All aboard the impulse train: an analysis of the two-channel title music routine in Manic Miner

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Dr Kenneth B. McAlpine
University of Abertay Dundee

Abstract

The ZX Spectrum launched in the UK in April 1982, and almost single-handedly kick-started the British computer games industry. Launched to compete with technologically-superior rivals from Acorn and Commodore, the Spectrum had price and popularity on its side and became a runaway success. One area, however, where the Spectrum betrayed its price-point was its sound hardware, providing just a single channel of 1-bit sound playback, and the first-generation of Spectrum titles did little to challenge the machine’s hardware. Programmers soon realised, however, that with clever machine coding, the Spectrum’s speaker could be encouraged to do more than it was ever designed to. This creativity, borne from constraint, represents a very real example of technology, or rather limited technology, as a driver for creativity, and, since the solutions were not without cost, they imparted a characteristic sound that, in turn, came to define the aesthetic of ZX Spectrum music. At the time, there was little interest in the formal study of either the technologies that support computer games or the social and cultural phenomena that surround them. This retrospective study aims to address that by deconstructing and analysing a key turning point in the musical life of the ZX Spectrum. The title music from *Manic Miner* was the first attempt at a true two-channel sound routine on the platform, and so marks the point at which its music moved from being largely functional and utilitarian to becoming an important – and expressive – dimension of the Spectrum gaming experience. We begin by discussing 1-bit sound and the range of tones that are natively supported by a 1-bit system, and show how these can be extended using frequency dividers and counters to create time-varying tones and pseudo two-channel sound. We conclude by highlighting the limitations of this technique and outline the key adaptations that would make it a viable approach for two-channel sound in later games.

Introduction

Game Studies, and particularly the subdiscipline that is concerned with computer and video games, is a relatively new and nascent field of study. It arrived at the end of the twentieth century, slightly lagging behind the growth of the games industry, as universities across the globe launched both undergraduate and postgraduate degree programmes in computer games, and a generation of academics and students began to take an interest in the critical study of game design, players, and their role in society and culture.

The study of game music and the hardware platforms that give voice to game music is yet more specialised, and while there have been some studies which delve into computer code to learn more about how such music is structured and functions, there have been few attempts to go deeper to look at the base hardware and software systems that are the foundation of game music expression. Yet hardware both supports and constrains the expressive capabilities of a gaming platform, and helps shape the concrete expressions of games written for it: There is little point, for example, in designing colour graphics for a device with a monochrome display. While some of these constraints, are concrete and immutable, others pose creators a challenge, a line in the sand that is begging to be erased and redrawn a little further down the beach. Such constraints function as spurs for creativity, and the solutions to the design problems that they pose is worthy of study, not just so that we might appreciate the ingenuity of the musicians and programmers – and often these were one and the same – but also so that we might understand better how creative musical expression on the platform came to sound the way it did.

We begin by exploring the ZX Spectrum from a platform perspective, highlighting the key features of its audio hardware and highlighting the constraints that these imposed on game designers.

The Spectrum cometh

The Spectrum was the fourth in a series of home computers by Sinclair Research Ltd, but unlike its predecessors, the MK-14, the ZX80 and the ZX81, which were available in kit form and aimed at the hobbyist market (Wilkins 2014, p.9), Sinclair targeted its new machine at the mass-market. The national newsagent chain, WHSmith had an exclusive contract to supply the Spectrum's predecessor, the ZX81, for six months, and it sold in the thousands (Abbot & Manuel 1985, p.65). Growing support from the popular press and a burgeoning mail-order games marketplace grew the market for the machine, so that when the ZX Spectrum launched, Sinclair had an established user base, and a number of developers selling through a national network of retail outlets.

The concept of home computing was also growing in the public consciousness. Following the broadcast of The Mighty Micro (1979), a groundbreaking television documentary series about the developing computer revolution, the British Broadcasting Corporation's (BBC) Further Education Department began to take an interest in the burgeoning home computer market, and established the BBC Computer Literacy Project, a series of television and radio programmes that would be based around a BBC-branded microcomputer, and which began broadcasting around the time of the Spectrum's launch (Lamb 1982, p.389). The BBC Computer Literacy project pushed strongly the idea of the home computer as a tool for learning, and without question, thousands of Spectrums were bought by parents keen to see their children using them to help with homework. Most of those machines, however, would be used almost exclusively for gaming.

At a hardware level, the ZX Spectrum is a very simple machine. Available in two guises, both models had 16 KB of ROM and either 16 KB or 48 KB of RAM, with a display resolution of 256 x 192. To conserve memory, the colour values for the display were stored separately from the pixel bitmap in a low resolution 32 x 24 grid overlay, corresponding to the character cells, meaning that each 8 x 8 character block shared one foreground colour and one background colour, from a palette of 15 shades (Marshall 1983, p.115). Nevertheless, the Spectrum's graphics represented a huge step forward from the ZX81, and for the first time, the British public could buy games that looked and played like arcade coin-ops. Indeed, many of the early Spectrum titles either borrowed heavily from commercial coin-op games or were blatant copies, right down to the graphics and screen layout. Artic Computing, for example, released Invaders (Wray 1982a) and Galaxians (Wray 1982b), both direct – and unofficial – ports of Space Invaders (Nishikado 1978) and Galaxian (Sawano 1979) respectively, and Sinclair's own Hungry Horace (Tang 1982) was one of several early Pacman (Iwatani 1980) clones.

