An integrated approach to Acoustics - sound propagation and the phenomena affecting it
Morse and Bolt in their 1944 paper say on page 87: “It has been demonstrated in a number of ways that the absorption coefficient entering into the geometrical acoustical formulas is not a fundamental property of the wall surface…. It is an average property, averaged for the particular distribution of sound which we have called "ergodic" in the previous section, and has no meaning in cases where the sound distribution is not ergodic. It is well to emphasize this limitation on the use of the term absorption coefficient, for an over-optimistic use of the term may lead to erroneous results…. It is true that the impedance is not a much more "fundamental" physical property than the absorption coefficient; its advantage lies in the fact that its measurement can be specified concisely and uniquely and that its value for a given material has a definite meaning no matter what the distribution of sound inside a room.”
PART 1: INTRODUCTION – FROM OPEN SPACES TO ROOMS

SPHERICAL & GROUND WAVES

“...Practically, one never has plane waves. They are a mathematical fiction which can be only approximated physically.”
Isadore Rudnick, 1947, JASA VOLUME 19, NUMBER 2, “The Propagation of an Acoustic Wave along a Boundary”
A ground wave occurs when the incident sound field spreads spherically, as from a small source near the ground, and so reaches different parts of a plane surface with different angles of incidence. Changing angles of incidence produce a reflection coefficient that varies with position along the surface....The result is that there cannot be an image I in the ground that is spatially a replica of the true source S, and not even one of reduced strength. Theoretical analysis shows that there is a “fuzzy” image distributed over an extensive region. It is strongest at the expected location but extends to infinity both horizontally and downward.”
“Therefore any argument which assumes that the reverberant sound can be represented by a multiplicity of simple images is likely to lead to fallacious results. The analyses of Sabine, Norris, Eyring, Millington, and Sette are subject to this criticism”.

REVIEWS OF MODERN PHYSICS, VOLUME 16, NUMBER 2 APRIL, 1944, Sound Waves in Rooms, PHILIP M. MORSE AND RICHARD H. BOLT
Theodore J. Schultz in his paper “Persisting questions in steady-state measurements of noise power and sound absorption” starts with, “...in view of the great number of recent studies on this subject, the reverberation room seems to be turning into a "research object" rather than a "useful tool." ...it is almost incredible to me that we could produce such a complex and mysterious thing, just by putting up four walls, a floor and a ceiling, and then radiating sound into it. And yet the more we study sound in an enclosed space, the more peculiar it seems. If our earlier theories made the behavior of sound in rooms appear simple, our recent studies are certainly correcting that naive view.”

“Persisting questions in steady-state measurements of noise power and sound absorption” Theodore J. Schultz, JASA Volume 54 Number 4 1973
PART 1: INTRODUCTION – ACOUSTICAL CURIORSITIES

A REFLECTION OVER A SURFACE –
IS THERE MORE THAN ONE ANSWER TO THE PROBLEM?
PART 1: INTRODUCTION – ACOUSTICAL CURIORSITIES

1: Spherical wave, Impedance, pressure summation

The figure on the left shows the configuration while the figure on the right
Excess Attenuation in dB (the ratio of total over direct sound field).

ROOM RESONANCES USING WAVE BASED GEOMETRICAL ACOUSTICS (WBGA), ECONOMOU ET AL, ICSV23, JULY 2016
PART 1: INTRODUCTION – ACOUSTICAL CURIOSITIES

2: Plane wave, Impedance, pressure summation

ROOM RESONANCES USING WAVE BASED GEOMETRICAL ACOUSTICS (WBGA), ECONOMOU ET AL, ICSV23, JULY 2016
PART 1: INTRODUCTION – ACOUSTICAL CURIORSITIES

3: Plane wave, absorption coefficient, pressure summation.

ROOM RESONANCES USING WAVE BASED GEOMETRICAL ACOUSTICS (WBGA), ECONOMOU ET AL, ICSV23, JULY 2016
PART 1: INTRODUCTION – ACOUSTICAL CURIOUSITIES

4: Plane wave, absorption coefficient, energy summation.

