Sound Composition with Pulsars*

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Pulsar synthesis (PS) is a method of electronic music synthesis based on the generation of trains of sonic particles. It can produce either rhythms or tones as it crisscrosses perceptual time spans. The basic method generates sounds similar to vintage electronic music sonorities, with several important enhancements. The advanced method combines multiple pulsar trains and convolution with sampled sounds. Together with Alberto de Campo, the author has designed a program for pulsar synthesis called PulsarGenerator. Applications of pulsar synthesis in compositions by the author are noted.

0 INTRODUCTION

> In July 1967 a young British astronomer detected in the sky by chance a radio signal in the form of a series of periodic impulses spaced every 1.33730113 seconds. The event was met immediately with incredulity. Deep in space, an object beat time with metronomic precision. The arrival time of the impulses was so regular that for a certain period it was believed that it was a message sent by an extraterrestrial civilization, destined for other beings in the universe [1].

All forms of music composition—from the freely improvised to the formally organized—are constrained by their sound materials. Thus the urge to expand the field of sound comes from a desire to enrich compositional possibilities. Much can be gained from the harvest of synthetic waveforms. Of special interest are those hybrids that crossbreed the richness of familiar sounds with unusual overtones.

Here we describe a powerful method of digital sound synthesis with links to past analog techniques. This is pulsar synthesis (PS), named after the spinning neutron stars that emit periodic signals in the range of 0.24 to 642 Hz. By coincidence, this same range of frequencies—between rhythm and tone—is of central interest in pulsar synthesis.

Pulsar synthesis melds established principles within a new paradigm. In its basic form, it generates electronic pulses and pitched tones similar to those produced by analog instruments such as the Ondioline [2], [3] and the Hohner Elektronium (introduced in 1950), which were designed around the principle of filtered pulse trains. Pioneering electronic music composers such as Karlheinz Stockhausen [4]–[7] and Gottfried Michael Koenig [8]–[10] used filtered impulse generation as a staple in their studio craft. Pulsar synthesis is a digital technique, however, and so it accrues the advantages of precise programmable control, waveform flexibility, graphical interface, and extensibility. In its advanced form, pulsar synthesis generates a world of rhythmically structured crossbred sampled sounds.

Pulsar synthesis belongs to a larger family of microsonic or particle synthesis techniques, one example of which is granular synthesis [11]–[18]. These techniques stream or scatter acoustic particles in myriad patterns to produce time-varying sounds.

This paper first presents the basic theory of pulsars and pulsar graphs. We then move on to the more advanced technique using pulsars to transform sampled sounds through cross synthesis. We present musical applications of pulsar synthesis in compositions by the author. Near the end we describe the features of a new interactive program called PulsarGenerator. The Appendix presents a mathematical analysis of one aspect of pulsar spectra.

1 BASIC PULSAR SYNTHESIS

Basic pulsar synthesis generates a family of classic electronic music timbres that are akin to those produced by an impulse generator connected to a bandpass filter. Unlike the classic technique, however, there is no filter in the basic pulsar synthesis circuit.

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1.1 Anatomy of a Pulsar

A single pulsar is a particle of sound. It consists of an arbitrary *pulsaret* waveform w with a period d followed by a silent time interval s [Fig. 1(a)]. The total duration of a pulsar is $p = d + s$, where p is the pulsar period, d is the duty cycle, and s is silent. Repetitions of the pulsar signal form a pulsar train. Let us define the frequency corresponding to the repetition period as $f_p = 1/p$ and the frequency corresponding to the duty cycle as $f_d = 1/d$. Typical ranges of f_p are between 1 Hz and 5 kHz, and the typical range of f_d is from 80 Hz to 10 kHz.

In pulsar synthesis both f_p and f_d are continuously variable quantities. They are controlled by separate envelope curves that span a train of pulsars. The train is the unit of musical organization on the time scale of notes and phrases. A pulsar train can last anywhere from a few hundred milliseconds to a minute or more.

Notice in Fig. 1(b) that the duty ratio, or d:s ratio, varies while p remains constant. In effect, one can simultaneously manipulate both fundamental frequency (the rate of pulsar emission) and what we could call a formant frequency (corresponding to the duty cycle), each according to separate envelopes. Lowering the fundamental means increasing s, and raising the fundamental means decreasing s.

So far the structure we described is similar to a standard impulse generator. Pulsar synthesis generalizes this configuration in several ways. First, it allows the pulsaret w to be any waveform. Fig. 2 shows some typical pulsaret waveforms, including those with multiple subperiods within their duty cycle [Fig. 2(b), (d), and (e)].

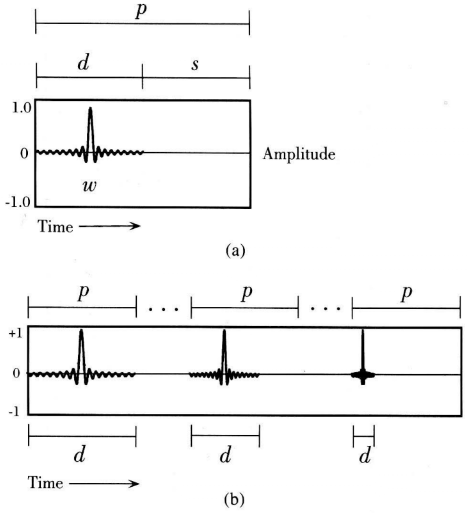


Fig. 1. Anatomy of a pulsar. (a) A pulsar consists of a brief burst of energy called a pulsaret w of a duration d followed by a silent interval s. The waveform of the pulsaret, here shown as a band-limited pulse, is arbitrary. It could also be a sine wave or a period of a sampled sound. The total duration $p = d + s$, where p is the fundamental period of the pulsar. (b) Evolution of a pulsar train, time-domain view. Over time, the pulsar period p remains constant while the pulsaret period d shrinks. The ellipses indicate a gradual transition period containing many pulsars between the three shown.

Let us assume that w is a single cycle of a sine wave. From a signal-processing point of view, this can be seen as a sine wave that has been limited in time by a rectangular function v, which we call the pulsaret envelope. An important generalization is that v can also be any shape. As we discuss later, the envelope v has a strong effect on the spectrum of the pulsar train.

Fig. 3 shows some typical pulsaret envelopes. A rectangular envelope [Fig. 3(a)] produces a broad spectrum with strong peaks and nulls for any pulsaret. Fig. 3(g) depicts a well-known configuration for formant synthesis, as seen in techniques such as window function synthesis [19], VOSIM [20], and FOF [21], where the waveform is fixed and the envelope has a sharp attack followed by an exponential decay. Such a configuration can be seen as a special case of pulsar synthesis, which allows complete flexibility in both the waveform and the pulsaret envelope. For example, as Fig. 3(b) shows, the envelope could also be a bipolar ring modulator.