One area, however, where the Spectrum could not live up to the arcade gaming experience, however, was the sound. It was Sinclair's first machine to feature a true onboard sound interface, adding an onboard 22mm, 40-ohm speaker to the square wave oscillator that had been used as a means of data storage on external analogue compact cassette tape since the MK14 (Science of Cambridge 1978). The Introductory Booklet that was bundled with the Spectrum claimed, rather optimistically perhaps, that the "ZX Spectrum can make sounds of an infinite variety" (Sinclair Research Ltd. 1982). Most users, however, would have realised fairly quickly that the speaker, which provided just a single channel of 1-bit playback across a 10-octave range, couldn't do much except 'beep'. To compound matters, all of the sound commands were managed directly by the main CPU, a Zilog Z80A processor running at 3.5MHz, and a custom Ferranti Uncommitted Logic Array (ULA) chip, and driving the speaker tied up the processor, meaning that while the Spectrum was beeping, it couldn't, without some clever machine code programming, do very much else.

Little wonder, then, that few of the early Spectrum titles featured much in the way of sound. In-game music was generally limited to key game events, such as losing lives, where the gameplay could be paused while the CPU replayed the music, and almost all Spectrum music was played using monophonic square waves. This, it seemed, was the basic formula for Spectrum game music. Until, that is, it was reimagined by a seventeen-year-old from Wallasey, and introduced with the Spectrum's first truly iconic character.

Manic Miner

Matthew Smith grew up around the mechanical fairground games in the seaside arcades of New Brighton in the North West of England. Like many school children, he doodled his way through classes, sketching characters and game mechanics on the covers of his schoolbooks and imagining them as arcade machines. In 1983, Smith was loaned a Spectrum by Liverpool-based publisher Bug Byte to develop three games. The first title, *Styx* (1983a), was a fairly simple action maze game, based around a single, repeating screen which got progressively more difficult each time the player completed a level, but it was Smith's second game, *Manic Miner* (1983b) that became a runaway success.

Manic Miner was based on *Miner 2049er* (Hogue 1982), a platform game that featured a Canadian Mountie, Bounty Bob, navigating his way through ten different screens and inspecting each area before his oxygen runs out. Several elements of Miner2049er appear in Manic Miner – the underground setting and the oxygen-level as a timer, for example – but in creating Miner Willy, Smith injected a particularly British spin on the game, with an absurd humour to the level and character design, and a Pythonesque boot which descends to squash Willy when the game is over.

On loading, the game displays a dynamic title screen showing the sun setting behind an idyllic cliff-top house, below which, an animated keyboard plays, pianola-style, the notes of a delightfully-clangorous two-channel rendition of The Beautiful Blue Danube, by Johann Strauss II. Although the music routine includes an algorithm that uses the note data to display the notes onscreen, the keyboard graphics use a short octave (C – E) to the left of middle C, making it almost impossible to use this as a visual point of reference for transcribing the music.

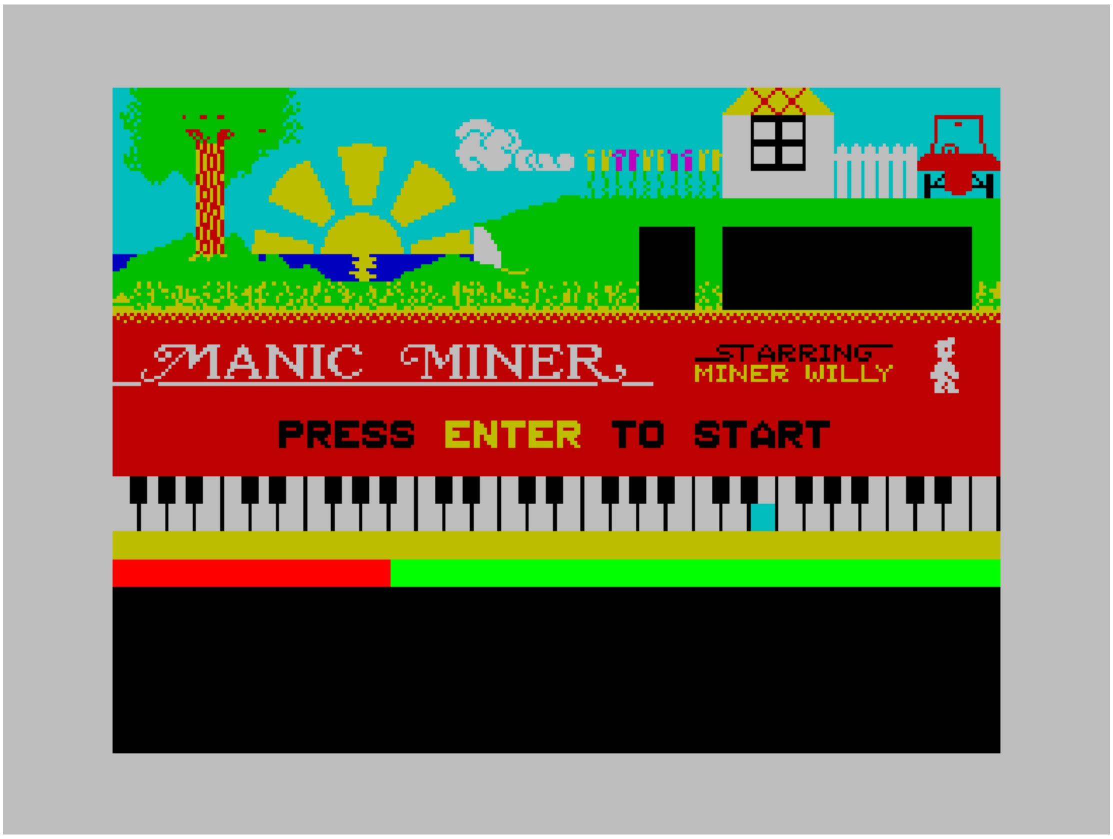


Figure 1 – The title screen from Manic Miner

Smith notes:

> The game needed music, as I felt it was an integral part of the attraction. The title song, I had an old, simple piano arrangement [of the Beautiful Blue Danube] in sheet music so it was easy to transcribe. I did everything as quickly as possible, got the loop running as fast as possible, but I never got too prissy about exact timings. (2014)

Extending the 1-bit sound pallette

The first thing to notice about the title music on *Manic Miner* is that tonally it is much more dynamic and complex than a series of simple square waves. Recall that the Spectrum provided only 1-bit sound. The speaker was controlled via bit 4 of port 0xFE of the ULA, meaning that the speaker could be switched fully on, corresponding to a bit value of 1, or fully off. No intermediate states were addressable, and consequently, there was no level control over the signal, which, by default, was a square wave.

A single cycle of a digital square wave is little more than a sequence of ones followed by an equal number of zeroes. Repeating this pattern over and over creates a continuous tone whose period, and therefore frequency, is determined by the number of ones and zeroes in each cycle. Increasing the number of ones and zeroes increases the period and so lowers the pitch, and vice versa:

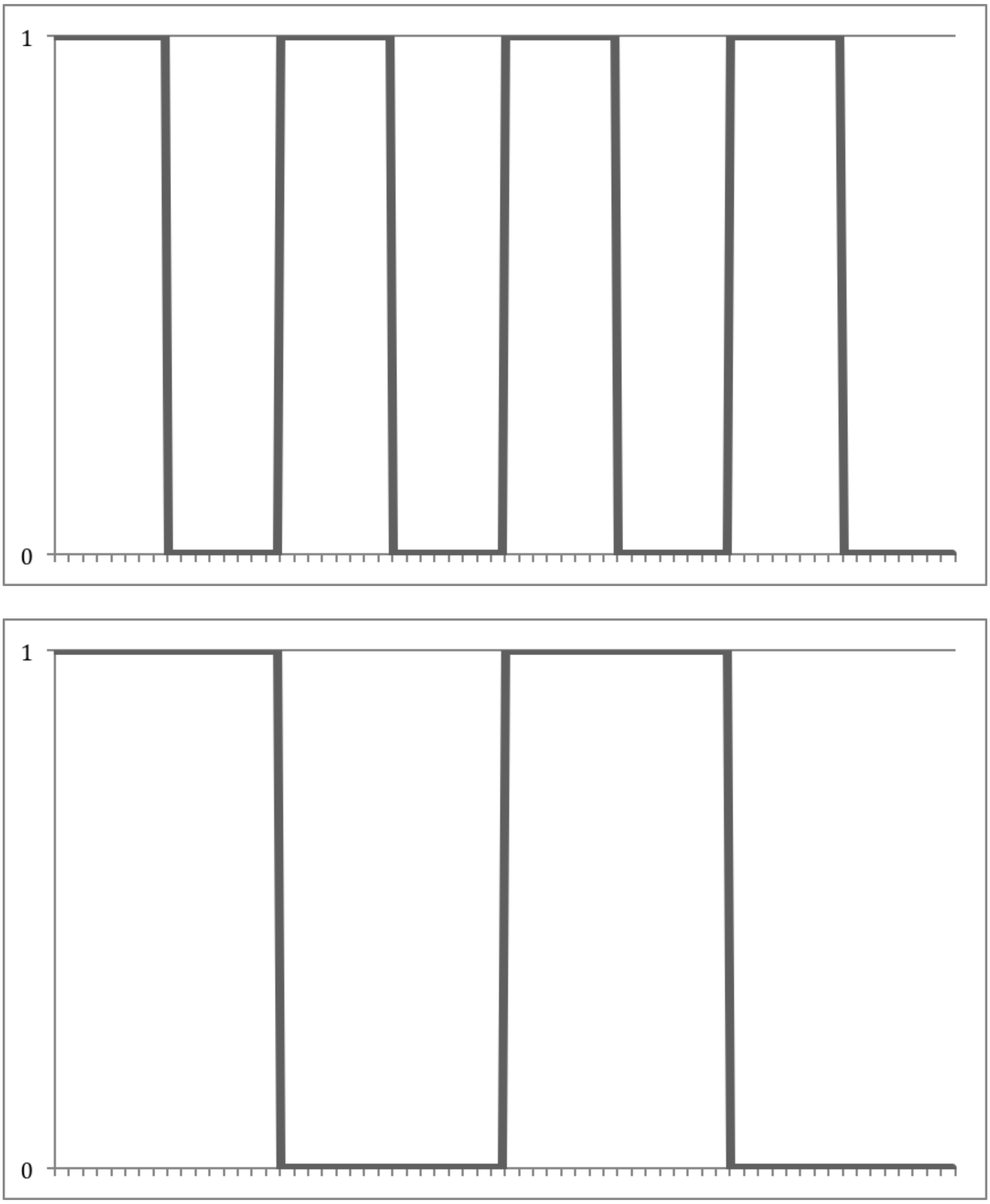


Figure 2 – A binary square wave is defined as a sequence of ones followed by an equal number of zeroes. Doubling the number of successive ones and zeroes sent to the speaker doubles the period of the resulting wave. This corresponds to a halving of frequency, and a drop in pitch by an octave.

