CHANGES AND CHALLENGES IN ENVIRONMENTAL NOISE MEASUREMENT *

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Many changes have occurred in the last seventy years, not least of which are the changes in our environment and interdependently our intellectual and technological development. Sound measurement had its origins in the 1920s at a time when people were still traveling by horse and cart or on steam trains and few people used electricity. The technology of electronics was in its infancy and our predecessors had limited tools at their disposal. Nevertheless, they provided the basis on which we rely for our present day sound measurements. Since then we have come far, but we still await a solution for the lack of accuracy we have come to accept.

THE BEGINNINGS

Harvey Fletcher, first President of the Acoustical Society of America. Courtesy Emilio Ségré Archives

In the early part of last century, the study of sound was given a large boost by the American Telephone and Telegraph (AT&T) Company's research headed by Harvey Fletcher at Western Electric to improve reception in the telephone. The Western Electric Laboratory as the name suggests was engaged primarily in electrical research and development. Acoustics was only a small facet of its work and the development of acoustical measurements occurred on the back of electrical developments. The Laboratory had been engaged for many years in the development of a means to measure an a.c. voltage. This was not easy and the Laboratory had to utilize a root mean square in order to always achieve a positive value for the moving coil meters then in use. In those days the unit for resistance was 1 mile of standard cable, which varied with frequency and temperature, and for measurement of a.c. power to make it independent of frequency and temperature, it was convenient to use a power (or logarithmic) series for its description based on the power developed by a one volt sinusoid across a mile of standard cable. This measure was called the Transmission Unit TU (Martin 1924)

Harvey Fletcher (whom this author is very privileged to be able to have called a friend) studied the reactions of (it is believed) 23 of his colleagues to sound in a telephone earpiece generated by an a.c. voltage. He came up with the idea of a "sensation unit" SU, based on a power series compared to the voltage that produced the minimum sound audible. Harvey initially called this the "Loudness Unit" (Fletcher 1923) but later changed his mind following his work on loudness with Steinberg (Fletcher and Steinberg 1924). As a ratio it was not really a unit, but nevertheless was called one, following the use of the "Transmission Unit". With the AT&T development of the Wente microphone (Wente 1917), an instrument to measure sound in sensitivity units could be developed based on an arbitrary sound pressure close to that simulated by Harvey Fletcher's voltage that produced the minimum audible sound for his research subjects. The idea of an "intensity level" meter was born – as was the idea of an acoustical society: The Acoustical Society of America founded in 1928 holding its first meeting in May 1929 (ASA 1929). Harvey Fletcher (Fig. 1) was its first president.

In the mid 1920s there were suggestions of renaming the Laboratory after Alexander Graham Bell who had recently died, and on February 8th 1924 AT&T and Western Electric created the Bell Telephone Laboratories or Bell Labs as it was called from then on. In 1927 there was a further suggestion to call the Transmission Unit the "Bell", but after some consultation with telephone engineers in France who objected to the word because it was too close to the French word "Belle" (Marsh 2005), Bell Labs decided to call the Transmission Unit the "Bel" with a tenth of it called the "Decibel" (Martin 1929). Later, of course, by international convention "deci" and "bel" are always lower case, with the bel abbreviation as "B" – hence our use of dB in electrical work. The Director of Research at AT&T – H. D.

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Arnold – had led the development of the vacuum tube and electronic amplification was becoming available to measure small values of power, which is of course proportional to the square of the voltage. In such work, a logarithmic measure was also quite useful in that when amplifiers and attenuators are connected in series, power levels could be added or subtracted arithmetically.

During the 1920s, quite independently there were similar studies being carried out in Europe with similar results, except that the Europeans (with the exception of the British) used a naperian logarithm series that resulted in development of the "neper" – the natural logarithm of a power ratio. It is understood this pre-dated the decibel (Lang 2005), but this author has been unable to find any reference to the development of a valve-voltmeter or wattmeter utilizing nepers and it is interesting to note that Georg von Békésy in his experiments in hearing (Békésy 1960) used the decibel for his research at the Royal Hungarian Institute for Research in Telegraphy. Professor Erwin Meyer of the University of Göttingen preferred the decibel for all his work in the 1930s, and his colleague Arnold Schock wrote a small book on Acoustics in which only the decibel was used (Bruel 2005). Békésy later worked in the Department of Telegraphy and Telephony at the Royal Institute of Technology in Stockholm and this may account for the use of the decibel in Scandinavia after World War II