Keeping p and w constant and varying d on a continuous basis creates the effect of a resonant filter swept across a tone. There is, of course, no filter in this circuit. Rather, the frequency corresponding to the duty cycle d appears in the spectrum as a formant peak. By sweeping the frequency of this peak over time, we obtain the sonic equivalent of a time-varying bandpass filter applied to a basic impulse train.

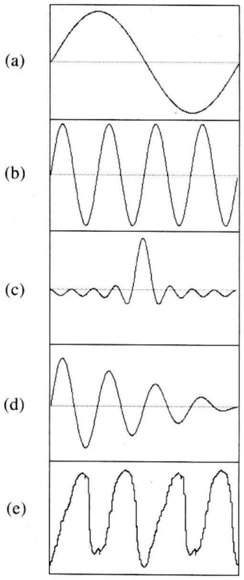


Fig. 2. Typical pulsaret waveforms. In practice, any waveform can be used. (a) Sine. (b) Multicycle sine. (c) Band-limited pulse. (d) Decaying multicycle sinusoid. (e) Cosmic pulsar waveform emitted by neutron star Vela X-1.

1.2 Pulsaret-Width Modulation

Pulse-width modulation (PWM) is a well-known analog synthesis effect that occurs when the duty cycle of a rectangular pulse varies while the fundamental frequency remains constant [Fig. 4(a)]. This produces an edgy "sawing" quality as the upper odd harmonics increase and decrease over the course of the modulation. At the extremes of PWM, the signal is silent. For example, when $d = 0$, PWM results in a signal of zero amplitude [Fig. 4(b)]. When $d = p$, PWM produces a signal of a constant amplitude of 1 [Fig. 4(c)].

Pulsaret-width modulation (PulWM) extends and improves this model. First, the pulsaret waveform can be any arbitrary waveform. Second, it allows the duty cycle frequency to pass through and below the fundamental frequency. Here $f_d \leqslant f_p$. Notice how the duty cycle of the sinusoid increases from Fig. 4(d) to Fig. 4(e). In Fig. 4(f), $p = d$. Finally in Fig. 4(g), $p < d$, that is, the duty cycle is longer than the fundamental period. Only the first quadrant of the sine wave repeats. The fundamental period cuts off the duty cycle of the pulsaret in mid-waveform. In our implementation we apply a user-controlled crossfade time around this cutoff point, which we call the edge factor. When there is no crossfade, the edge factor is high.

We have also tested an alternative approach to pulsaret-width modulation, which produces a different sound. In overlapped pulsaret-width modulation (OPulWM) the fundamental frequency is interpreted as the rate of pulsar emission, independent of the pulsaret duty cycle. That is, the duty cycle of an individual pulsar always completes, even when it crosses below the fundamental frequency. Whenever the fundamental period expires, our algorithm spawns a new pulsar. Thus when $d > p$, several pulsars overlap with others whose duty cycle has not yet completed. As d increases, the generator spawns more and more overlapping pulsars. For practical reasons, then, we stipulate an arbitrary overlap limit. In general, OPulWM results in a great deal of phase cancellation and thus tends to be a more subtle effect than regular PulWM.

1.3 Synthesis across Time Scales

Pulsar synthesis operates within and between musical time scales. It generates a stream of microsonic particles at a variable rate, across the continuum spanning the infrasonic pulsations and the audio frequencies. When the distance between successive impulses is less than about one-twentieth of a second, the human hearing mechanism causes the impulses to fuse into a continuous tone. This is the forward masking effect [22]. As Helmholtz [23] observed, in the range between 20 and 35 Hz, it is difficult to distinguish the precise pitch of a sustained tone; reliable pitch perception takes hold at about 40 Hz, depending on the waveform. Thus for p between approximately 25 ms (corresponding to $f_p = 40$ Hz) and

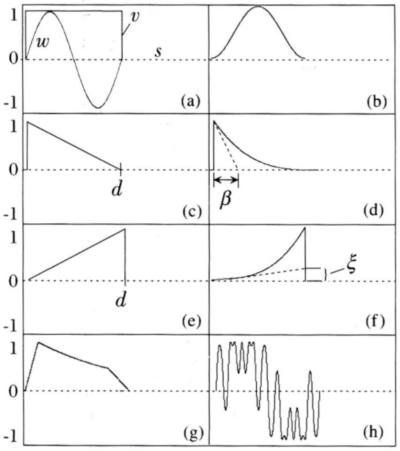


Fig. 3. Typical pulsaret envelopes v. (a) Rectangular. (b) Gaussian. (c) Linear decay. (d) Exponential decay. β—steepness of exponential curve. (e) Linear attack, with duty cycle d. (f) Exponential attack. ξ—steepness of exponential curve. (g) FOF envelope [21]. (h) Bipolar modulator.

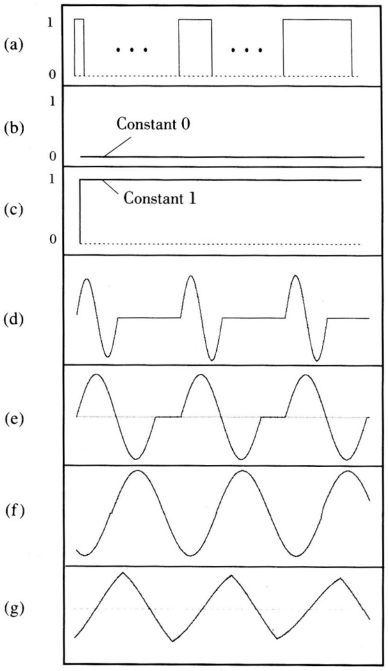


Fig. 4. PWM and PulWM. (a) Classical PWM with rectangular pulse shape. Ellipses indicate a gradual transition between pulses. (b) PWM when $d = 0$ results in signal of zero amplitude. (c) PWM when $d = p$ (fundamental period). Result is a signal with constant amplitude 1. (d) Pulsar train with sinusoidal pulsaret. (e) Same period as (d), but duty cycle is increasing. (f) Duty cycle and period are equal, resulting in a sinusoid. (g) Duty cycle is greater than fundamental period, which cuts off final part of sine waveform.

200 μs (corresponding to $f_p = 5$ kHz), listeners ascribe the characteristic of pitch to a periodic sustained tone.