A Fourier analysis (Roads 1996, pp.1084 – 1112) of the square wave reveals it to have a very well-defined and characteristic spectral signature, defined by the following equation:

$$\text{Relative magnitude of the } n^{th} \text{ harmonic} = \begin{cases} 1, & \text{if } n \text{ is odd} \\ 0, & \text{otherwise} \end{cases}$$

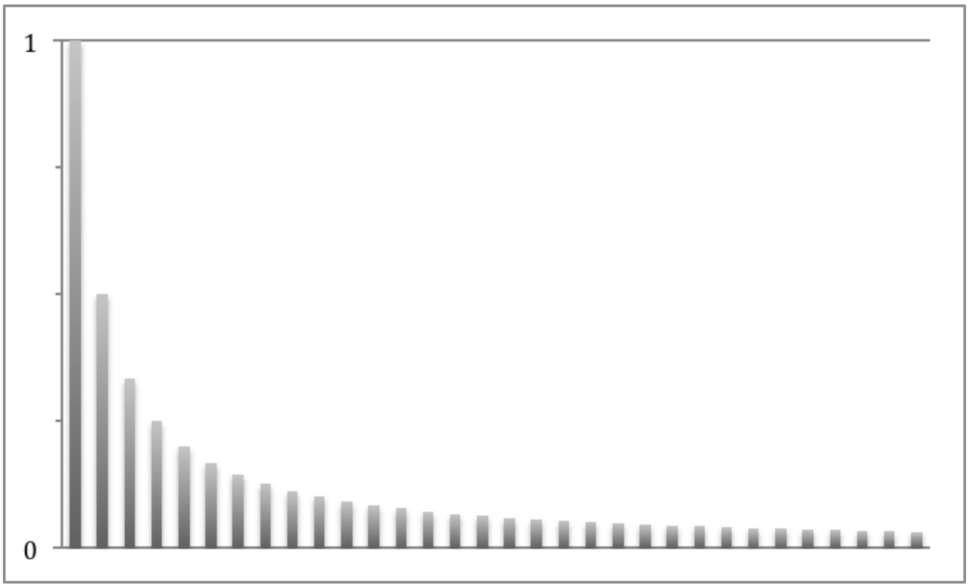
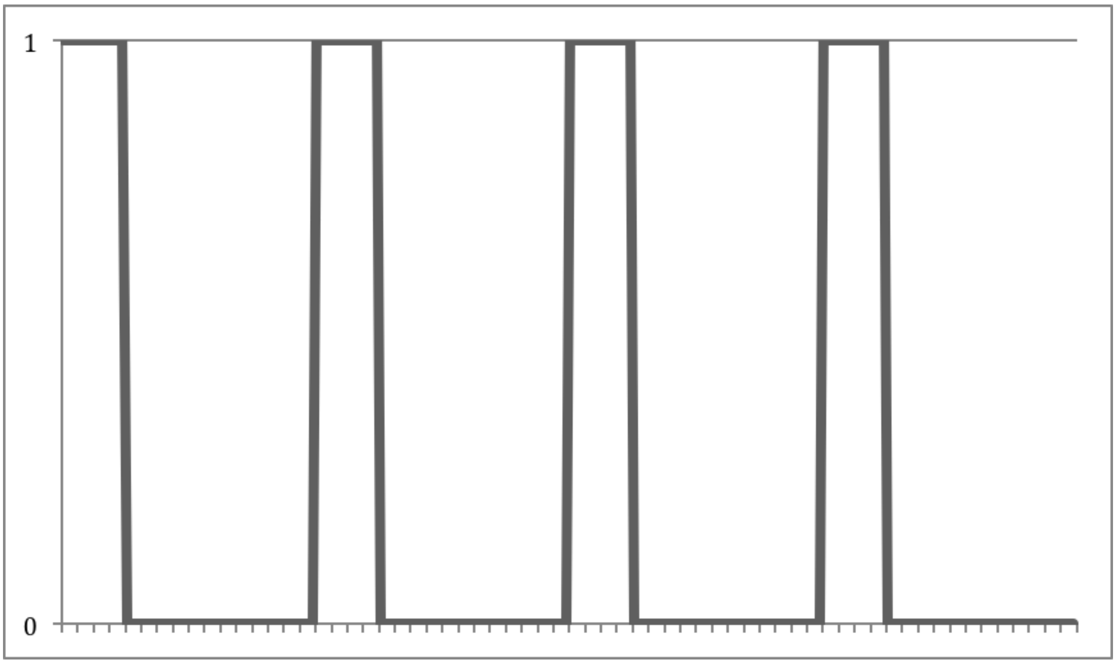


Figure 3 – Plot showing the first 32 harmonics of a square wave.

The square wave is not, however, the only waveform that we can create by sending a stream of ones and zeroes to a 1-bit sound device. Suppose that, rather than outputting ones and zeroes in equal measure, we output a sequence of ones followed by three times as many zeroes. This is a pulse wave, an asymmetrical version of the square wave. In this case, 25% of the pulse is made from ones, and the rest from zeroes, and so we say that the pulse wave has a duty cycle of 25%. The tonal characteristics of the pulse wave are similar to those of the square wave, although a Fourier analysis reveals a different frequency spectrum. The magnitude of its harmonics are related by a more complex relationship:

$$\text{Relative magnitude of the } n^{th} \text{ harmonic} = \operatorname{sinc}(n) = \frac{\sin(\frac{\pi n M}{N})}{\frac{\pi n M}{N}},$$

where M is the number of successive ones in the N sample points that represent a complete cycle of the wave.



