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The Weak-Signal Capability of the Human Ear

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Much attention has been given recently, and deservedly so, to digital technologies such as PUA43[1] and JT44[2] as alternatives to the human ear copying Morse code, for application to earth-moon-earth (EME) and weak-signal terrestrial propagation modes at VHF and higher frequencies. It is not the purpose of this paper to evaluate their relative merits, since the author has, as yet, no first-hand, on-the-air experience with them. That will be left to others. Rather, this paper explores the available evidence in an attempt to establish the approximate limits of the human ear-brain, using Morse code, as a weak-signal copying instrument. The results derived here might then serve as a sort of benchmark for future researchers and designers of digital systems.

Many radio amateurs, especially those who specialize in EME, have long prided themselves on their ability to copy weak Morse code signals by ear. Research conducted by the U.S. Army Signal Corps during and after World War II agreed, showing that the human ear is indeed a remarkably efficient and versatile instrument for copying Morse[3]. Even when presented with wideband noise, their results found, the trained operator mentally reduces the effective noise bandwidth to a range of approximately 50-200 Hz depending upon the audio frequency of the signal being copied, with the narrowest bandwidth being reached when the signal frequency is approximately 400 Hz.

Jim Shaffer, WB9UWA, has taken this research a step further. In recent private correspondence, he observed that in a noise bandwidth of 22 Hz, the ear can further discriminate between frequencies as close as 5 Hz. "I even hear 3 Hz pitch changes from an audio generator and speaker at 350 Hz tone," he writes. "I am not sure if my ability to detect pitch changes so fine is selectivity, but it seems likely to me. I am a musician and have perfect pitch. This may be helpful and tends to suggest that selectivity can be taught."

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[1] PUA43 was written by Bob Larkin, W7PUA, for his DSP-10, a software-defined 2m transceiver. For further information on PUA43 and the DSP-10 platform, go to http://www.proaxis.com/~boblark/wksig1.htm.

[2] JT44 is one of two digital signaling modes currently supported by WSJT, a software package written by Joe Taylor, K1JT, the other being FSK441for high-speed meteor scatter. It is based on PUA43 but runs on Windows-based systems. For further information on WSJT, including the latest version available for downloading, go to http://pulsar.princeton.edu/~joe/K1JT/.

[3] Joe Reisert, W1JR, "VHF/UHF World: Minimum Requirements for 2-Meter EME," *HAM RADIO*, August/September 1987.

These findings, however, do not answer the more fundamental question of just how weak a signal, as measured by signal-to-noise ratio (SNR), the human ear can copy.

Defining Terms

Before proceeding to answer that, we must define what we mean by SNR. While any definition would probably suffice as long as it is properly specified, this paper will, unless otherwise noted, follow the commonly-used convention in EME work of specifying SNR as the ratio of key-down signal to average noise level, in the absence of signal, in an effective noise bandwidth of 100 Hz. (Note that this is S/N, not (S+N)/N.) Since the Morse code duty cycle is approximately 50%, it is assumed here that the average SNR, as is measured by some software and test equipment, will be 3 dB below key-down SNR for the same signal strength and noise level.

For example, a value of unity SNR (0 dB), key-down at 100 Hz as used in this paper, is equivalent to –3 dB average SNR at 100 Hz and –17 dB average SNR at 2500 Hz, if the duty cycle is 50%. So, to relate the SNR values used in this paper to those displayed by your favorite software, for average SNR at 100 Hz (e.g., FFTDSP) subtract 3 dB, and for average SNR at 2500 Hz (e.g., JT44, if you're receiving it in a 2500 Hz bandwidth), subtract 17 dB. For key-down SNR at 50 Hz, *add* 3 dB.

The AMSAT ZRO Tests

In the 1980s and 1990s, AMSAT conducted a unique series of weak-signal Morse copying experiments using its high-altitude AMSAT-OSCAR 10 and, primarily, AMSAT-OSCAR 13 satellites. These were called the ZRO Tests in memory of the early amateur radio satellite pioneer Kaz Deskur, K2ZRO[4].