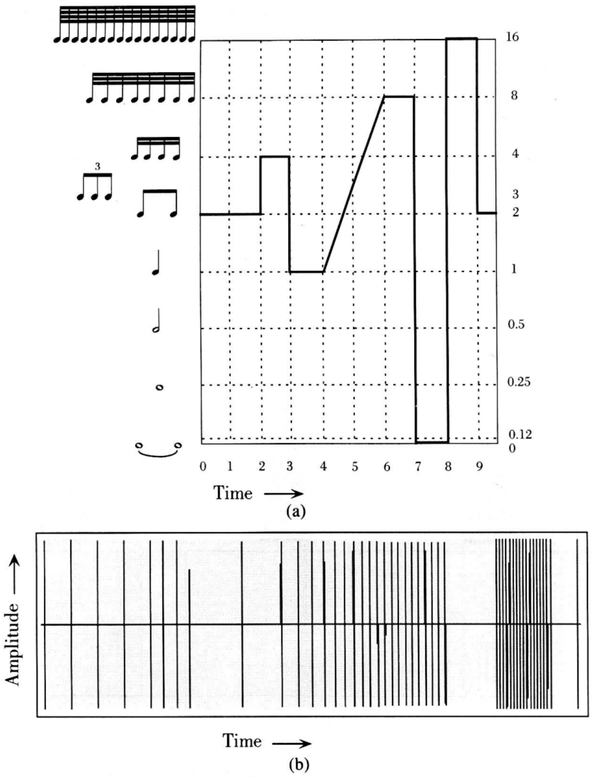
As the rate of pulsar emission slows down and crosses through the threshold of the infrasonic frequencies ($f_p <$ 20 Hz), the sensation of continuous tone evaporates, and we can perceive each pulsar separately. When the fundamental f_p falls between 62.5 ms (corresponding to the time span of a 32nd note at ♩ = 60 MM) and 8 seconds (corresponding to the time span of two tied whole notes at ♩ = 60 MM), we hear rhythm. The fundamental frequency envelope becomes a graph of rhythm (Fig. 5). This pulsar graph can serve as an alternative form of notation for one dimension of rhythmic structure, namely, the onset time of events. The correspondence between the musical units of rhythmic structure (such as note values, tuplets, rests) can be made clear by plotting note values on the vertical or frequency scale. For example, assuming a tempo of 60 MM, a frequency of 5 Hz corresponds to a quintuplet figure. Note that the duration of the events is not represented by a two-dimensional pulsar graph, but could be represented by adding a third dimension to the plot.

In order to interpret the rhythm generated by a function inscribed on a pulse graph, one has to calculate the duration of the particle emission curve at a given fixed frequency rate. For example, a particle emission at 4 Hz that lasts for 0.75 second emits 3 particles. When particle emission switches from one value to the next, the pulsar corresponding to the new duration is immediately played, followed by a silence equal to the period of particle emission. Fig. 5 plots a rhythm that alternates between fixed-rate pulses, accelerandi, and silence.

2 SPECTRA OF BASIC PULSAR SYNTHESIS

The spectrum of the pulsar stream is the convolution product of w and v, biased in frequency by f_d and f_p. Since w and v can be arbitrary waveforms, and f_d and f_p can vary continuously, the range of spectra produced by pulsar synthesis is quite large.

When the formant frequency is set at a specific frequency, for example, 1 kHz, this spreads energy in that region of the spectrum. Precisely how the energy is spread depends on w and v. The pulsaret waveform w can be considered a template of spectrum shape that repeats at the stipulated fundamental frequency f_p and



(a)

(b)

Fig. 5. Pulsar rhythms. (a) Pulse graph of rhythm showing rate of pulsar emission (vertical scale) versus time (horizontal scale). Left-hand scale measures traditional note values; right-hand scale measures frequencies. (b) Time-domain image of generated pulsar train corresponding to plot (a).

is scaled in time by the duty cycle or formant frequency f_d. If, for example, the ratio of the amplitudes of the first five harmonics of w is 5:4:3:2:1, this ratio is preserved independently of p and d, when $f_p \leq f_d$.

The contribution of the pulsaret envelope to the spectrum is significant. Fig. 6 shows the spectra of individual pulsars where the waveform w is fixed as a sinusoid, and the pulsaret envelope v varies between three basic shapes. In the case of Fig. 6(a) v is rectangular. Consequently, the formant spectrum takes the form of a broad sinc function in the frequency domain. The spectrum shows strong peaks at factors of $1.5f_d$, $2.5f_d$, etc., and nulls at harmonics of f_d. This is characteristic of the sinc function. An exponential decay or *expodec* envelope [such as in Fig. 3(d)] tends to smooth the peaks and valleys in the spectrum [Fig. 6(b)]. The bell-shaped Gaussian envelope compresses the spectral energy, centering it around the formant frequency [Fig. 6(c)].

Thus by modifying the pulsaret envelope one can alter the profile of the pulsar spectrum. The Appendix presents a mathematical analysis of the spectra of simple pulsaret envelopes.

3 ADVANCED PULSAR SYNTHESIS

The technique presented thus far, basic pulsar synthesis, is the starting point for advanced pulsar synthesis. The advanced technique adds several features, which take the method beyond the realm of vintage electronic sonorities. In particular, advanced pulsar synthesis is built on three principles:

1) Multiple pulsar generators sharing a common fundamental frequency, but with individual formant and spatial trajectories

2) Pulse masking to shape the rhythm of the pulsar train

3) Convolution of pulsar trains with sampled sounds.

Fig. 7 outlines the schema of advanced pulsar synthesis. The different parts of this schema are explained in the following sections.

3.1 Multiple Pulsar Generators

A pulsar generator has seven parameters:

1) Pulsar train duration
2) Pulsar train fundamental frequency envelope f_p
3) Pulsaret formant frequency envelope f_d
4) Pulsaret waveform w
5) Pulsaret envelope v
6) Pulsar train amplitude envelope a
7) Pulsar train spatial path s.

The individual pulsar train is the simplest case. To synthesize a complex sound with several resonance peaks, we can add several pulsar trains with the same fundamental frequency but with different time-varying formant frequencies f_d. One envelope controls their common fundamental frequency, whereas two or more separate envelopes control their formant trajectories f_{d1}, f_{d2}, etc.

One of the unique features of pulsar synthesis is that each formant can follow its own spatial path. This leads to complex spatial interplay within a single tone or rhythmic phrase.