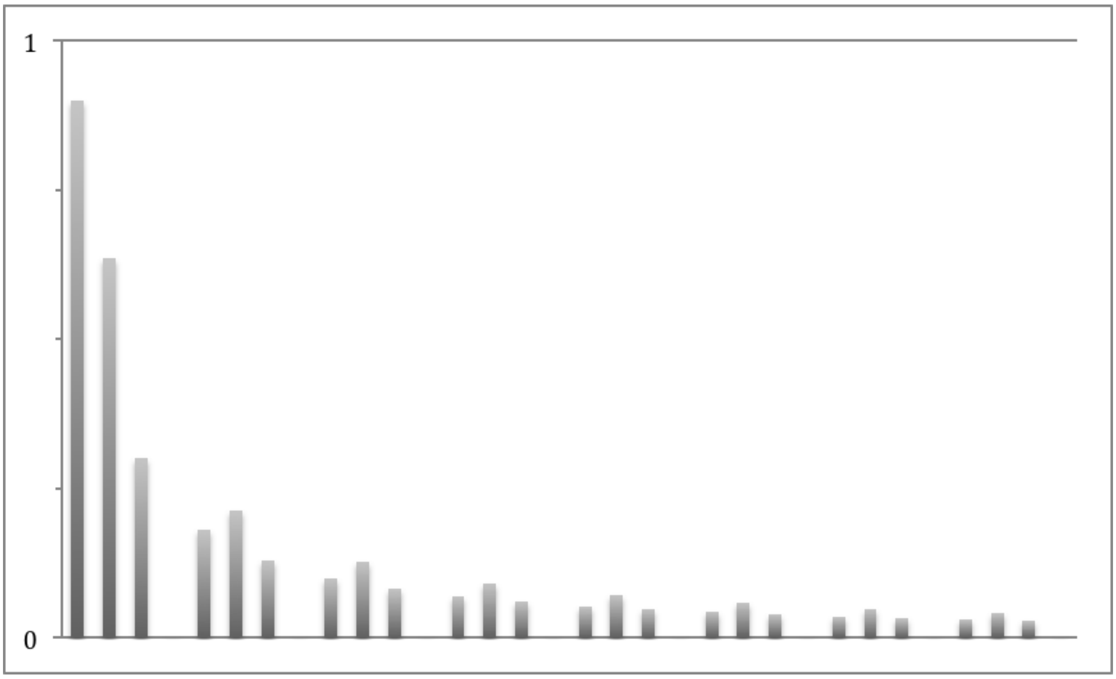


Figure 4 – Outputting a sequence of ones followed by three times as many zeroes creates 25% pulse wave, which exhibits a different frequency spectrum to the square wave

We could further reduce the number of ones in each cycle of the wave to create smaller and smaller duty cycles, varying the frequency spectrum and tone of the sound, until we send the beeper just a single positive bit, followed by a stream of zeroes. This signal is a binary impulse, and its Fourier transform is a constant. In other words, an impulse contains all possible frequencies in equal strength.

It is not possible to hear an impulse on its own, but it is possible to hear the effect on the speaker of trying to play an impulse, the so-called impulse response. Any speaker exhibits a degree of inertia, taking a short but finite time to move from rest to maximum displacement and back again, and it’s this response that can be heard as a noticeable click. Sequence a series of binary impulses together, separated by short gaps, and the result is an impulse train, a pitched tone whose frequency is determined by period between successive impulses, and which contains all of the harmonics of the signal at equal strength.

