Effects of science-based noise control laws, standards and policies

Wayne R. Lundberg*

Aerospace Engineer, 3312 Braddock St., Kettering OH 45420-1203, USA

*corresponding author: e-mail: wayne29rl@gmail.com

ABSTRACT

The US Noise Control Act of 1972 (NCA 1972) directs the US Federal Aviation Administration (FAA) and Department of Defense (DoD) to develop separate standards and polices regulating source noise. The current Federal Aviation Regulation Part 36 (FAR 2002) compels use of Aerospace Recommended Practices (ARP) and noise exposure methods which compare with scientifically developed and approved International Organization for Standardization (ISO) methods. Annual average noise metrics also do not afford the public the full benefits of scientific research. This paper will advocate advances in two areas: 1- atmospheric attenuation of aeroacoustic noise using the acoustical model ISO 9613-1 (1993); 2- seasonal averaged noise exposure level policies and practices. Scientific improvements in either area would provide more fidelity for estimating biological effects and human response. (1) Atmospheric attenuation discrepancies primarily affect noise analyses of high-performance aircraft and rockets. Aerospace noise predictions are effected by range-dependant high-frequency discrepancies from all louder (than ~stage 3) sources. Aviation noise exposure estimates applying SAE (1975) ARP 866A under-predict levels affecting nearby communities under most weather conditions. Studies of high-performance military aircraft and rockets indicate that ISO 9613-1 may be extended for application to all aerospace sources. (2) Annual-averaged noise exposure fails to account for seasonal variations in atmospheric effects, aircraft performance and airport operations. Science-based noise control laws, standards and policies are thus practicable, compelled by Environmental Management Systems, and benefit aviation and community noise control.

INTRODUCTION

Biological effects of noise in the environment are often predicted using Effective Perceived Noise Level (EPNL) or Day-Night average noise Level (DNL) metrics. This paper considers two primary approaches that could improve the fidelity of community noise prediction metrics in comparison to actual noise environs and sources. It is asserted without discussion that the proposed methods, when refined for standard application, would serve to better predict biological effects and thus enable an improved regulatory approach for future aerospace noise sources.

The historical development of aircraft noise regulations preceded scientific understanding of aerospace sources and environmental propagation effects. Nonetheless, the compelling need to regulate aircraft noise led the US Congress to direct Federal agencies to prescribe standards and regulations respecting noise (NCA 1972 section 4). Military weapons were exempted from explicit regulation (NCA 1972 section 3) but their community noise is limited by the practical application of the National Environmental Policy Act (NEPA 1969). Application of noise estimates for NEPA planning activities has the potential to avoid science-based environmental impact assessments to the extent that public agencies allow.

Empirical modeling of aircraft noise propagation was employed using many aircraft measurements that were available in the 1970's. The US Society of Automotive Engineers developed a series of Aerospace Recommended Practices designed to measure aircraft noise and to model environmental propagation to the extent that it was able. Atmospheric attenuation of sound is fundamental to all empirical, and scientific, acoustical methods and was modeled by SAE (1975) ARP 866A. The FAA prescribes it explicitly in US aviation regulations (FAR 2002) at section H36.113. Aircraft noise propagation models of excess ground attenuation and lateral attenuation require modeling of atmospheric attenuation during data analyses.

The sciences of aeroacoustics and sound propagation in the outdoor environment have progressed considerably since SAE (1975) was developed. Ray-tracing acoustics has been studied and validated to model atmospheric refraction of acoustic noise (Pierce 1994). Atmospheric absorption has been researched sufficiently to produce both US national (ANSI 1995) and international (ISO 1993) standard models. Excess ground attenuation and lateral attenuation are known to be the result of source-receiver geometry and ground absorption (Delany & Bazley 1971; Chessell 1977), although time-averaged propagation through turbulent air reduces ground-absorption effects.

Nonetheless, US aircraft noise compatible-use prediction models have not yet adopted a science-based approach in their implementation. This is partly due to a known discrepancy in model predictions of high-frequency noise measured from high-amplitude sources. The term high-amplitude sources generally refers to aerospace propulsion systems capable of powering supersonic flight.