3.2 Pulsar Masking, Subharmonics, and Long Tone-Pulses

A pulsar generator emits a metronomic sequence of pulsars, where the rate of emission can vary over time according to the fundamental frequency envelope function f_p. Pulsar masking breaks up the stream by introducing intermittencies (regular or irregular) into the metronomic sequence. It deletes individual pulsarets, leaving an interval of silence in their place. This takes three forms: burst, channel, and stochastic masking.

Burst masking [Fig. 8(a)] models the burst generators of the classic electronic music studios. It produces a

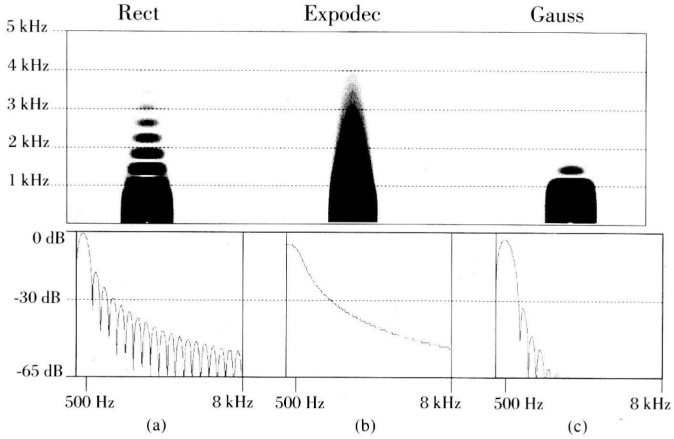


Fig. 6. Effect of pulsaret envelope on spectrum. Top—frequency-versus-time sonograms of individual pulsar with sinusoidal pulsaret; fundamental frequency 12 Hz, formant frequency 500 Hz. Sonograms are based on 1024-point fast Fourier transform plots using a Von Hann window; linear frequency scale. Bottom—sonograms produced by (a) rectangular envelope; (b) expodec envelope; (c) Gaussian envelope. Spectra of these pulsars on a dB scale.

regular pattern of pulsarets that are interrupted at regular intervals. The on–off pattern can be stipulated as the burst ratio $b{:}r$, where b is the burst length and r a rest length, both in pulsaret periods. For example, a $b{:}r$ ratio of 4:2 produces an alternating sequence of four pulsarets and two silent periods: 111100111100111100111100 and so on. If the fundamental frequency is infrasonic, the effect is rhythmic.

When the fundamental is in the audio frequency range, burst masking imposes an amplitude modulation effect on the timbre (Fig. 9) dividing the fundamental frequency by a subharmonic factor $b + r$. With the PulsarGenerator program (described later) we can alter the burst ratio in real time, producing a gamut of subharmonic permutations. When $b + r$ is large, the subharmonic crosses through the threshold separating

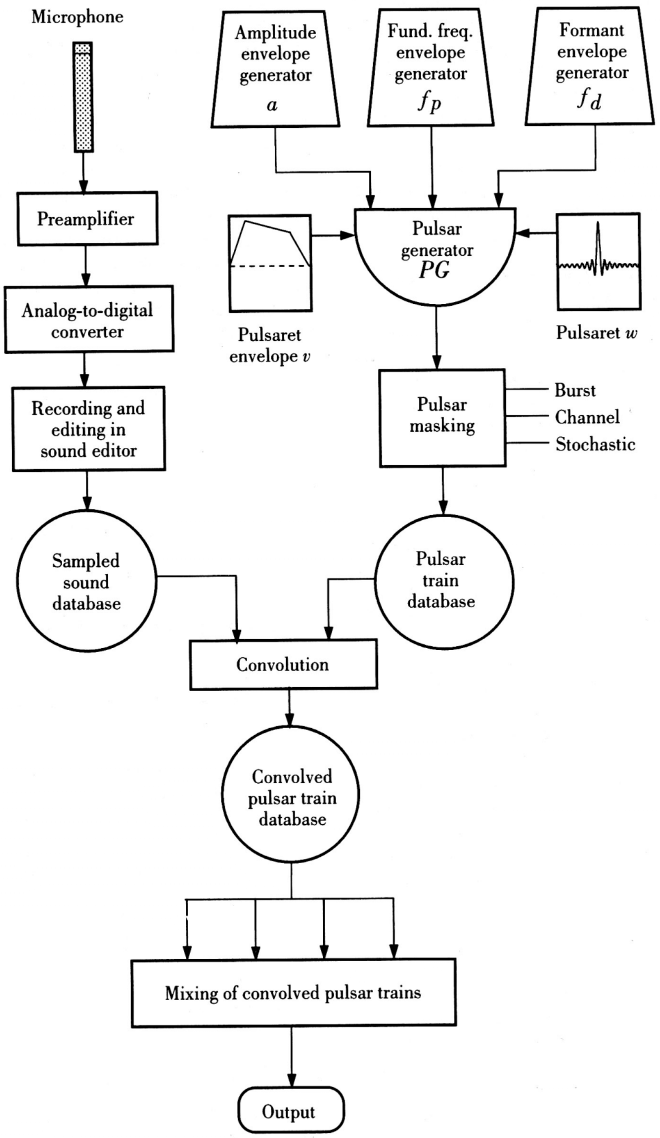


Fig. 7. Schema of pulsar synthesis. A pulsar generator with separate envelope controls for fundamental frequency, formant frequency, amplitude, stochastic masking, and spatial position. In advanced pulsar synthesis, several generators may be linked with separate formant and spatial envelopes. A pulsar stream may be convolved with a sampled sound.

tone and rhythm. The result is a series of alternating long tone-pulses (at the fundamental pitch) and silent intervals.

Channel masking [Fig. 8(b)] deletes pulsars in alternate channels. By selectively masking pulsars in two channels 1 and 2, one creates a dialog within a phrase, articulating each channel in turn. Fig. 8(b) shows two channels only, but we can generalize this scheme to N channels.

Stochastic masking introduces random intermittency into the regular stream of pulsars. We have implemented stochastic masking as a weighted probability that a pulsar will be emitted at a particular point in a pulsar train. The probability is expressed as an envelope over the duration of the pulsar train. When the value of the envelope is 1, a pulsar is emitted. If the value is less than 1, it has less possibility. A value of 0 results in no pulsar emissions. Values between 0.9 and 0.8 produce an interesting analog-like intermittency, as if there were an erratic contact in the synthesis circuit [Fig. 8(c)].