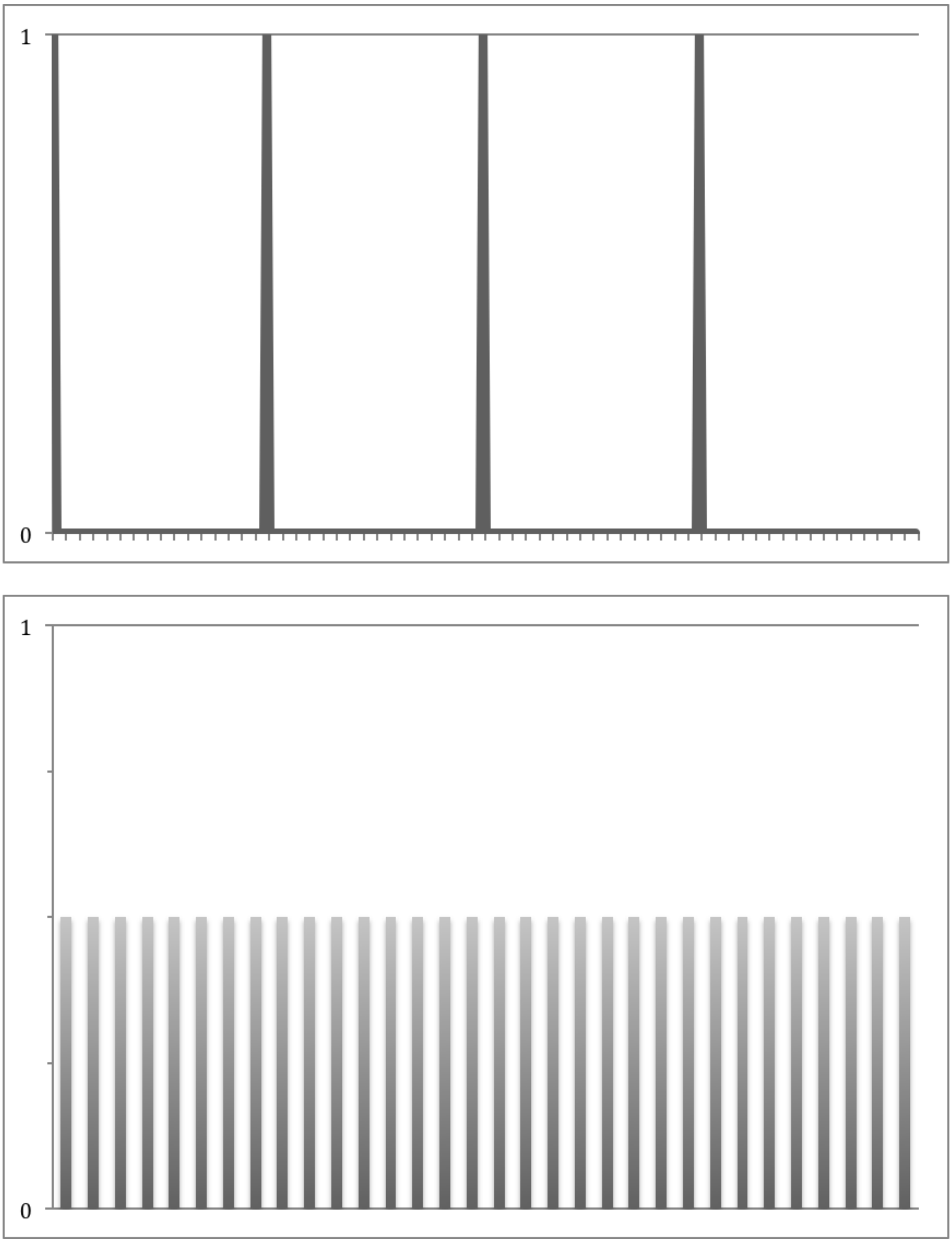


Figure 5 – Outputting a pulse train generates a signal whose frequency spectrum contains an equal amount of energy across each harmonic

A RAM dissassembly of Smith's code reveals that Smith used impulse trains as the basis for the title music routine. The title music was stored in memory as a series of ninety-five groups of three data bytes. Each triplet corresponds to a separate beat (or sub-beat) in the arrangement, and encodes each as a duration and a pair of pitch values, or more accurately, as counter values which are used to calculate the period between successive impulses, using a technique known as *Frequency Divider*, or *Divide Down Synthesis* (Roads 1996, p.925).

The technique generates a waveform by counting the pulses of a master clock, triggering an impulse when a chosen divisor – the counter limit – is reached. The counter is then reset and begins again. This generates a periodic impulse train at a frequency of:

$$\frac{sample\ frequency}{counter\ \ limit}$$

For example, if the sample frequency was 48000 Hz, and the counter limit was 48, the Frequency Divider technique would generate a tone at 1000 Hz. There is a problem, however. Rearranging the equation, we can calculate the counter limit that corresponds to any given frequency. Table 1 below shows the results for the 12 notes of the equally-tempered chromatic scale starting at concert A (440 Hz). None of the calculated counter limit values are integers, and so would be rounded to the nearest integer, introducing pitch errors which, because frequency and pitch relate multiplicatively, increase in relative terms with increasing frequency, meaning that notes begin to sound more and more out-of-tune as pitch increases, something that can be heard on the shrill upper notes of Manic Miner's theme.

Pitch	Frequency in Hz	Counter limit at 48kHz
A	440	109.0909091
A#	466.1637615	102.9681068
B	493.8833013	97.18895107
C	523.2511306	91.73415439
C#	554.365262	86.58551193
D	587.3295358	81.72584056
D#	622.2539674	77.13892158
E	659.2551138	72.80944659
F	698.4564629	68.72296636
F#	739.9888454	64.86584264
G	783.990872	61.22520264
G#	830.6093952	57.78889606
A	880	54.54545455

Table 1 – The frequencies of the 12 notes of the equally-tempered chromatic scale beginning on A = 440 Hz and the calculated counter limits for a 48kHz system.

In the case of *Manic Miner*, the counter is updated on each cycle of the theme-music subroutine, and so the timing of each 'master clock tick' is determined by two factors: the clock speed of the Z80 CPU, which runs at 3.5 MHz, and the length of time taken by the CPU to execute each of the machine instructions in the loop, which can be obtained experimentally. From these, Smith was able to construct a frequency table that mapped the notes of the musical arrangement to a series of counter values, and it is these values that provide the note data for his routine.

Using these note data, the original manuscript can be reconstructed:

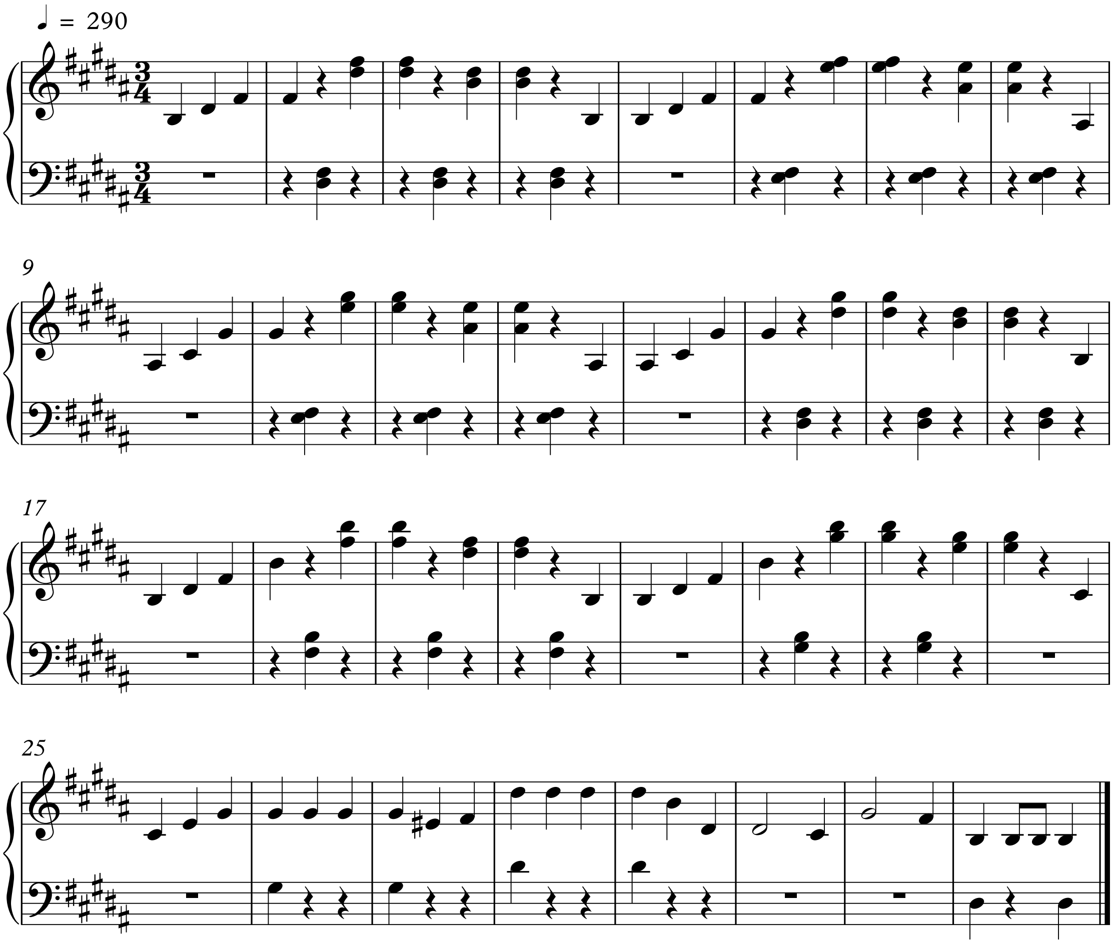



Figure 6 – Matthew Smith's arrangement of Strauss's *Beautiful Blue Danube* for the theme to *Manic Miner*.

Smith's music routine uses two counters to calculate two simultaneous impulse trains. The routine reads the two counter values stored in the data triplets into two memory registers and calculates the period between successive impulses, effectively interleaving the two impulse trains on playback to create two-channels of playback. For single notes, such as those in bar 1, Smith encodes the pitch as a pair of counter values separated by 1, to create a phasing effect. Chords are encoded as two distinct frequency values.

The phasing effect works well, creating a harmonically rich, time-varying tone on the single notes with a characteristic sweeping effect at the beat frequency. The chord tones, however, while interesting are not entirely successful. Smith's routine lacks any amplitude enveloping, which means that successive notes tend to run into one another, losing any sense of articulation. This is particularly evident from bar 25 until the end, when the sense of ¾ time, already somewhat vague because of the very fast tempo, is lost, and, using the anacrusis on middle C as the main audible point of reference for the beat, the music takes on more of the character of common time.

More challenging, however, is the balance of harmonics. Recall that the monophonic notes were encoded as pairs of counter values separated by a single unit, the effect of which is to create two binary impulse trains separated in frequency by only a few Hertz. This results in a frequency spectrum that is very close to a harmonic series, like that of Figure 7 below.

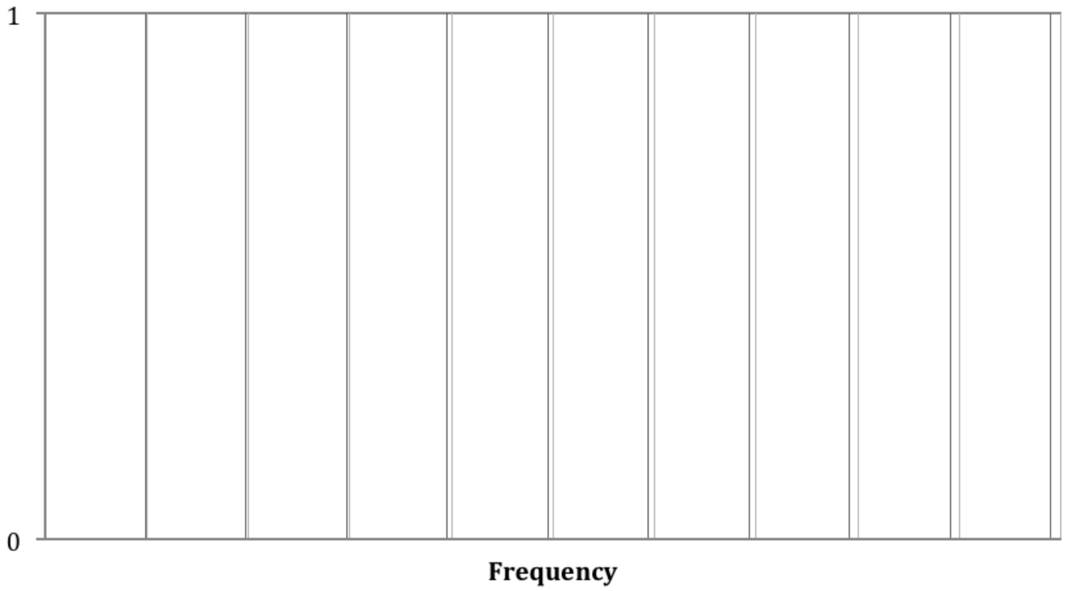


Figure 7 – A spectral plot of the two near-coincident impulse trains shows a pseudo-harmonic series, although the concordance between the harmonics of the lower tone, illustrated by the dark bands, and the upper tone, illustrated by the lighter bands, decreases with increasing frequency, lending the tone a shrill quality. The harmonic character, however, makes it easy to identify a unique pitch.