The first sound level meters were large, consisting of a condenser microphone, an amplifier with thermionic valves and a valve-voltmeter with a logarithmic scale covering the voltage range of one sensation unit split into 10 segments. Almost immediately it was found that something had to be done to the meter to make the movement of the needle readable and some damping was inserted so that the needle would move over the whole scale in 1 second. The (logarithmic) scale had a range of one bel divided into decibels with a reference level of 10-16 watts/cm^2 (Fletcher 1953). At the same time, the first audiometers started to appear with voltage settings linked to sensation units (Fletcher 1923A). Speech clarity and hearing studies were the main acoustics focus and sound level meters and audiometers were research instruments only for comparison studies. There were no standards to give the reference power or voltage – indeed some researchers used 10-13 watts/m^2 and some used 10-12 watts/m^2 (GenRad 1963) – and accuracy was questionable. So the next step was to try to get some order and a standard by which everyone could work. Such a standard was not to appear until circa 1936 when the Acoustical Society of America published the first embryo standard for sound level meters. (ASA 1936).

In conjunction with CBS and NBC, Bell Labs explored the way to describe audio power levels in recording and broadcast studios and developed the "volume unit" VU based on a reference power level of 1 milliwatt into an impedance of 600 ohms. The metric was labeled dBm and a standard produced in the late 1930s (Chinn et al 1940)

At a time when electronics was in its infancy and the choice of materials very limited, a good structural base had been set for the development of acoustics research in an era of a relatively quiet environment for most people. There were very few cars on the road and even fewer aircraft to upset the noise environment. The main transportation was by steam train supplemented by horse and cart in country areas and by the omnibus and bicycle in towns. Certain industrial processes such as stamp mills were abominably loud and the noise in textile factories and mills much more than experienced today. In general, however, the home and school were quiet places, but children were still employed in factories and Harvey Fletcher even in those days noted the large number of children with hearing loss (Fowler and Fletcher 1926).

THE DEVELOPMENTAL YEARS - 1935 TO 1959

The early work of Fletcher and Wegel (Fletcher and Wegel 1922) and Fletcher and Munson (Fletcher and Munson 1933) into auditory thresholds and sensitivity, clearly showed that the reading on a sound level meter did not represent a measure of how loud or intense the subject sound might be. Something was needed in the meter's circuitry to give a measure of loudness. Initial work produced the A, B and C frequency weightings (ANSI 1961). Sometime in this period – this author has been unable to find out exactly when – the decibel became the official measure for sound pressure level. It is popularly attributed to Harry Olsen, the Chief Engineer of RCA who, when talking about electrical sound recording, said he could see no difference between acoustical watts and electrical ones (Wallis 2005). Whatever the source, by the end of World War II, the decibel was in general use for the description of sound. Rapid developments in electro-technology, as a result of the War effort, spawned a number of companies producing sound level meters in the late 1940s and the formation of the International Electrotechnical Commission which in 1953 formed Technical Committee 29 to develop and establish performance standards for acoustical instrumentation (Rasmussen 2005). ISO Technical Committee TC 43 was also formed around this time and the decibel adopted by them also (Rasmussen 2005). It became possible to buy sound level meters off the shelf enabling researchers to study environmental noise and develop ways of describing it (Fig. 2).

Type 1551-C SOUND-LEVEL METER

- 24- to 150-dB measurement range
- meets common standards:
  ANSI Standard S1.4-1961
  IEC Publication 123, 1961
- 20-Hz to 20-kHz amplifier response
- internal calibration system

specifications

Fig 2. An early sound level meter used by the author [GenRad 1963]

Quite surprisingly, little thought initially was given to maintaining accuracy of measurement, and acoustic calibrators were not part of the measurement regime until the 1960s.

Indeed, from personal experience, in some countries the use of acoustic calibrators was not introduced until the 1990s. Early calibrators were simply a box with a diaphragm onto which tiny ball-bearings were dropped from a fixed height by inverting the box (Fig. 3). By use of a spacer bar, the sound level meter was set up with the microphone 4 inches away. It was not accurate, but better than nothing.

Fig. 3. Falling ball calibrator, Courtesy Cirrus Research.

THE AGE OF SURVEYING - 1950 TO 1975

Following World War II and the introduction of jet aircraft into commercial travel, environmental noise levels rose to such an extent that people started to complain. Military air bases in particular faced confrontation from local residents for making too much and quite unnecessary noise. Some air bases responded by placing large notices at their boundary saying "Listen to the Sound of Peace and Security" or "Hear the sound of safety" etc. Whereas the military might well get away with the noise, commercial airports were much more vulnerable and moves were made to restrict the noise emission to reasonable levels (Fig. 4).