3.3 Transformation of Sampled Sounds by Convolution with Pulsars

The technique of pulsar synthesis can be harnessed as a method of sound transformation through the technique of convolution. Convolution is fundamental to the physics of waves [24]. It "crosses" two signals, creating a new signal, which combines the time structures and spectra of both inputs. Many transformations emerge from convolution, including exotic filters, spatializers, models of excitation or resonance, and a gamut of temporal transformations (echoes, reverberation, attack smoothing, rhythm mapping). See [25]–[27] for applications of convolution in musical sound transformation. Pure convolution has no control parameters, that is, the type of effect achieved depends entirely on the nature of the input signals.

Sophisticated transformations involving rhythm and spatial mapping can be achieved through convolution. It is well known that any series of impulses convolved with a brief sound maps that sound into the time pattern of the impulses. These impulses can be emitted by a pulsar generator such as the one we implemented. If the pulsar train frequency is in the infrasonic range, then each pulsar is replaced by a copy of the sampled sound object, creating a rhythmic pattern. The convolution of a rhythmic pattern with a sound object causes each impulse to be replaced by a filtered copy of the sound object. Each instance of the sampled object is projected in space according to the spatial location of a specific pulsar's position in space.

In convolution, each pulsar represents the impulse response of a filter. Thus timbral variations can derive from two factors: 1) filtering effects imposed by the time-varying pulsar train, and 2) overlapping effects caused by convolution with pulsar trains whose fundamental period is shorter than the duration of the sampled sound.

Fig. 10 shows the temporal and filtering effects of convolution in the form of sonograms. The input signal [Fig. 10(b)] is the Italian word "qui" (pronounced "kwee"). It convolves with the pulsar train [Fig. 10(a)] with a variable infrasonic fundamental frequency and a variable audio formant frequency. The resulting convolution [Fig. 10(c)] combines the time structure and the spectra of the two signals.

A database of sampled sound objects can be stockpiled for crossing with trains selected from the pulsar database. If the goal of the synthesis is to retain the time structure of the pulsar train (for example, to maintain a specific rhythm), the sampled sound objects should be of short duration (less than the fundamental period of the pulsar train) and have a sharp attack (a rise time less than 100 ms). These constraints minimize the time-smearing effects of convolution [27]. Thus a good starting point for a sound database is a collection of percussion samples. The constraints can be relaxed if one seeks a smoother and more continuous texture. Samples with long durations superimpose multiple copies of the sampled object, creating a rippling sound stream. Samples with slow attacks blur the onset of each sample copy, smearing the stream into a continuum. Thus by controlling the attack shape of the sample one has a handle on the sonic texture.

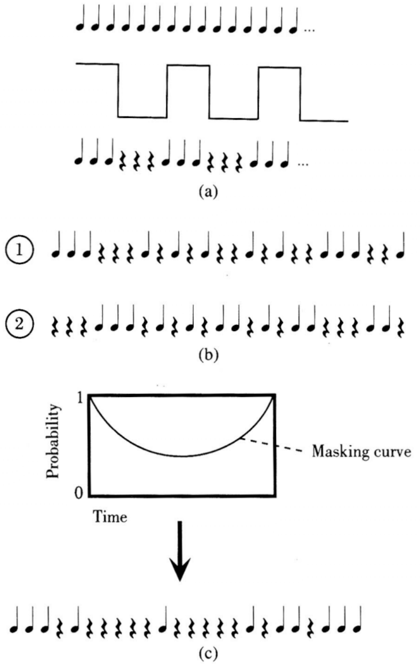


Fig. 8. Pulsar masking turns regular train into irregular train. Pulsars are illustrated as quarter notes, masked pulsars as quarter rests. (a) Burst masking; burst ratio 3:3. (b) Channel masking. (c) Stochastic masking according to a probability table. When the probability is 1, there is no masking; when the probability is 0, there are no pulsars. In the middle, pulsar train is intermittent. Notice thinning out of texture as probability curve dips in center.

4 IMPLEMENTATIONS OF PULSAR SYNTHESIS

My original implementation of pulsar synthesis dates to 1991, using James McCartney's Synth-O-Matic, a programmable sound synthesis environment for Apple Macintosh computers [28], [29]. In 1996 Mr. McCartney replaced Synth-O-Matic with SuperCollider 1—an object-oriented programming language with an efficient MacOS runtime system [30]. Using SuperCollider 1, Stephen T. Pope and I created a new implementation of pulsar synthesis in 1997.

Based on the improved SuperCollider 2 [31], Alberto de Campo and I developed a new realization of pulsar synthesis. We premiered it in a 1999 summer course at the Center for New Music and Audio Technology, University of California, Berkeley. Further refinement of this prototype has led to the PulsarGenerator application, distributed by CREATE.[1] Fig. 11 presents the graphical interface of the PulsarGenerator, version 1. Notice the control envelopes for synthesis variables. These envelopes can be designed in advance of synthesis, or manipulated in real time as the instrument plays. We have implemented a scheme for saving and loading these envelopes in groups called settings. The program lets one crossfade at a variable rate between multiple settings, which takes real-time performance with the PulsarGenerator to another level of synthesis complexity.

In wave-oriented synthesis techniques, an algorithm loops through a wavetable and varies the signal according to relatively slowly updated control functions. Thus the efficiency of synthesis corresponds to the number of simultaneous unit generators (oscillators, filters, and so on). By contrast, particle synthesis is more demanding, since the synthesis algorithm must also handle the task of scheduling possibly thousands of events per second, of which each may be unique. The efficiency of pulsar synthesis is thus related to the rate of particle emission. At infrasonic rates (<20 pulsars per second), the PulsarGenerator application consumes no more than 3.6% of the processor on a single-processor Apple G4 running at a 500-MHz clock speed. At a high audio rate (such as a three-formant instrument emitting 6000 pulsars per second, corresponding to the fundamental frequency of 2 kHz), the application consumes approximately 45% of the processor. It is a testimony to SuperCollider 2 that the entire implementation, including the graphical interface, required less than 1500 lines of code and comments. Our code builds the interface, defines the synthesis algorithm, schedules the pulsars, and handles file input and output. McCartney's SCPlay, an efficient real-time sound engine, calculates the samples.