To provide the greatest possible consistency from one ZRO Test to the next, the tests were conducted with the satellite near its apogee of approximately 36,000 km, when its antennas are pointed directly at the center of the earth, giving all participating stations an optimal antenna pointing angle. In addition, it should be noted that for any reasonably well-equipped receiving station, e.g., one with a fairly low-noise receiver (noise figure of 3 dB or less at 144 MHz) and antenna gain of approximately 10 dB or more, the SNR was limited by the satellite's own transponder noise rather than the ambient noise level at the listener's station, so that test participants experienced a similar SNR regardless of where on the earth they were located or the specific capabilities of their own receivers and antennas. The ZRO Tests, then, provided a reasonably controlled environment for measuring operators' weak-signal receiving performance.

During a ZRO Test, which ran for approximately 25 minutes, the control station began by matching its downlink signal strength to the level of the satellite's general beacon. After a short message announcing the test, the control station began by transmitting, three times, a random five-digit number. This strength level was defined as

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[4] Andy MacAllister, WA5ZIB (now W5ACM), "The AMSAT Awards Program," *Proceedings of the Tenth AMSAT-NA Space Symposium*, published by ARRL, October 1992.

Level Z0. Then, the control station reduced its power by 3 dB to Level Z1, and a new five-digit number was again transmitted three times. This sequence was repeated, each time with a reduction in power of 3 dB from the preceding level, until eventually the control station's signal reached 27 dB below the starting point, or Z9. In later ZRO Tests, a further 3 dB reduction took place, to –30 dB; this was referred to as Level A. All ZRO Test transmissions were made in Morse code at 10 WPM.

Most ZRO Tests were conducted using the 145 MHz downlink (Mode B), while some were also conducted at 70cm while the AO-13 Mode JL transponder was functioning. This paper will focus exclusively on the 145 MHz results although those at 70cm were consistent with those at 2m and may be found in the W5ACM paper referenced above.

Test Results

Darrel Emerson, AA7FV, was the only person ever to achieve Level A. To accomplish this feat, he developed an ingenious DSP solution specifically tailored to the signal characteristics and information content of the ZRO Tests, which he described in a paper presented at the 1993 AMSAT-NA Space Symposium[5].

How weak is Level A? When he copied it on April 24, 1993, AA7FV measured the average (S+N)/N ratio as 2.2 dB in a noise bandwidth of 8.33 Hz, which is mathematically equivalent to a key-down SNR of –9.6 dB in a noise bandwidth of 100 Hz, the definition used in this paper.

The best AA7FV was able to do by ear was Z7, which is 9 dB stronger than Level A, i.e., a key-down SNR of –0.6 dB at 100 Hz. He writes that at Z8 (-3.6 dB), he was able to copy only occasional CW characters by ear and at Z9 (-6.6 dB), only the presence of signal could be detected but no characters copied.

Giving It a Try

AA7FV has placed some of the actual audio from that April 24, 1993 test on the Web, including Levels Z8, Z9, A and the end-of-test notice which was transmitted at the reference level of Z0 (+20.4 dB)[6]. Feeding the audio from my computer's sound card into a 50 Hz active analog filter (Autek QF-1), I found that I was able to do one level better than AA7FV had on that particular occasion. I had no difficulty copying Z8 (-3.6 dB).

[5] Darrel Emerson, AA7FV, "Digital Processing of Weak Signals Buried in Noise," *Proceedings of the Eleventh AMSAT-NA Space Symposium*, published by ARRL, October 1993.
[6] Go to http://ourworld.compuserve.com/homepages/demerson/zrodata.htm

Try it yourself; I won't spoil your fun by publishing the five random digits here, but if you would like to compare your copy with mine, drop me an e-mail at w2rs@amsat.org.

At Z9 (-6.6 dB), my copy was too marginal to get all five random digits, but had this been an EME schedule, I'm sure that I would have been able to tell the difference between callsigns, Rs and Os. Could I have gotten complete callsigns, under schedule conditions when I knew which callsigns to listen for? Perhaps, but I cannot say for certain. The situation was not helped by the high frequency of the audio tone – above 800 Hz – nor by its upward drift caused by Doppler and other factors. At Level A, I could detect the presence of a signal but was unable to derive any intelligence.