In order to find out what was a reasonable level of noise (as judged by government, of course) surveys were made around some of the major airports of the day, (e.g. the Wilson Report, 1963). In each, the occupiers of certain picked residences were interviewed about their reactions to the noise outside which latter was measured very simply with a short series of instantaneous measurements of A-frequency weighted sound pressure level (although it is believed no survey ever admitted it). Relating the respondents survey answers to the given noise level outside seemed often to have political overtones for in general the study came up with a relationship between the residents' reaction and the environmental noise involving some obscure metric that no one could measure and hence prove the researchers or the government wrong. And with the obscure metric, compatible land use policies were developed (Galloway & Bishop 1970) with which the local territorial authorities were expected to comply, whereas no control was placed on the airports or airfields to reduce the noise emission.

Relating the respondents survey answers to the given noise level outside seemed often to have political overtones. For example: The surveys around London (Heathrow) Airport produced a relationship called the noise and number index NNI where:

NNI = Average Perceived Noise Level (PNdB)
+ 15 log10 (Number of flights) - 80.

Fig. 4. One of the noisiest aircraft at London (Heathrow) Airport: A de Havilland Trident.

This was readily accepted by the British Government and regulations involving maximum levels permitted by aircraft were introduced into law in the late 60s. Noise insulation grants were given to residences receiving (or at least predicted to be receiving) more than 35 NNI. Everyone was led to believe the government had accurate figures for the noise exposure, but not only could the local people not measure the noise in PNdB, neither could the government officers. They (We) simply made an A-frequency weighted measurement in decibels and added 13. A system of noise monitoring stations were set up around the airport with noise limits in PNdB that the aircraft were obliged not to exceed. The monitoring stations were set up very carefully in prominent positions and this author recollects the pilots were very worried about being prosecuted for making more noise than the limit. They all kept very carefully to the allocated flight tracks, little realizing that this was all the monitoring system was set out to accomplish. It, too, only took A-frequency weighted readings in dB and added 13. The outdoor microphone systems were prone to corrosion and several (somewhat questionable) methods were used to keep out the wind and the rain – all of which must have rendered the system way out of calibration. At one major airport, not in England, hydrophones were used to overcome these problems. Several other countries came up with their own aircraft noise measures, and monitoring systems, and it is believed all used metrics in which no-one outside of government could measure – and nor could the government officers, but this was never publicised!

Not all noise surveys targeted major airports. The reaction to noise in a number of major cities was also surveyed. The Greater London Survey was one of the first noise surveys, predating the airport noise surveys, and differed from almost all the rest by the introduction of a metric that the general public themselves could measure – the "percentile level" – but then it did not include a (government) sensitive facility such as a major airport. From the author's own recollections, the metric stemmed from a meeting over morning tea between four British representatives at an ISO meeting in Paris circa 1955 including Peter Parkin, George Vulkan and Hugh Humphries. Who raised the question cannot be remembered, nor who answered, but on being asked “What do you think would be the best way to describe the background noise level?” someone answered “The level that is there 90% of the time.” The others thought this a very good idea and one of them suggested that the noise that is there for 10% of the time was the nuisance noise. Unfortunately they were not mathematicians and termed the measure the “Percentile Level”. This stuck for some years until someone dared to suggest that the L90 was mathematically the 10th percentile level and the L10 the 90th percentile level. At the time, few people listened, but eventually the measure became known as the “Centile Level”. Although a very poor measure of community reaction (Schultz 1982) it was all that was really possible with an instantaneous reading sound level meter and the methodology was simple. Although obsolete in modern day technology, the measure still lingers on in a very few places that favour industry being able to make whatever noise it likes as long as it is for not longer than just under 10% of the time.

Importantly the US Federal Aviation Administration FAA and the International Civil Aviation Organization ICAO introduced noise certification for all new aircraft entering service in Europe and the United States after 1972. Again politics was involved in that the first step (to Stage 2 or Chapter 2 aircraft noise certification) would be achievable by 75% of the civil aircraft then extant. A next step (to Stage 3 or Chapter 3) was to be achieved by 1976 and gradually introduced throughout the world. Although some airlines still employed Chapter 2 aircraft well into the 1990s the overall result is that aircraft individually are much quieter than they were and public reactions noticeably reduced. For example at Wellington International Airport New Zealand, in the 1980s there were hundreds of complaints every month about aircraft noise. Today with adherence to good airport noise management, and a workable national standard (NZS 6805:1992) aircraft noise exposure is only a tenth of what it was, and complaints are very few. Some monthly records each year register no complaints at all.