Development and fielding of high-speed civil transport aircraft is dependent on accurate flight noise prediction models applicable to their high-performance engines, as well as acceptance of the well-understood science of sonic boom propagation. Supersonic civil aircraft airframe and engine designs benefit directly from the acoustical science derived for use with military high-performance jet aircraft.

The sciences of aeroacoustics and outdoor noise propagation are well-developed and, with adequate support, capable of being implemented in aerospace laws, standards and policies. This paper will discuss the extent to which the fidelity of community noise predictions are influenced by current purely empirical methods. To that extent, existing regulatory approaches effect aerospace engineering and devel-opment of the international air transport system including supersonic civil aviation.

ATMOSPHERIC ATTENUATION

Atmospheric absorption theory and practice has long been suspected as the cause of discrepancies between theory and aircraft noise measurements at high frequencies (Bass et al. 1995). Although Morfey & Howell (1981) concluded that nonlinear propagation effects were responsible, the extremely complex time-domain computations required, coupled with legitimate concerns about measurement instrumentation (Joppa et al. 1994), effectively delayed productive research of this acoustic phenomenon.

Nonlinear propagation of noise is a finite-amplitude effect in which the waveform steepens with distance. It appears in flight/launch noise measurements initially as a broadening of high-amplitude spectra (weak nonlinearity), and with higher amplitudes small shocks form at long ranges (strong nonlinearity). In the trans-sonic regime, these small shocks join with near-field shock waves created by supersonic flight, which would otherwise dissipate, yielding sonic boom (pure nonlinear) propagation.

Further evidence of weak nonlinear effects was afforded by Lundberg (1994a) and eventually confirmed by (Gee et al. 2005; Falco et al. 2006). The computationally intense time-domain methods of Gee et al. (2005) and others substantiate the frequency-domain methods proposed by Lundberg (2003, 2006).

Although the empirical SAE ARP 866A model incorporates nonlinear effects owing to the use of C-135A high-amplitude noise data, it cannot be extended to account for this source-dependent effect. Figure 1 shows the nature of the discrepancy at high frequencies for an old fighter aircraft, and that both ANSI S1.26-95 and ISO 9613-1 models are able to be extended to incorporate nonlinear atmospheric attenuation.

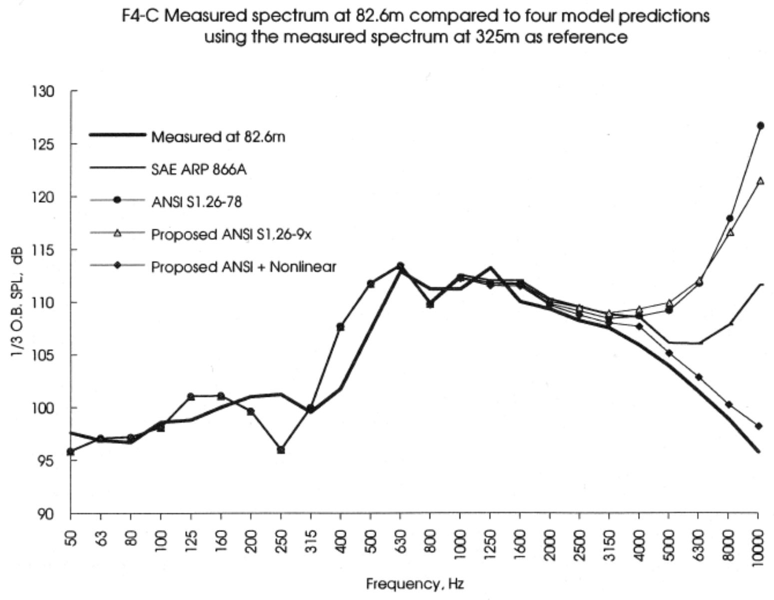

Figure 1: Comparison of SAE ARP 866A to ANSI S1.26-78, (then-proposed) ANSI S1.26-95 and ANSI S1.26-95 with inclusion of weak nonlinear effects (Lundberg 1994a). ISO 9613-1 is closely comparable to ANSI S1.26-95.

The difference between ANSI S1.26-78 and -95 results are due to extensive research of atmospheric absorption and filter effects (Joppa et al. 1994; Bass et al. 1995).