The Results in Full

How did my results, and those of AA7FV, compare with those of other ZRO Test participants? Table 1, compiled from data in W5ACM's paper referenced above, shows the best levels achieved by the 391 serious participants with adequate receiving stations – those able to reach Z4 or better – over a seven-year period.

As may be seen, the performance of AA7FV's ears was right in the middle of the pack; the median participant also achieved Z7 (-0.6 dB). However, a substantial number, 81 or 20% of the total, reached Z8 (-3.6 dB) along with me and 15 were able to copy all five random digits at Z9 (-6.6 dB).

In view of the 3 dB steps with which the ZRO Tests were conducted, as well as some inevitable variations in the actual listening conditions, e.g., movement of the satellite's ALC level, I believe it best to interpret these ZRO Test results as being accurate within a margin of error of plus/minus 3 dB. From these tests, then, I consider it reasonable to conclude that a good operator can copy random digits by ear at a key-down SNR of approximately –3.6 dB in a noise bandwidth of 100 Hz, plus/minus 3 dB.

EME Results

However, copying random digits is a tougher challenge than is usually faced by operators in an EME schedule, where all they need to copy are two already-known callsigns, plus Os and Rs. Moreover, ZRO Test participants have less than two minutes to copy the digits at each level, while typical half-hour 144 MHz EME schedules allow for 14 minutes listening time each way, 30 minutes in an hour-long schedule.

From 1985 to 1995, the author operated 144 MHz EME with 150W output to a 3.2-wavelength Yagi (CushCraft 3219). The antenna was not elevated and produced ground gain of approximately 5 dB in its first lobe, at about 3 degrees elevation, and approximately 3 dB in its second lobe at about 10 degrees. Because the other stations normally ran far more power, the limiting factor most of the time was the other operator's ability to copy the very weak signal from W2RS.

In all, 88 two-way EME QSOs were completed with 37 initials. Two of these initials were two-Yagi stations; nine were four-Yagi stations. The smallest station worked, WB2VVV, used two 2.85-wavelength Yagis (M285XX). Of the four-Yagi initials, three – AA4FQ, W7VXW and W7HAH – were made without mutual ground gain, i.e., with ground gain only at W2RS. In addition, lunar echoes were tape-recorded and the tape was played at the 1992 Central States VHF Society Conference.

The propagation mechanisms that made these QSOs possible have been described elsewhere[7] so there is no need to go into them here. Rather, the focus here will be on the 36 operators trying so hard to copy the author's signal – one, K3HZO, was worked at two different station locations – and the signal-to-noise ratios they faced.

Table 2 is an abstract of the author's EME log compiled over that ten-year period. For each QSO, it lists the antenna used by the station worked, its estimated gain (from best available sources, in most cases the tables published by VE7BQH), the DGRD prevailing at the time of the QSO, and the SNR predicted by those conditions with and without the effect of ground gain. In all cases except the two SSB QSOs, the predicted SNRs are for key-down at 100 Hz; in those two cases (which are for peak power at 2.1 kHz), contact was established first on CW, with the predicted SNR listed.

These SNR values are predicted, i.e., calculated by formula taking antennas and DGRD into account, not measured. In all cases except VE3ONT, which was circularly polarized and the 3 dB mismatch with the author's horizontal antenna included, they are probably optimistic in that they do not take polarity into account; they assume a perfect match which we know happens in practice only infrequently. Other variations are covered in the footnotes which appear at the end of the table.

These 36 excellent operators, I believe, have demonstrated what the unaided human ear is capable of under actual 144 MHz EME conditions. A significant number of QSOs were completed with predicted SNR, including ground gain, in the –4 to –5 dB range (again, key-down at 100 Hz). Under particularly favorable propagation conditions, even better results were sometimes achieved.

If signal enhancements due to favorable propagation, such as libration peaks and ionospheric scintillation, are considered, these EME results do not seem to be quite as good as those achieved in the ZRO Tests. However, the offsetting effect of polarity mismatch must also be factored in so, on balance, I consider them generally consistent.

Random vs. Schedules

It is worth noting that the results achieved from schedules were significantly better than those from random operation. Only four stations were worked on random, all with very large antennas: W5UN, KB8RQ, VE3ONT and DL8DAT (the smallest, with sixteen 5-wavelength Yagis). The lowest predicted SNRs for random QSOs were in the

[7] Ray Soifer, W2RS, "QRP EME on 144 MHz: How and Why," *Proceedings of the 26th Conference of the Central States VHF Society*, Kerrville, Texas, published by ARRL, 1992.