ROOM RESONANCES USING WAVE BASED GEOMETRICAL ACOUSTICS (WBGA), ECONOMOU ET AL, ICSV23, JULY 2016
PART 1: INTRODUCTION – FROM OPEN SPACES TO ROOMS

Tony F. W. Embleton: Sound propagation outdoors

FIG. 6. Relative sound pressure levels measured 5 m from a point source at the surface of an acoustically soft ground (grass). Results are for four different receiver heights, $h_r = 0.02, 0.3, 0.6, \text{ and } 1.2$ m, respectively (Ref. 13, Fig. 5).
PART 1: INTRODUCTION – ACOUSTICAL CURIORSITIES

SOUND DIFFRACTION
PART 1: INTRODUCTION – FROM OPEN SPACES TO ROOMS

THE SEAT DIP EFFECT USING WAVE BASED GEOMETRICAL ACOUSTICS (WBGA), ECONOMOU ET AL, ICSV23, JULY 2016
PART 1: INTRODUCTION – FROM OPEN SPACES TO ROOMS

THE SEAT DIP EFFECT USING WAVE BASED GEOMETRICAL ACOUSTICS (WBGA), ECONOMOU ET AL, ICSV23, JULY 2016
PART 1: INTRODUCTION – FROM OPEN SPACES TO ROOMS

THE SEAT DIP EFFECT USING WAVE BASED GEOMETRICAL ACOUSTICS (WBGA), ECONOMOU ET AL, ICSV23, JULY 2016
PART 2: PEMARD APPROACH

THE P. E. MEDITERRANEAN ACOUSTICS RESEARCH & DEVELOPMENT (PEMARD) APPROACH
What is Wave Based Geometrical Acoustics (WBGA)?
It is the method by which the calculation of acoustical fields take into account the principle of superposition of waves using both amplitude and phase, producing interference phenomena.
PART 2: PEMARD APPROACH

SOUND REFRACTION IN THE ATMOSPHERE
PART 2: PEMARD APPROACH

Figure 2: Comparison between OTL-Suite calculations (red line) and 1995 Benchmark Cases (black line). Left graph is for the case of a strong positive linear sound speed gradient of 0.1 s\(^{-1}\) while the right graph is for the case of a strong negative sound speed gradient of -0.1 s\(^{-1}\). Both curves show transmission loss vs distance at 100Hz. Calculated graphs are superimposed on published data.

WIND TURBINE NOISE PREDICTION USING OLIVE TREE LAB TERRAIN, WTN, INCE-EUROPE, BIGOT, ECONOMOU, MAY 2017
Figure 7: Left graph: Measured and predicted noise levels for WTN Case 2. Right graph: Measured and predicted Noise Levels for Case 2 in dB(A) for a set of 10-minute meteorological data. Downwind conditions with a range of 500m.
Bent sound rays and multiple ground reflections due to downwind conditions, On the left, few rays for clarity and on the right 1000 sound paths.
PART 2: PEMARD APPROACH

Sound speed gradient: -0.01/m considered as strong upward refraction

Mapping area L=1km, W=0.5km
PART 2: PEMARD APPROACH

Temp.: 20°C on ground, 15°C at 10 m., Wind Speed: 12 m/s at 10m, Roughness constant: 0.71 a typical value.

dB(A) mapping in 2D
50 Hz 2D

50 Hz 3D

500 Hz 2D

500 Hz 3D

Temp.: 20°C on ground, 15°C at 10 m., Wind Speed: 12 m/s at 10m, Roughness constant: 0.71 a typical value.
ISO 9613 vs PEMARD APPROACH
PART 2: PEMARD APPROACH

Figure 1: Geometry of set up in Terrain, $H_s=0.3m$, $H_r=1.2m$, $H_b=3m$, $D_{sr}=35m$, $HG=GFR=20$ MNs/m$^4$, $PG=GFR=300$ kNs/m$^4$

Figure 2: Validation of Isei’s geometry from Error! Reference source not found. 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 PEMARD results which are almost indistinguishable from the original graphs, in solid lines and markers the ISO results. (b) Excess Attenuation with barrier in place, colored dashed lines represent PEMARD results.

ACCURACY OF WAVE BASED CALCULATION METHODS COMPARED TO ISO 9613-2, NOISE-CON, ECONOMOU ET AL, SEPT 2014
PART 2: PEMARD APPROACH

*Isei’s geometry, barrier height 3m, thin & wide, Hard vs Porous Ground*

Figure 1: SPL spectra, $L_p$ and $L_{pA}$ values based on Isei’s geometry, HG=GFR=20 MNs/m$^4$, PG (SG)=GFR=300 kNs/m$^4$ (a) $H_s=0.3$m, $H_r=1.2$m, $H_b=3.0$m, $Dsr=35$m, (b) $H_s=0.3$m, $H_r=1.2$m, $H_b=1.5$m, 1m thick barrier, $Dsr=35$m.

ACCURACY OF WAVE BASED CALCULATION METHODS COMPARED TO ISO 9613-2, NOISE-CON, ECONOMOU ET AL, SEPT 2014
Figure 1: 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.

ACCURACY OF WAVE BASED CALCULATION METHODS COMPARED TO ISO 9613-2, NOISE-CON, ECONOMOU ET AL, SEPT 2014
Figure 1: Sound spectra at various distances from the source over hard ground. The legend includes dB(A) values at each distance from the source, (a) ISO results, (b) PEMARD 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.