5 COMPOSING WITH PULSARS

To interact with the PulsarGenerator in real time is to experiment with sonic ideas. In the course of experimen-

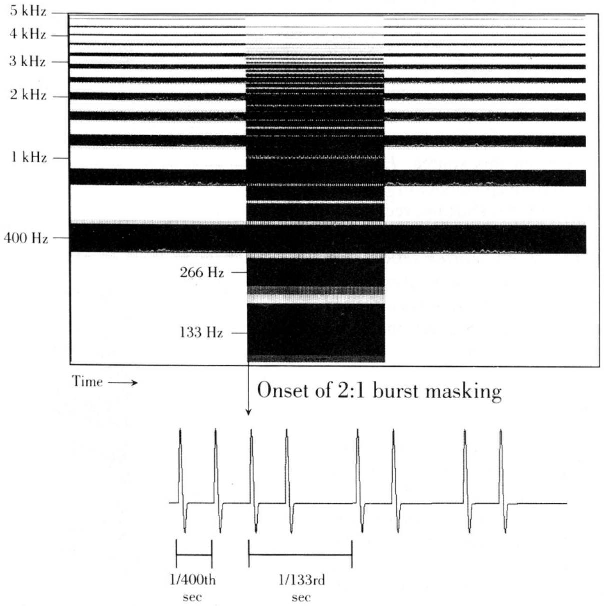


Fig. 9. Sonogram depicting effect of burst masking in audio frequency range. Pulsaret is one cycle of a sinusoid, and pulsaret envelope is rectangular. $b:r = 2:1$; fundamental frequency 100 Hz; formant frequency 400 Hz. Notice subharmonics at 133 and 266 Hz caused by extended periodicity of pulse masking interval (400 Hz/3).

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[1] www.create.ucsb.edu.

tation, a composer can save various settings and plan how these will be used within a composition. The PulsarGenerator program can also record the sounds produced in a real-time session. This session can be edited by the composer and possibly convolved or mixed with other material.

A final stage of pulsar composition is to merge multiple trains to form a composite texture. This is a question of montage, and is best handled by editing and mixing software that is designed for this purpose. Each layer of the texture may have its own rhythmic pattern, formant frequency envelope, choice of convolved objects, and spatial path. Working on a variety of time scales, a composer can apply signal processing transformations on individual pulsars, pulsar trains, and pulsar textures. These may include mixing with other sounds, filtering, modulations, reverberation, and so on.

6 MUSICAL APPLICATIONS OF PULSAR SYNTHESIS

I developed pulsar synthesis in the course of realizing *Clang-tint* [32], an electronic music composition that was commissioned by the Japanese Ministry of Culture (Bunka-cho) and the Kunitachi College of Music, Tokyo. The second movement of this work, entitled *Organic*, focuses on expressive phrasing. It combines bursts of insect, animal, and bird calls with electronic pulse tones. The electronic sound palette is based on pulsar synthesis in multiple forms: pulsating blips, elongated formant tones, and clouds of asynchronous pulsars. For the latter, I first generated multiple infrasonic pulsar trains, each one beating at a different frequency in the range of 6 to 18 Hz. I then mixed these together to obtain the asynchronous pulsar cloud.

The raw material of my electronic music composition *Half-life*, composed in 1998 and 1999, is a 1-minute pulsar train that varies wildly. Most sounds in the rest of the work were derived from this source. *Half-life* extends the pulsar material through processes of granulation, microfiltration, granular pitch-shifting, recirculating feedback echo, individual pulsar amplitude shaping, and selective reverberation. *Tenth Vortex* (2000) and *Eleventh Vortex* (2001) continue in this direction.

We have begun to distribute the PulsarGenerator application to other musicians, so we expect that there will be more musical results in the near future.

7 CONCLUSIONS

Music transpires on multiple time scales, from a high-level macrostructure down to a myriad of individual sound objects or notes. Below this level is another hierarchy of time scales. Here are the microsonic particles such as the classical rectangular impulses, Gaussian grains, wavelets, and pulsars [18], [33]. Impulse generation as an effective means of music synthesis was established decades ago in the analog electronic studio. By comparison, digital pulsar synthesis offers a flexible choice of waveforms and envelopes, increased precision, and graphical programmable control.

Unlike the typical wave-oriented synthesis techniques (such as additive synthesis), the notion of rhythm is built into techniques based on particles. Pulsar synthesis offers a seamless link between the time scales of individual particle rhythms, periodic pitches, and the meso or phrase level of composition. Another novel feature of this technique is the generation of multiple independent formant trajectories, each of which follows its own spatial path.

As we have shown, the basic pulsar technique can be extended to create a broad family of musical structures: singular impulses, rhythmic sequences, continuous tones, time-varying phrases, and beating textures. The pulsar microevents can be deployed in rhythmic sequences or, when the density of events is sufficiently high, in sustained tones, thus allowing composition to pass directly from microstructure to mesostructure.

8 ACKNOWLEDGMENT

Pulsar synthesis was inspired by numerous conversations in Naples with my late friend, Professor Aldo Piccialli, and his colleagues in the Department of Physics at