When two impulse trains are interleaved at distinct frequencies, this pseudo-harmonic spectrum breaks down as shown in Figure 8 below. This spectral plot illustrates a major third interval. As in Figure 7 above, the dark bands correspond to the harmonics of the lower tone in the interval, and the light bands to the harmonics of the upper tone. It can be seen immediately that there is no regular structure to these frequency components. The spacing between spectral components is variable, and includes a number of very closely clustered components, which introduces an unpleasant beating to the tone. In addition, because each of the harmonics of each tone has equal magnitude, one of the key auditory cues that we normally use to locate and identify pitch, that is the fundamental, which is usually the strongest of these frequency components, is not evident. Like Alice's caucus race in Lewis Carroll's classic tale, which was run in a circle with no identifiable start or finish line, resulting in the absurd situation that all who took part were winners, with no clear dominant frequency to use as a pitch reference in the sound's spectrum, every frequency component arbitrarily becomes the dominant one as the ear focuses in on different regions, creating a very vague sense of pitch. The overall effect is to create a sense in the listener of a rough, complex tone rather than two discrete and distinct pitches.

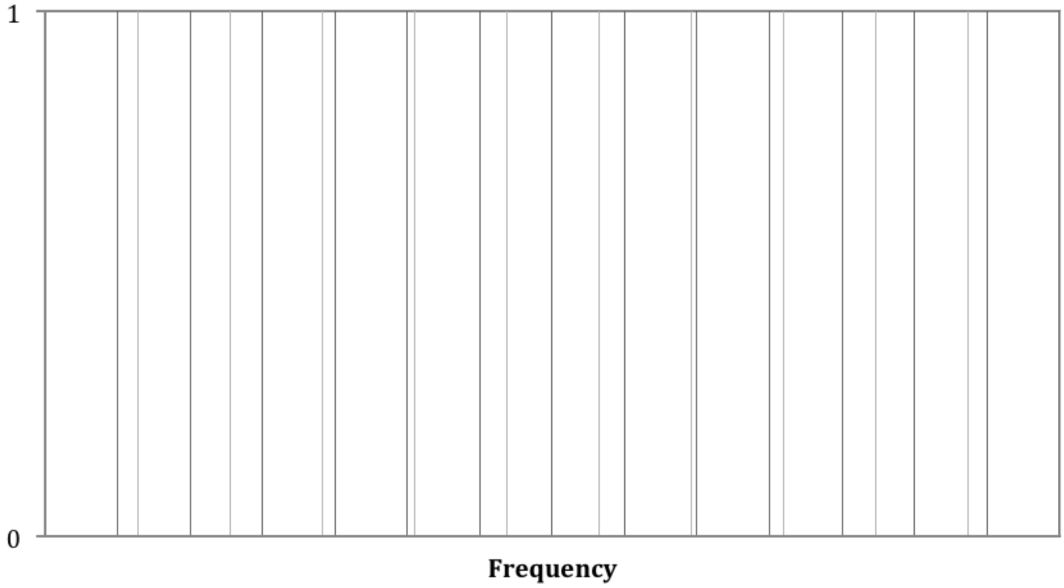


Figure 8 – A spectral plot of two non-coincident impulse trains shows a more complex relationship. There is variability in the spacing between components and some clustering, leading to beating. The uniform magnitude of the components makes it very difficult to identify discrete pitches.

Conclusion

Manic Miner was a notable game in many ways. In Miner Willy it brought the Spectrum its first truly iconic character, and it was one of the first Spectrum games to become a runaway commercial success, making a superstar out of its young programmer, Matthew Smith. Musically, although its implementation of a two-channel sound routine was not entirely successful, its approach, the notion of using counters to interleave sound pulses, would be refined and used with greater success in the pulse-wave modulation routines of games like *Zombie Zombie* (White & Sutherland 1984) and *Fairlight* (Jangeborg & Wilkes 1985). *Manic Miner's* biggest failing in this respect was to strive for efficiency in execution, using impulse trains as the source for the sound routine, and in so doing, creating complex sound spectra that lost the musical detail that Smith had so cleverly tried to weave from the Spectrum's single-channel speaker. By swapping impulse trains for pulse waves of varying duty cycle, that is, by modulating the pulse width of the speaker, Sandy White and Mark Alexander proved, just a year later, that two into one didn't just go, but could be controlled with a degree of musical finesse.

Interestingly, for his next title, Jet Set Willy, Smith dropped his impulse train sound routine in favour of a simpler monophonic square-wave routine, using a pattern of broken octaves, similar to the left-hand bass patterns of Boogie

Woogie or Stride piano, to arrange Beethoven's Piano Sonata no. 14, *Moonlight*. The effect is striking, in places sequencing melody and accompaniment notes to create a sense of implied duophony, and it is easy to forget that there is nothing more complex at work than a sequence of monophonic square wave tones.

Smith's legacy to the world of computer gaming is huge, and he is rightly regarded as one of the Spectrum's founding figures. With *Manic Miner*, he provided a glimpse of what the Spectrum, and its humble sound speaker, might one day achieve, paving the way for the more complex and refined multi-channel sound routines that were to follow.

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