ACCURACY OF WAVE BASED CALCULATION METHODS COMPARED TO ISO 9613-2, NOISE-CON, ECONOMOU ET AL, SEPT 2014
Figure 1: Sound spectra at various distances from the source over porous ground. The legend includes dB(A) values at each distance from the source, (a) ISO results, (b) PEMARD 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.
Figure 1: PEMARD results demonstrate how the -6dB/dd rule does not apply over finite impedance ground, (a) over hard ground, (b) over porous ground. Any deviation from zero indicates that the rule does not apply.

ACCURACY OF WAVE BASED CALCULATION METHODS COMPARED TO ISO 9613-2, NOISE-CON, ECONOMOU ET AL, SEPT 2014
PART 2: PEMARD APPROACH

ROOM RESONANCES
PART 2: PEMARD APPROACH

Using Wave Based Geometrical Acoustics (WBGA) to Investigate Room Resonances, Johansson, Economou, BNAM, June 2016

Upper mapping: Calculated results

Lower mapping: Measured results
Figure 1: Mapping on the left is at 1721 Hz (higher by a scale factor of 10, experimental data, courtesy of the JASA) while the coloured mapping in the 1/3rd octave band of 200 Hz. The mapping on the right is at 2302 Hz (higher by a scale factor of 10, experimental data) while the coloured mapping in the 1/3rd octave band of 250 Hz. In red high sound levels and in green low [5].

ROOM RESONANCES USING WAVE BASED GEOMETRICAL ACOUSTICS (WBGA), ECONOMOU ET AL, ICSV23, JULY 2016
PART 2: PEMARD APPROACH

DIFFRACTION EFFECTS
PART 2: PEMARD APPROACH

Real Time Sound Path Propagation in Courtyard using Acoustics-Lib
the Rosetta Stone of Acoustics Library
by PEMARD
Figure 1: On the left, the 3D full scale model used for our calculations. On the right Ando’s results compared to experimental data. Our calculations are superimposed as a red curve over the original graph by Ando (courtesy of the Journal of the Acoustical Society of America).

THE SEAT DIP EFFECT USING WAVE BASED GEOMETRICAL ACOUSTICS (WBGA), ECONOMOU ET AL, ICSV23, JULY 2016
PART 2: PEMARD APPROACH

THE SEAT DIP EFFECT USING WAVE BASED GEOMETRICAL ACOUSTICS (WBGA), ECONOMOU ET AL, ICSV23, JULY 2016
APPLICATIONS OF WBGA
SOUND REFLECTIONS OFF A MIXING CONSOLE

Direct sound and reflections from the mixing desk. Green diffractions, blue reflections

IMPROVED ROOM ACOUSTICS CALCULATIONS USING COMPLEX IMPEDANCE AND SPHERICAL WAVE REFLECTION & DIFFRACTION COEFFICIENTS, ECONOMOU ET AL, ICSV23, JULY 2016
APPLICATIONS OF WBGA
SOUND DIFFRACTIONS OFF A MIXING CONSOLE

Direct sound and diffracted paths (2nd order).
Green diffractions, blue reflections

IMPROVED ROOM ACOUSTICS CALCULATIONS USING COMPLEX IMPEDANCE AND SPHERICAL WAVE REFLECTION & DIFFRACTION COEFFICIENTS, ECONOMOU ET AL, ICSV23, JULY 2016
APPLICATIONS OF WBGA
SOUND DIFFRATIONS WITH IN BETWEEN REFLECTIONS OFF A MIXING CONSOLE

Direct sound and diffracted paths (2nd order) and 1 reflection in between diffractions. Green diffractions, blue reflections

IMPROVED ROOM ACOUSTICS CALCULATIONS USING COMPLEX IMPEDANCE AND SPHERICAL WAVE REFLECTION & DIFFRACTION COEFFICIENTS, ECONOMOU ET AL, ICSV23, JULY 2016
APPLICATIONS OF WBGA
SOUND REFLECTIONS & DIFFRACTIONS (ALL) OFF A MIXING CONSOLE

All possible sound paths together. Blue curve 1 reflection in between diffractions while the green curve 3 reflections

IMPROVED ROOM ACOUSTICS CALCULATIONS USING COMPLEX IMPEDANCE AND SPHERICAL WAVE REFLECTION & DIFFRACTION COEFFICIENTS, ECONOMOU ET AL, ICSV23, JULY 2016
PART 2: PEMARD APPROACH