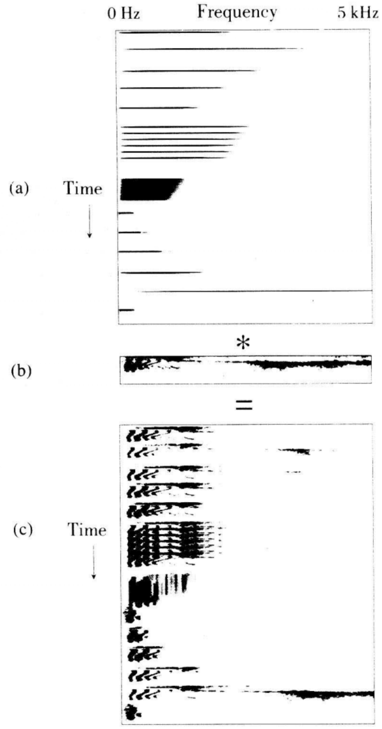
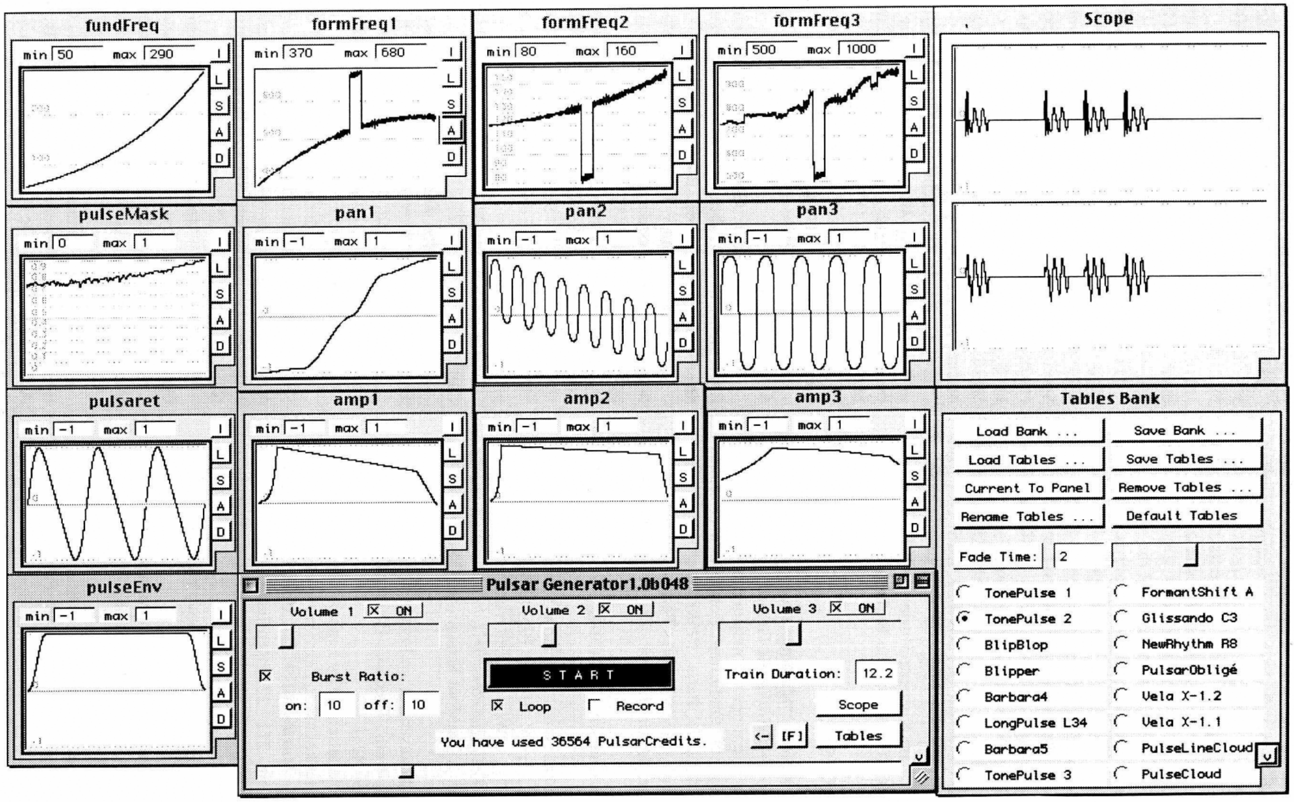


Fig. 10. Effect of convolution with pulsar train. (a) Infrasonic pulsar train with variable fundamental and formant frequency. (b) Sampled sound; Italian word "qui" (pronounced "kwee"). (c) Convolution of (a) and (b).



☒ Burst Ratio: on: 10 off: 10

☒ Loop ☐ Record

Train Duration: 12.2

You have used 36564 PulsarCredits.

Fade Time: 2

Fig. 11. Control panel of PulsarGenerator application by Alberto de Campo and Curtis Roads. © Regents of the University of California 2000.

the Università di Napoli «Federico II» [34]–[36]. My deep thanks go to Alberto de Campo for his collaboration on the PulsarGenerator application, which he coded. I thank James McCartney for the excellent SuperCollider 2 software, which was the basis for our development of the PulsarGenerator. I am grateful to Brigitte Robindoré and Stephen T. Pope for their comments on an early draft of this manuscript. Dr. Luca Lucchese of the Department of Electrical and Computer Engineering at UCSB consulted on the analytic form of the pulsar spectrum equations. The mathematical analysis in the Appendix is largely his. Throughout the period in which I originally developed this technique (1991–1995) I was fortunate to have the support of Maestro Iannis Xenakis and Dr. Gerard Pape of Les Ateliers UPIC (now the Centre de Création Musicale «Iannis Xenakis») in Paris, and Professor Horacio Vaggione of the Département Musique at the Université de Paris VIII. During the final preparation of this paper I enjoyed the generous support of Professor JoAnn Kuchera-Morin of CREATE at the University of California, Santa Barbara.

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APPENDIX
ANALYSIS OF PULSARET ENVELOPE SPECTRA

The pulsaret envelope has a strong effect on the spectrum of a pulsar train. This appendix presents a brief analysis of this effect. In practice, many time-varying parameters interact to produce the pulsar timbre. These include the pulsaret, the pulsaret envelope, the fundamental frequency, multiple formant frequencies, and the burst masking ratio.

A.1 Spectrum of a Rectangular Pulsaret Envelope

Let us assume that the sampling rate is infinite and the pulsaret envelope is an ideal rectangular impulse. A rectangular signal can be defined as follows:

$$\mathrm{Rect}(t) = \begin{cases} 1\,, & \text{for } t \leq 1/2 \\ 0\,, & \text{otherwise}\,. \end{cases}$$

It starts at a definite instant of time, and may be considered to have decayed to zero after a fixed length of time T_1, the duty cycle. If the repetition period is infinite, the pulse is reduced to a single isolated transient. In this ideal case, the repetition period is ∞ and the fundamental frequency of the Fourier spectrum is 0 Hz. Since the harmonics are multiples of 0, the spectrum consists of terms that are infinitely close to one another on a frequency scale, producing a continuous spectrum. Since the energy of an ideal impulse is infinite, these spectrum components must be infinitesimally small [37]. The spectrum shape is the sinc function

$$\mathrm{Rect}(f) = \mathrm{sinc}(f) = \frac{\sin(f\pi)}{f\pi}\,.$$

Fig. 12 shows the spectrum of a rectangular impulse with a duty cycle T_1. Notice the discrete energy peaks at $1.5T_1$, $2.5T_1$, $3.5T_1$, etc., and the energy zeros at $1/T_1$, $2/T_1$, $3/T_1$, etc., which is typical of the sinc function.

With its high peaks and strong nulls, the presence of specific frequencies in the spectrum depends greatly on the chosen formant frequency. Formant frequencies of 450 and 500 Hz, for example, distribute the spectral energy into different specific frequencies, even though they sound rather similar. Tracing a line along the peaks of the rectangular pulsaret spectrum, we see a general rolloff at a rate of approximately −15 dB per octave.