SCIENCE OF NOISE CONTROL OF AEROSPACE SOURCES

The regulatory distinction between civil, military aircraft and rocket noise emissions becomes increasingly blurred with the advance of aerospace engineering. As the science of aeroacoustics of high-performance aircraft engine/airframes advances to facilitate practical designs, environmental noise prediction methods must also advance to facilitate the fielding of supersonic civil and military vehicles.

The following subsections briefly discuss legal, technological and economic factors that presently apply to military and civil aircraft noise constraints and roughly how the respective programs would be affected by science-based noise control laws.

Civil Aircraft

The FAR Part 36 approach to regulating civil aircraft limits noise produced by individual aircraft. Noise-reducing technology often takes the form of higher engine bypass ratios, in which cool air is mixed with hot combustion jet before being ejected. Civil aircraft powered by lower bypass engine designs (e.g. JT8D series) require advanced noise suppression retrofitting to comply with Stage 4 (ICAO Chapter 4). This retrofit technology is currently designed into proposed supersonic business jets.

Economics of prospective supersonic aircraft include operation at airports serving densely populated communities. However, un-supressed military supersonic aircraft routinely operate in airports serving less dense communities owing in large part to their contribution to local economies.

A crucial technological and economic limiting factor to development of large commercial supersonic civil aircraft was compliance with Stage 3 limits, as discussed by the Committee on High Speed Research (1997) and illustrated by the conceptual mixer-ejector design in Figure 2.

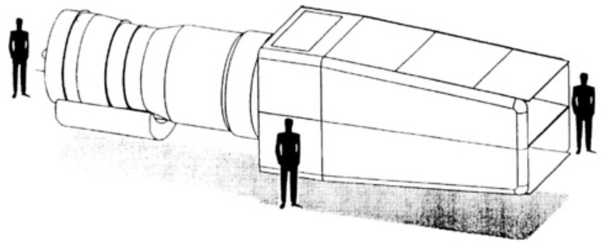

Figure 2: Conceptual commercial supersonic civil aircraft engine and nozzle, without air intake. Courtesy of NASA

Supersonic aircraft research has demonstrated application of airframe shaping as a means to minimize sonic boom. Furthermore, sonic booms may not reach the ground as they propagate by pure nonlinear attenuation. FAA regulations hinder prospective supersonic aircraft operations by limiting flight speeds to less than Mach 1 rather than a scientific limit to achieve boomless flight (Pierce 1988, Figure 3).

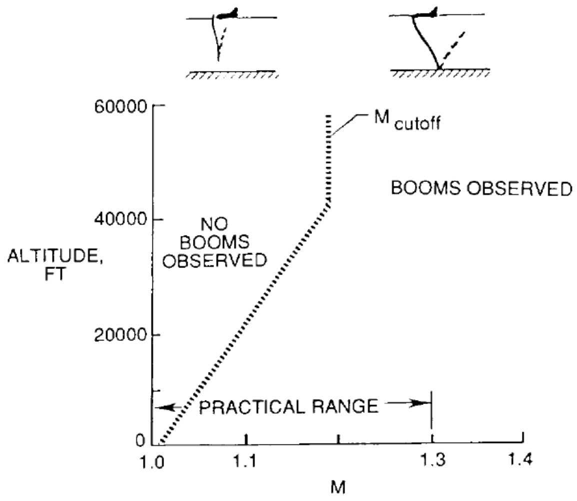

Figure 3: Conditions for boomless flight (Pierce 1988)

Possible large supersonic or hypersonic vehicles are not likely to be economically viable without recourse to environmental assessment methods (NEPA 1969). Compatible use zoning as an aerospace vehicle constraint could substantially reduce mixer-ejector designs but requires operations far away from affected communities.

Military Aircraft

The US DoD has developed a policy which requires new transport aircraft, whose mission includes operation in domestic civil and foreign airfields, to comply with the latest FAR Part 36 amendments. Multi-billion-dollar aircraft re-engine programs have substantially reduced the number of US military aircraft that are incapable of compliance with FAR Part 36 Stage 3 (harmonized with ICAO Annex 16 Chapter 3).