University research benefited also in having government research money readily available for studies into people’s reactions to noise, and a multitude of frequency weightings appeared to describe the sound produced by different sources. Indeed, until a stop was called internationally in 1973, more than a hundred different frequency weightings had been produced for sounds ranging from those of different types of jet aircraft to that of noise in pipes or the barking of different types of dog. None were significantly better than the original A-frequency weighting and so by international agreement all were dropped by ISO and IEC except for the A-frequency weighting. One other – the C-frequency weighting – was temporarily retained to provide a lower and upper cut-off frequency when measuring peak levels so as to avoid recording any high levels of sound outside the audio-frequency range. Modern sound level meters now employ a Z-frequency weighting to provide such cut-off frequencies (IEC 61672) Yet perhaps the greatest advance during this age was the development in the sound recording industry. The new plastics allowed the development of the reel to reel tape recorder to quite sophisticated levels with Ampex, Grundig, and above all Nagra producing some exceptional recording machines that could be used in conjunction with the instantaneous reading sound level meters to store sounds for future analysis. However it was a little known company called ”Soundstream” led by Dr Thomas Stockham that arguably produced the most important advance in acoustics since the work of Harvey Fletcher in the early 1920s – that of the flash card and digital recording and analysis. Sadly Tom died trying to protect his invention from piracy by big business, but the advantages he gave to the acoustics industry was a quantum leap forward at a time when computers were in their infancy and RAM almost an unknown quantity.

The world at last had a reliable way of measuring environmental sound and well researched guidelines for planning the home environment to protect residents from the adverse effects of too much noise.

Perhaps the most useful (measurement) development of this time was that of a true time-average-level based on short Leq measurements (Holding 1985). The computer, of course, had made this possible and from then on high grade sound level meters used computer chips capturing sound exposure in Pa2.s and then converted it to whatever unit or decibel measure was desired. It became possible to log sound level measurements at one second intervals over several hours and obtain a time history of the sound. We now benefit greatly from this, but at a cost: A number of major companies could not keep up with the pace and went into liquidation.

As the development of the computer advanced, so did that of the sound level meter. Electronically the sound level meter advanced to be capable of doing almost anything one wanted, but then other concerns came to the fore.

THE AGE OF UNCERTAINTY - 1995 TO 2005

Two things caused much concern in this particular decade. The international Institute of Metrology pointed out that to conform with Standard International convention the SI unit should be the neper and not the decibel. This resulted in much heated discussion and no conclusion could be drawn at the ISO/TC43 meeting in 2003 although the decision was taken that some existing draft standards should continue to employ decibels (ISO 2003).

The meeting did conclude however that for field quantities, the quantity should be written as:

$$L_F = 10 \log [F^2/F0^2] \text{ dB and not as}$$
$$L_F = 20 \log_{10} [F/F_0].$$

Not until the 31st meeting in Toronto was the problem resolved. Almost unanimous agreement was reached that the decibel would remain the descriptor for sound (ISO 2005).

The other concern was a directive by ISO and IEC that in reporting all measurements there must be a statement of percentage uncertainty. It is difficult enough for a testing laboratory using carefully controlled environmental conditions to put such a value on its measurements, but for measurements outside it is almost impossible. The problem is always the microphone, how it receives the signal and how it sends on the response to the central processing unit of the meter. When we have a fixed signal and calibrator in a controlled environment we can expect accuracy rather better than a dB.

For field measurements it is a totally different matter: the variability of many environmental noises and the effects of wind make fractions of a dB impossible, and variations of 5 dB or so typical. (Kerry & Craven 2001) This is probably one reason for the retention of the decibel as the metric rather than the Pa2.s. It is not that we have to measure in decibels with all its inherent complications, but stating the uncertainty of a sound measuring system ± 1 dB, clearly sounds much better than ± 26% .

THE CHALLENGING YEARS AHEAD

Now in the 21st century, technology has progressed almost beyond our wildest dreams. We have sound measurement instrumentation we would never have thought possible a decade or two ago. We can log sound in third octave bands at intervals of a few milliseconds and immediately read off reverberation times across the entire spectrum, or we can log sound levels at one second intervals over long periods of time and analyse any period at will. We can also store raw data to give measurement results in any metric we like, all with instant graphs in wonderful colours, and have an audio play back as well, if we wish. We can operate a sound level meter by remote control from a thousand miles away while watching the activity through a telelink, and synchronise the recordings of a multitude of noise monitors. We can also record in several channels at once incorporating sound pressure, particle velocity and phase in three dimensions. The new "Microflown" system (Microflown 2002) gives a measure of velocity. Drawbacks remain: the microphone has not reached the precision available in the other parts of the sound level recording systems. Nevertheless, acoustics must still be considered one of the less accurate sciences. We can measure the light from a star millions of kilometres away, we can measure the time for light to travel a distance less than a tenth of a millimetre, we can measure the heat output of a candle more than a kilometre away – all to an accuracy of 3% or better, but it is difficult or impossible to measure sound levels in the field with comparable precision.

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