouting to a neighbor's façade. Figure 14 (b) shows the spectra at the façade, in 1/1 octave bands, for the ISO calculation results, and in 1/3 octave bands for the OTL-Terrain calculations. OTL-terrain levels are lower since they are in 1/3 octave bands.

7. DISCUSSION AND CONCLUSIONS

A. Effect of barriers at normal sound incidence

As expected, the 9613-2 does not provide interference (constructive and destructive) effects, therefore, the SPL spectrum at the receiver lacks information about interference effects from barrier and ground due to sound diffraction and reflection. Overall, A-weighted levels (L_{pA}) calculated by the 9613-2 method are higher than those using OTL-Terrain, whereas the opposite applies in linear broadband levels. As it is also evident from the spectra, OTL Terrain's calculations show significant low frequency contribution at the receiver. Even though usually the effect of noise on humans is rated using A-weighted values, the effects of sound on building elements and habitable spaces depend on incident sound spectra. Usually low frequency sounds excite building facades resonances, which in turn excite room modes in habitable spaces with adverse effects on humans, especially low frequency sounds from road and air traffic noise. Therefore, there is value in assessing noise effects by the use of accurately calculated spectra rather than approximations. Concerning differences between OTL-Terrain and 9613-2 A-weighted values, these range between 1 – 5 dB depending on geometry.

B. Effect of barriers at oblique sound incidence

From Figure 6, it can be seen that the 9613-2 methodology is insensitive to oblique sound incidence, while the OTL-Terrain methodology shows that SPLs increase at oblique incidence. This phenomenon, is similar to sound absorption and transmission, which, depending on surface impedance, tends to increase with the angle of incidence reaching maximum effect close to grazing angles of incidence.

C. Hard and porous ground effects between source and receiver in terms of distance

Comparison of the A-weighted SPLs between OTL-Terrain and 9613-2 methodologies show consistent small differences with distance. However, they conceal ground interference effects, which can be very dramatic at certain frequencies and at certain distances. ISO 9613-2 fails to imitate hard and porous ground excess attenuation due to interference. Comparing A-weighted broad band values between OTL-Terrain and 9613-2, for hard ground there is a consistent 0 - 1dB difference, with OTL-terrain values being lower. This difference increases for porous ground propagation and it varies from 1-3 dBs, with OTL-terrain values being higher. On the other hand By including ground effects, Figures 13 (a) and (b) demonstrate how OTL-Terrain results deviate from the accepted rule of thumb of -6dB/dd rule over hard and porous ground respectively.

D. A case study – Basketball court affecting neighbors with people shouting

The results of a case study show there is a difference of 2 dBA between OTL-Terrain and 9613-2 calculations, with the latter being higher.

Overall, it is obvious that the 9613-2 method fails to accurately portray acoustical phenomena such as reflection and diffraction. Then again, it was never meant to fulfill this task, but merely provide a standardized method by which all engineers studying the same project should end up having the same results. On the other hand, the need for increased accuracy seems obvious – that is applying scientific not engineering in practice. Technology now provides such tools, because not only more accuracy and precision in the field is needed, but also it is also very instructional to be able to simulate problems and see how each physical parameter affect each other as well as the overall system and to which degree. The increased accuracy and sensitivity help identify and quantize propagation paths, provide better understanding of the phenomena, and the extent to which each path affects the overall results. This can be done as a function of both frequency and distance.

E. Future Uses of OTL Terrain

Since two authors are employed by PEMARD, Frank Brittain is solely responsible for this paragraph to help avoid the impression of bias. As described in Section 4, OTL-Terrain offers what appears to be unique abilities to accurately perform wave (length) based calculations with a convenient graphic user interface and acceptable runtimes. Other software known to this author cannot do this, except full-wave methods, which have their own limitations, very clumsy user interfaces, and normally excessive runtimes. OTL-Terrain can be used to study geometries where wave-length effects affect sound propagation, to estimate whether wavelength effects appreciably affect the calculations, to design noise controls that cannot otherwise be practically modeled, and/or compute insertion losses of controls or configurations for use in ray-tracing software, including those with simple and more sophisticated (and accurate) methodologies to compute outdoor propagation. While little has been done with this capability, it is expected that OTL-Terrain's capabilities to accurately calculate wave length effects have important practical applications. Figures 7a, b, and c from Brittain and Hale[8] show three configurations where OTL Terrain can accurately calculate wave-based effects, but even more advanced ray tracing cannot. These configurations come from actual cases where the then-available and practical software could not accurately perform these wavelength calculations. (FEM and BEM were not considered practical.)

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