Other military transport and supersonic aircraft must comply with the US National Environmental Policy Act (NEPA 1969) by preparing Environmental Impact Statements using DNL contours. The noise produced by each aircraft model is combined with their operations model to predict DNL contours. Local communities develop compatible-use zoning ordinances accordingly. There is a common perception that military aircraft are ‘unregulated’ noise sources, due to their exemption from NCA 72. However, the combination of local compatible-use zoning ordinances and determination to maximize flight operations compels use of noise abatement procedures. Thus, the number of operations of modern turbojets is affected by historic noisiness and compatible uses of predecessor aircraft. It is thus beneficial from a flight training operations standpoint to implement noise reduction technologies (e.g. Nesbitt et al. 2006) in developmental engines and require designs capable of noise abatement departures. Figure 4 shows an example of the new F-35 fighter aircraft engine with chevron nozzles.

An engineering policy to design-in noise abatement approaches could be applied to future civil aerospace vehicles, particularly any that are over-constrained by Stage 4.

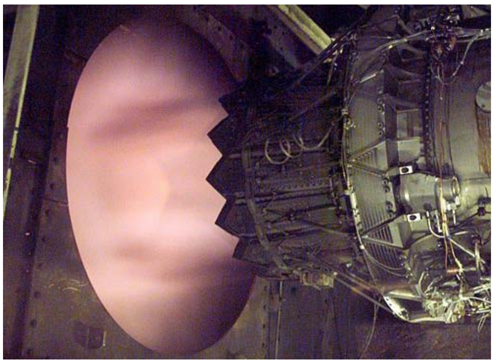

Figure 4: F135-PW-100 engine test illustrating noise-reducing chevron nozzle implementation in a high-performance jet engine (courtesy wikipedia)

NOISE CONTROL OF AEROSPACE OPERATIONS BY SEASON

Both EPNL and DNL metrics average sound exposure over the entire year, while including night-time sleep disturbance penalties. There are essentially three reasons to consider regulatory implementation of seasonal-averaged noise exposure metrics. First, regional weather affects atmospheric propagation through both attenuation and refraction. Second, colder winter air is more dense, which is beneficial to both airframe lift and engine performance. Third, daily operations at most major airports vary by a few percent between summer and winter seasons. Overall departures tend to be slightly more frequent in summer when aircraft are less able to gain altitude. The first two effects warrant discussion in the context of advocating regulatory changes.

Weather effects sound propagation

The FAA conducted studies (Rickley & Fleming 1998; Reherman et al. 2002) to consider application of ISO 9613-1 in the US civil aircraft noise certification and prediction programs. These studies determined that the SAE ARP 866A method is nearly as accurate for civil aircraft except at “the extreme limits of the current FAR part 36 test window” (Rickley & Fleming 1998). A *similar discrepancy exists in noise prediction models.* Figure 5 shows representative results of analyses pertaining to turbofan aircraft, where weather conditions adversely affect the results at long range. Although “the exact method presented in both the ISO and ANSI standards was considered the reference or 'gold standard'..," it yields increases in predicted DNL or EPNL which would *slightly* adversely impact compatible use zoning.

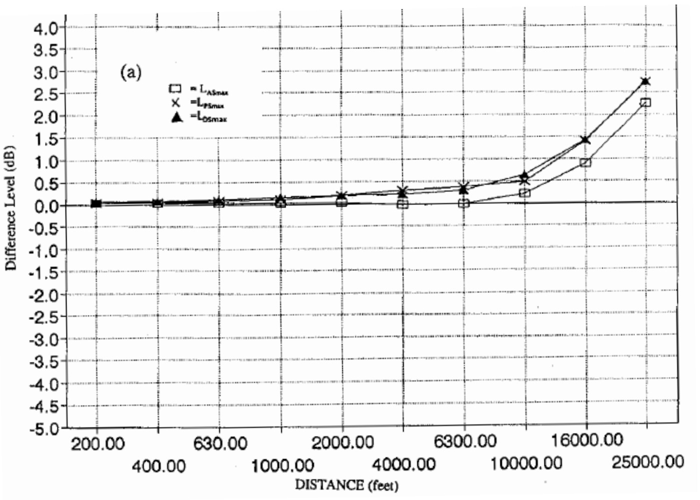

Figure 5: Comparison of noise-distance curves: ANSI/ISO Pure-Tone Mid-band Frequency Method minus SAE ARP 866A, reference 25°C, 70 % relative humidity (Rickley & Fleming 1998)