STUDYING THE PHENOMENON - REVERBERATION
PART 2: PEMARD APPROACH

PHILIP M. MORSE AND RICHARD H. BOLT

Fig. 24. Oscillograms illustrating beats in sound decay for different driving frequencies. Top and bottom curves are for driving frequency equal to a resonance frequency of the room, so only one mode is strongly excited. Middle curve is for an intermediate driving frequency, with two modes equally excited, showing the beats between the two natural frequencies as they damp out. Redrawn from reference K5.
PART 2: PEMARD APPROACH

"... at the frequencies of the lowest resonant modes of the room, there is very little absorption by the walls and hence the reverberation time is high; whereas at frequencies only a few cycles away from the resonance there is a much shorter reverberation time and, therefore, the walls must be much more absorptive. Presumably if the room were a different size, the absorption dips (hence, reverberation peaks) exhibited by the walls would occur at different frequencies corresponding to the new modes of the room. **One can hardly believe that the ordinary rigid, bare walls of a room could show such wide (and variable!) differences in absorption within such a narrow frequency range. What, then, is the trouble with these curves? Surprisingly, there appear to be at least three methods of measurement which would give this kind of wrong answer!**" (Courtesy of JAES, from Theodore Schultz’s paper “Problems in Measurement of Reverberation Time”, *Journal of The Audio Engineering Society*, 11(4), 307-317, (1963))
Figure 9: Detailed view of the 100 Hz 1/3 Octave Band frequency range (a) from Fig. 8a above and (b) from Fig. 8b. Spherical reflection factor was used for RT calculations. The dashed curves (-- ---) represent the RT curves for the individual resonance peaks while the solid curve shows the envelope of the superimposed resonance peaks.
Figure 5: Sound decay in a small rectangular room. Plane vs spherical wave propagation.

BEYOND SABINE: INVESTIGATING THE ACOUSTICAL PHENOMENON OF REVERBERATION USING ROOM MODAL DECAY, UPCOMING ICSV24, ECONOMOU ET AL, JULY 2017
PART 2: PEMARD APPROACH

Figure 7: Sound decay with and without sound edge diffractions.

BEYOND SABINE: INVESTIGATING THE ACOUSTICAL PHENOMENON OF REVERBERATION USING ROOM MODAL DECAY, UPCOMING ICSV24, ECONOMOU ET AL, JULY 2017
PART 3: AN EXAMPLE OF INTEGRATED ACOUSTICS

THE MUNICIPALITY BUILDING OF LATSIA – CYPRUS, AN EXAMPLE OF THE INTEGRATED APPROACH IN ACOUSTICS
PART 3: AN EXAMPLE OF INTEGRATED ACOUSTICS
PART 3: AN EXAMPLE OF INTEGRATED ACOUSTICS

MODELING
PART 3: AN EXAMPLE OF INTEGRATED ACOUSTICS
PART 3: AN EXAMPLE OF INTEGRATED ACOUSTICS
TRAFFIC NOISE AFFECTING LIBRARY GLAZING & THE EFFECT OF NOISE BARRIER
PART 3: AN EXAMPLE OF INTEGRATED ACOUSTICS
PART 3: AN EXAMPLE OF INTEGRATED ACOUSTICS
PART 3: AN EXAMPLE OF INTEGRATED ACOUSTICS
DESIGNING THE LIBRARY WALL USING THE TRANSFER MATRIX METHOD (TMM)
PART 3: AN EXAMPLE OF INTEGRATED ACOUSTICS
PART 3: AN EXAMPLE OF INTEGRATED ACOUSTICS
PART 3: AN EXAMPLE OF INTEGRATED ACOUSTICS
PART 3: AN EXAMPLE OF INTEGRATED ACOUSTICS
PART 3: AN EXAMPLE OF INTEGRATED ACOUSTICS

INVESTIGATING STI USING ISO 3382-3:2012
PART 3: AN EXAMPLE OF INTEGRATED ACOUSTICS
PART 3: AN EXAMPLE OF INTEGRATED ACOUSTICS
PART 3: AN EXAMPLE OF INTEGRATED ACOUSTICS

INVESTIGATING THE THEATRE USING ISO 3382-1:2009
PART 3: AN EXAMPLE OF INTEGRATED ACOUSTICS
PART 3: AN EXAMPLE OF INTEGRATED ACOUSTICS
PART 3: AN EXAMPLE OF INTEGRATED ACOUSTICS

[Graph showing pressure over time]
PART 3: AN EXAMPLE OF INTEGRATED ACOUSTICS
PART 3: AN EXAMPLE OF INTEGRATED ACOUSTICS
PART 3: AN EXAMPLE OF INTEGRATED ACOUSTICS
PART 3: AN EXAMPLE OF INTEGRATED ACOUSTICS
THANK YOU

WWW.PEMARD.COM