A.2 Spectrum of a Linear Decay Pulsaret Envelope

A linear decay envelope has a sharp attack followed by a decaying tail, reaching 0 at the end of its duty cycle *d*. Let us define it as follows [see Fig. 3(c)]:

$$\mathrm{Lindec}(t) = \begin{cases} -\dfrac{t}{d} + 1\,, & \text{for } 0 \leq t \leq d \\ 0\,, & \text{otherwise} \end{cases}$$

where *d* is the duty cycle. Its spectrum

$$\mathrm{Lindec}(f) = \frac{1}{\mathrm{j}2\pi f d}\left[(d+1) - \mathrm{e}^{-\mathrm{j}2\pi f d}\right]\,.$$

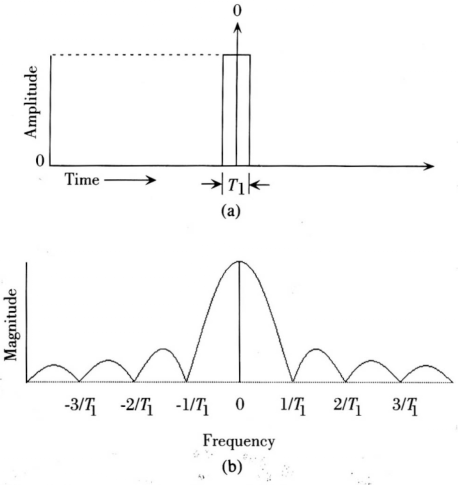

Fig. 12. Impulse and its spectrum. (a) Impulse, with amplitude versus time. (b) Absolute magnitude of impulse spectrum. Notice characteristic sync function in spectrum, with peaks at intervals of $1.5f$, $2.5f$, etc. and nulls at harmonic frequencies.

A.3 Spectrum of an Exponential Decay Pulsaret Envelope

An exponential decay (*expodec*) pulsaret envelope falls quickly from its initial peak to arrive at zero at the end of the pulsaret period. It can be defined as follows [see Fig. 3(d)]:

$$\mathrm{Expodec}(t) = \begin{cases} \mathrm{e}^{-t/\beta}, & \text{for } t \geq 0 \\ 0, & \text{for } t < 0 \,. \end{cases}$$

Its spectrum is

$$\mathrm{Expodec}(f) = \frac{1}{1/\beta + \mathrm{j}2\pi f} .$$

This spectrum is a smooth continuum of frequencies without null points, sloping off at a rate of about −12 dB per octave. This is less steep than the rectangular pulsaret envelope, which accounts for the breadth of the spectrum.

A.4 Spectrum of a Linear Attack Pulsaret Envelope

A linear attack (linatt) envelope reaches its peak at the end of the pulsaret duty cycle d. Let us define it as follows [see Fig. 3(e)]:

$$\mathrm{Linatt}(t) = \begin{cases} \dfrac{t}{d}, & \text{for } 0 \leq t \leq d \\ 0, & \text{otherwise} \,. \end{cases}$$

Its spectrum is

$$\mathrm{Linatt}(f) = \frac{1}{\mathrm{j}2\pi f d}\left[(1 - d)\,\mathrm{e}^{-\mathrm{j}2\pi f d} - 1\right] .$$

A.5 Spectrum of an Exponential Attack Pulsaret Envelope

An exponential attack envelope (*expoatt*) reaches its peak with a sweep at the end of the pulsaret period. Let us define it as follows:

$$\mathrm{Expoatt}(t) = \begin{cases} \dfrac{\mathrm{e}^{-\lambda t} - 1}{\mathrm{e}^{\lambda d} - 1}, & \text{for } 0 \leq t \leq d \\ 0, & \text{otherwise} \,. \end{cases}$$

In Fig. 3(f), the steepness factor is ξ, which is defined as follows:

$$\xi = \frac{\lambda d}{\mathrm{e}^{\lambda d} - 1} .$$

Its spectrum is

$$\mathrm{Expoatt}(f) = \frac{1}{\mathrm{e}^{\lambda d} - 1}\left[\frac{\mathrm{e}^{(\lambda - \mathrm{j}2\pi f)d} - 1}{\lambda - \mathrm{j}2\pi f} + \frac{\mathrm{e}^{-\mathrm{j}2\pi f d} - 1}{\mathrm{j}2\pi f}\right] .$$

In shape, the expoatt spectrum is the same as the exponential decay, but temporally reversed.

A.6 Spectrum of a Gaussian Pulsaret Envelope

A Gaussian pulsaret envelope can be defined as follows:

$$\mathrm{Gauss}(t) = \mathrm{e}^{-\pi t^2}$$

Its Fourier transform is an eigenfunction of its time-domain function:

$$\mathrm{Gauss}(f) = \mathrm{e}^{-\pi f^2}$$

The spectral effect of the Gaussian pulsaret envelope is to narrow the formant spectrum to a tight band. An inspection of the sonogram reveals that beyond the central lobe it drops off at a rate of approximately −30 dB per octave.

THE AUTHOR

Curtis Roads was born in 1951. He holds a joint appointment as Assistant Professor in Media Arts and Technology and in Music at the University of California, Santa Barbara (UCSB). He is affiliated with the Center for Research in Electronic Art Technology (CREATE) at UCSB.

He studied music composition, languages, and computer programming at the California Institute of the Arts and the University of California, San Diego. From 1980 to 1986 he was Research Associate in computer music at the Massachusetts Institute of Technology. He received the doctorate in music from the University of Paris VIII in 1999.

His interest in the synthesis of sound particles dates back to the 1970s, when he first implemented granular synthesis on a mainframe computer. In 1995, he and John Alexander developed Cloud Generator, a MacOS program for granular synthesis. In collaboration with Alberto de Campo, he designed the PulsarGenerator program. Roads and de Campo have also implemented a working prototype of the Creatovox—a keyboard synthesizer for the expressive performance of several varieties of particle synthesis. Another of his interests is the spatial projection of sound. He organized the symposium Sound in Space 2000 and has developed the Creatophone, a system for multichannel spatial projection.

His recent compositions include *Clang-tint* (1994, commission of the Japanese Ministry of Culture and Kunitachi College of Music), *Half-life* (1999), and *Tenth Vortex* (2000), all of which use pulsar and granular synthesis. Several new works are in progress.

Cofounder of the International Computer Music Association (1979), he also served as the Editor of *Computer Music Journal* (MIT Press) from 1978 to 1989, and as Associate Editor from 1990 to 2000. Recent books include the textbook *The Computer Music Tutorial* (MIT Press, 1996), which has been translated into French (*L'audionumérique*, Éditions Dunod, 1999), Japanese (*Konpyu-ta Ongaku—Rekishi Tekunoroji A-to*, Tokyo Denki University Press, 2001), and Korean (*The Computer Music Tutorial—Korean edition* (Eumaksekye Music Publishing, forthcoming). Also published recently was *Musical Signal Processing* (coeditor, Swets and Zeitlinger, 1997). His latest book, *Microsound* (MIT Press, 2001), explores the aesthetics and techniques of composition with sound particles.