Sound exposures predicted by applying the science behind ISO/ANSI methods yield more significant results for high-performance aircraft engines. Earlier sensitivity analysis for low-bypass turbojet engines (Lundberg 1994a) show similarly increased predictions using the ISO/ANSI method. The incomplete atmospheric attenuation (neglecting nonlinear propagation) model for high-amplitude aerospace sources appears to exacerbate the discrepancy near the source (Figure 6). Since nonlinear propagation shifts acoustic energy into more hearing-sensitive high-frequencies, extension of the ISO/ANSI methods to correctly account for nonlinear propagation would both eliminate the near-field model discrepancy while exacerbating increased sound exposures at long ranges relevant to communities' planning for compatible uses. The empirical SAE ARP 866A method cannot effectively be extended to account for nonlinear effects since that would require extensive measurement and data-reduction of many different high-performance aircraft.

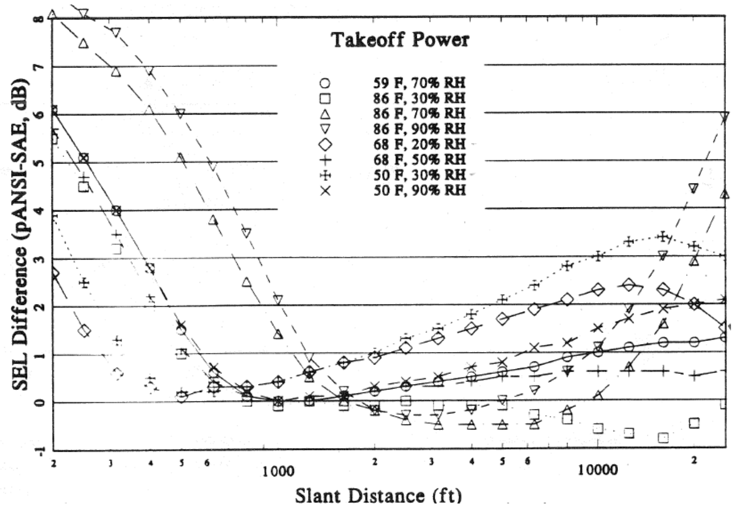

Figure 6: Discrepancy between SAE ARP 866A method prediction of SEL attenuation from laboratory measurements as modeled by the (then-proposed) ANSI S1.26-95, for an F-4C aircraft in takeoff power (Lundberg 1994a)

Weather affects acoustic refraction

Acoustic refraction depends on atmospheric wind-vector and temperature gradients. Since these meteorological variables change statistically of any season, scientifically exact methods for determining representative refractive atmospheres for each season are quite complex. Such methods must account for acoustic energy averaging over the season. Calculations by Lundberg (1994b) estimate seasonal acoustic refractive effects using the TRAPS 89 sonic boom model (Figure 7).