-1 dB range, all with W5UN; apart from Dave, the lowest predicted SNR for a random QSO was with KB8RQ at approximately +1 dB.

SSB

The two SSB QSOs with W5UN, which were completed despite predicted SNRs of –7.4 and –10.7 dB, respectively (at the receiver's bandwidth of 2.1 kHz), demonstrate that the adaptive power of the human ear to pull weak signals out of the noise is not limited to CW[8]. Although good libration peaks helped, in order to complete the contacts under these conditions the ear's effective noise bandwidth had to be significantly less than 2.1 kHz, a result consistent with work done in the 1970s on narrow-band voice modulation which showed that only a portion of the full SSB bandwidth is actually occupied by signals carrying useful information[9].

The Aided Ear

Several amateurs have been working with techniques that show significant promise of improvement over what can be done by the unaided ear.

Leif Asbrink, SM5BSZ, is continuing to develop a Linux software suite known as Linrad, which among other things features a flexible array of narrowband DSP filters and coherent processing, which makes use of the phase continuity between Morse characters[10]. In EME work, he estimates improvement of up to 2-3 dB, depending upon the characteristics of the received signal. Linrad also supports automatic polarity selection and a growing number of other desirable features.

WB9UWA is currently using a modified MFJ-1784 filter, which has somewhat greater ringing than SM5BSZ's filter. He found that binaural audio, feeding a 22 Hz noise bandwidth into one ear and a wider bandwidth into the other, helps to counteract the ringing and produces improvement over the unaided ear comparable to that achieved by SM5BSZ.

With these techniques, it is sometimes possible to copy random signals as weak as –5 to –7 dB at 100 Hz, approximately equivalent to unity (0 dB) SNR in an effective noise bandwidth of 20-30 Hz. However, not all the time: SM5BSZ tried Linrad on the ZRO Test signal discussed earlier, and found that the combination of phase jitter and frequency instability resulted in there being no significant improvement over the Z8 (-3.6 dB) copy reported by the author. Had this signal had the degree of coherence typical of EME, however, SM5BSZ believes that Linrad would have enabled him to achieve Z9, or at least to copy an unknown callsign at that SNR level (-6.6 dB)[11].

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[8] Ray Soifer, W2RS, "Low Power Earth-Moon-Earth Communications: An Update," *Proceedings of the RSGB AMSAT-UK UoSAT Colloquium, Data Space 1989*, published by AMSAT-UK, 1989.
[9] R.W. Harris and J.F. Cleveland, "A Baseband Communications System," *QST*, November 1978.
[10] For further information and downloadable software, go to http://ham.te.hik.se/homepage/sm5bsz/linuxdsp/linrad.htm

[11] Private correspondence.

Conclusions

The AMSAT ZRO Tests, in which several hundred amateurs participated in a controlled experiment over more than seven years, established that many good operators, approximately the top quartile of test participants, were able to copy by ear a sequence of five random digits at a key-down SNR of –3.6 dB in a noise bandwidth of 100 Hz, with a few (4%) able to reach –6.6 dB. The median participant required a SNR of –0.6 dB. Given the test conditions, these findings are considered to be accurate plus/minus approximately 3 dB. A study of the W2RS 144 MHz EME log from 1985 to 1995, when the author operated with 150W output to a single Yagi antenna, yielded fairly comparable results.

The W2RS EME log also shows that in prearranged schedules, when operators know what they are listening for, contacts were completed with SNRs at least 3 dB lower than was possible in random operation. Only four stations could be worked on random, out of 37 worked in total. For a good weak-signal operator in a prearranged EME schedule, copy by ear down to –6 or –7 dB key-down SNR in a 100 Hz bandwidth, equivalent to –23 or –24 dB average at 2.5 kHz, would not be unreasonable to expect (again, plus/minus approximately 3 dB).

Signal-processing techniques developed by SM5BSZ and WB9UWA may be able to improve upon the performance of the unaided ear by as much as 2-3 dB, depending upon the characteristics of the received signals.

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