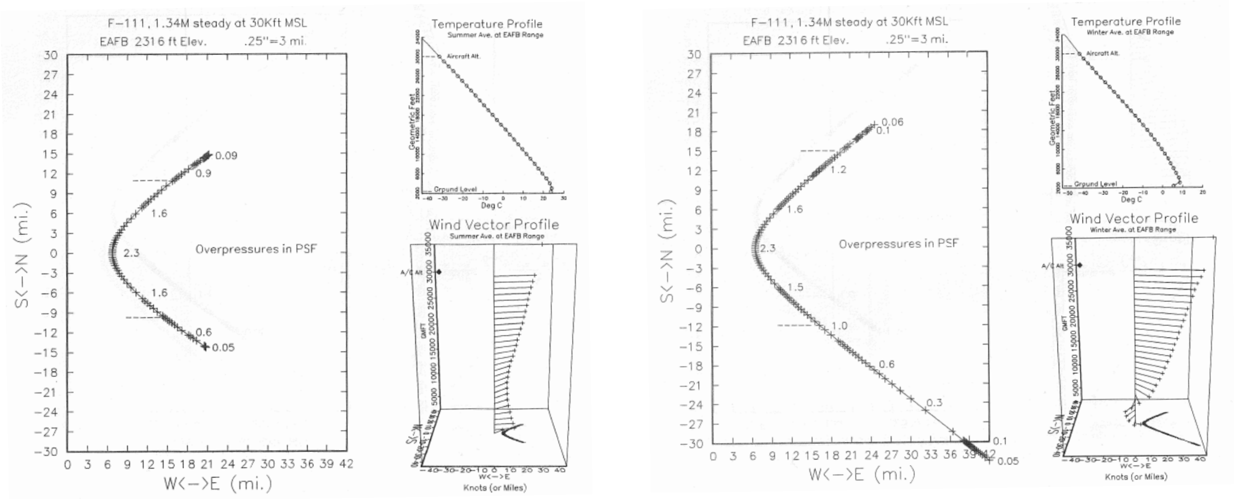

Figure 7: Estimation of seasonal acoustic refraction effects using sonic boom ray-tracing methods for F-111 operations at Edwards AFB Military Operating Area, summer (left) and winter (right) (Lundberg 1994b)

Weather effects aircraft performance

The International Center for Air Transportation (Huber et al. 2003, Figure 8) developed a single-event aircraft noise simulator, NOISIM, which implements modern sciences of acoustic propagation in the outdoor environmental as well as weather effects on aircraft performance. While dramatic reductions in community noise exposure were documented for specific departures, such results are tempered by the multiple aircraft operations involved in long-term average noise exposure predictions.

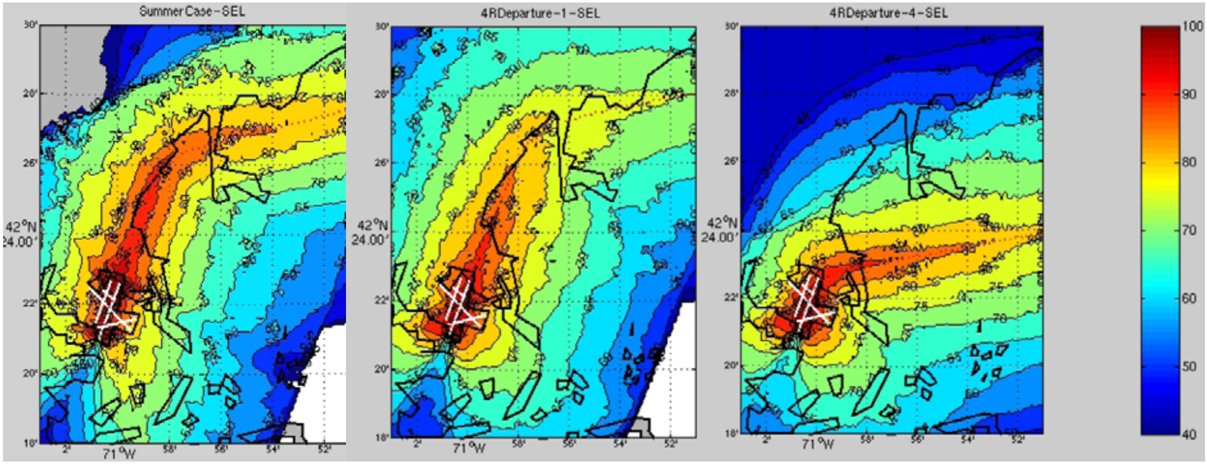

Figure 8: SEL contours for a single departure in summer (left) with standard climb rate, winter (center) with cold-air climb rate and winter (right) taking advantage of additional lift produced by colder air to turn seaward earlier (Huber et al. 2003; reproduced with permission by MIT)

RECOMMENDATIONS

Minor technical issues remain to be resolved to establish science-based noise control laws, standards and policies. Supersonic overland boomless flight is understood. Use of ISO 9613-1 for certification requires analysis of various third-octave band filters. Frequency-domain calculation of nonlinear aeroacoustic effects is achievable. Methods for seasonal-averaged noise exposure levels require further study.

REFERENCES

ANSI (1995). ANSI S1.26-Method for calculation of the absorption of sound by the atmosphere. New York, N.Y.: American National Standards Institute, Committee S1, Acoustics.

Bass HE, Sutherland LC, Zuckerwar AJ, Blackstock DT, Hester DM (1995). Atmospheric absorption of sound: further developments. J Acoust Soc Am 97: 680-683.

Chessell CI (1977). Propagation of noise along a finite impedance boundary. J Acoust Soc Am 62: 825-834.

Committee on High Speed Research, Aeronautics and Space Engineering Board (1997). U.S. Supersonic Commercial Aircraft: Assessing NASA's High Speed Research Program. Washington, DC: National Academy of Sciences, Division on Engineering and Physical Sciences.

Delany ME, Bazley EN (1971). A note on the effect of ground absorption in the measurement of aircraft noise. J Sound Vibr 16: 315-322.

Falco LE, Atchley AA, Gee KL (2006). Investigation of a single-point nonlinearity indicator in the propagation of high-amplitude jet noise. In: 12th AIAA/CEAS Aeroacoustics Conference, Conf Paper 2529. Washington, DC: AIAA.

FAR, Federal Aviation Regulation (2002). Part 36: Noise Standards: Aircraft Type and Airworthiness Certification. Washington, DC: US Federal Aviation Administration.

Gee KL, Gabrielson TB, Atchley AA, Sparrow VW (2005). Preliminary analysis of nonlinearity in military jet aircraft noise propagation. AIAA J 43: 1398-1401.

Huber J, Clarke JB, Maloney S (2003). Aircraft noise impact under diverse weather conditions. In: 9th AIAA/CEAS Aeroacoustics Conference, Conf Paper 3276.

ISO (1993). ISO 9613-1: Acoustics – Attenuation of sound during propagation outdoors – Part 1: Calculation of the absorption of sound by the atmosphere. Geneva: International Organization for Standardization, Committee ISO/TC 43, Acoustics, Sub-Committee SC 1, Noise.

Joppa PD, Sutherland LC, Zuckerwar AJ (1994). Filter effects in analysis of noise bands. In: 128th Acoustical Society of America meeting, Paper 2aNS5, Austin, TX.

Lundberg WR (1994a). Nonlinear aeroacoustics: Experimental evidence from the F-4C. In: Havelock DI, Stinson MR (eds.): Proceedings of the 6th International Symposium on Long-Range Sound Propagation: 1-20.

Lundberg WR (1994b). Seasonal sonic boom propagation prediction. AL/OE-TR-1994-0132. Wright-Patterson Air Force Base, OH: US Dept of Defense, Armstrong Laboratory.

Lundberg WR (2003). Prediction of nonlinear acoustic propagation effects for high-intensity aerospace noise sources in the natural far-field environment. PhD Dissertation, University of Dayton, Dayton, OH.

Lundberg WR (2006). Extent of nonlinear aeroacoustic propagation from single frequency-domain measurements. In: 12th AIAA/CEAS Aeroacoustics Conference, Conf Paper 2702, AIAA, Washington, DC.

Morfey CL, Howell GP (1981). Nonlinear propagation of aircraft noise in the atmosphere. AIAA J 19: 986-992.

NCA, Noise Control Act (1972). 42 US Code 4901 et seq. Public Law 92-574, amended 1976, 1978, 1988.

NEPA, National Environmental Policy Act (1969). 42 US Code 4321-4347, Public Law 91-190, amended 1975, 1982.

Nesbitt E, Mengle V, Czech M, Callender B, Thomas R (2006). Flight test results for uniquely tailored propulsion-airframe aeroacoustic Chevrons: community noise. In: 12th AIAA/CEAS Aeroacoustics Conference, Conf Paper 2438, AIAA, Washington, DC.

Pierce AD (1988). Atmospheric effects. In: Status of sonic boom methodology and understanding. NASA Conference Publication 3027. Hampton, VA.

Pierce AD (1994). Acoustics, an introduction to its physical principles and applications. American Institute of Physics, College Park, MD.

Reherman CN, Roof CJ, Fleming GG (2002). SAE ARP 866A vs. ISO 9613-1/ANSI S1.26-1995: A sensitivity analysis comparing two procedures for adjusting as-measured spectra to reference conditions. Cambridge, MA: US Dept of Transportation, Volpe National Transportation Systems Center.

Rickley EJ, Fleming GG (1998). Computing the absorption of sound by the atmosphere and its applicability to aircraft noise certification. Cambridge, MA: US Dept of Transportation, Volpe National Transportation Systems Center.

SAE (1975). ARP 866A Standard values of atmospheric absorption as a function of temperature and humidity. Warrenville, PA: Society of Automotive Engineers, Committee A-21, Aerospace Recommended Practice No. 866A.