

Spatial Modulation Synthesis

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ABSTRACT

In 1962 Karlheinz Stockhausen’s “*Concept of Unity in Electronic Music*” introduced a connection between the parameters of intensity, duration, pitch, and timbre using an accelerating pulse train. In 1973 John Chowning discovered that complex audio spectra could be synthesized by increasing vibrato rates past 20Hz. In both cases the notion of increased speed to produce timbre was critical to discovery. Although both composers also utilized sound spatialization in their works, spatial parameters were not unified with their synthesis techniques. Spatial Modulation Synthesis is introduced as a novel, physically-based control paradigm for audio-visual synthesis, providing unified control of spatialization, timbre, and visual form using high-speed sound trajectories.

1. INTRODUCTION

Spatial modulation synthesis (SM) is a paradigm through which modulation synthesis and granulation effects can be produced via high-speed sound spatialization within periodic trajectory orbits. Hence the name, spatial parameters are modulated to result in frequency and amplitude modulation of an input signal rather than controlling FM and AM directly. Spatialization algorithms include a means for distributing the output to each loudspeaker, such as VBAP [1] or Ambisonics [2], and are typically paired with multiple distance cues including Doppler shift and a distance-based gain attenuation. Additional distance cues may include air absorption filtering, presence filtering, and reverberation. For now, the concept of spatial modulation synthesis focuses only on Doppler shift and gain attenuation, leaving other possible cues as future research.

While the spatialization of sounds along calculated trajectories and FM have been used together in many monumental compositions, spatialization has not been used to synthesize tones through precise control of sound source trajectories. Similarly, while the spatialization of sound grains has been implemented by various composers, spatialization itself has not been used to create granular streams through rapid motion

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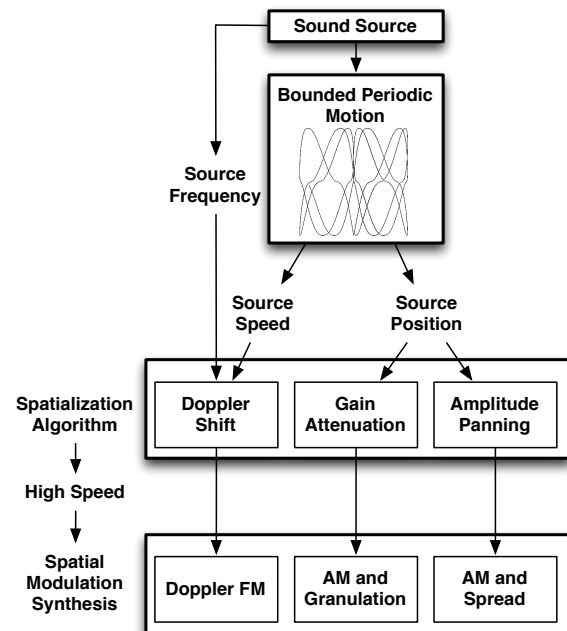


Figure 1. Spatial Modulation Synthesis

over distance. Using existing spatialization, Doppler, and attenuation techniques, spatial modulation synthesis provides a new control and visualization paradigm through which space and timbre are unified.

1.1 Background

Beginning with Karlheinz Stockhausen’s monumental *Gesang der Junglinge* in 1956, several 20th century works of electronic and computer music have utilized sound spatialization as an independent parameter of composition choreographed alongside timbre, pitch, intensity and duration. While early choreography of spatial trajectories relied simply on amplitude panning between speakers, John Chowning’s 1977 paper, *The Simulation of Moving Sound Sources* [3], detailed various techniques to implement localization cues. Thereafter, many spatial compositions have utilized more realistic, physically based distance simulation including Doppler shift and gain attenuation with distance.

Both FM and granular synthesis techniques have allowed composers to fuse perceptibly discrete sound events into new

timbres. Chowning accomplished this by increasing vibrato rates into the audio domain (above 20 Hz) to discover FM synthesis [5], and Stockhausen morphed a series of impulses into tone by altering their duty cycle. Stockhausen's Concept of Unity in Electronic Music [6] states the composition and decomposition of timbres as a fundamental principle of electronic music and expresses the idea of unity between timbre, pitch, intensity, and duration. To achieve this unity, Stockhausen had to take pulse trains to extremely short durations while Chowning took vibrato rates to extreme frequencies. Likewise, spatial modulation synthesis is based on extremes of sound source velocity to produce new timbres.

2. SPATIAL MODULATION SYNTHESIS

2.1 Doppler FM

Doppler shift is the physical phenomena of increased pitch for sound sources moving toward a listener and decreased pitch for sound sources moving away from a listener. Through the simulation of precise trajectories and velocities of moving sound sources it is possible to sculpt the resulting Doppler curve for use as a frequency modulator. The term Doppler FM is used to describe audio rate frequency modulation resulting from bounded, high-velocity sound source movement oscillating around a listener. First, the simplest case involving the motion of a sound source with a constant magnitude of velocity moving back and forth along one dimension is demonstrated. Then, the acceleration required to produce classic sinusoidal FM is described. Finally, the technique is extended to 3-dimensional motion resulting in parallel multiple modulator FM.

The Doppler shift for a stationary listener and moving sound source is given by Equation (1).

$$f = \left(\frac{c}{c \pm v_s} \right) f_s \quad (1)$$

f is the observed frequency, f_s is the frequency of the source, c is the speed of sound in air ($\approx 340m/s$) and v_s is the speed of the moving sound source, positive when moving away from the listener and negative when moving towards the listener. For $v_s \ll c$ the magnitude of the shift is roughly equal as the source moves towards and away from the listener at a constant v_s . However, for higher velocities, the change in frequency, $\Delta f = |f - f_s|$, will be uneven and greater when the source is approaching as shown in figure 2. For $v_s = c$ the observed frequency goes to ∞ and, in reality, a sonic boom occurs.

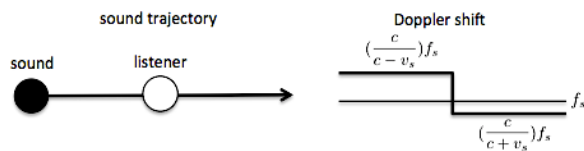


Figure 2. Physically Accurate, Asymmetrical Depth Doppler

Most digital audio Doppler simulations use an approximation for Doppler shift that is relatively accurate for $v_s < 100m/s$ and gives an equal shift of frequency both towards and away from the listener [7]. This symmetric depth Doppler approximation is given by (Equation 2) and the resulting shift is shown in figure 3.

$$f = \left(1 \pm \frac{v_s}{c} \right) f_s \quad (2)$$

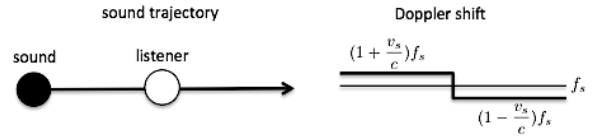


Figure 3. Symmetric Doppler Approximation, $v_s \ll c$

Although Equation 2 is not physically accurate for high values of v_s , the approximation conveniently provides a symmetrical modulator than can be used to replicate exact FM timbres from SM. However, an additional implementation of the true Doppler shift (Equation 1) has also been implemented since its use is necessary for SM to achieve higher modulation indices in addition to keeping the paradigm as physically accurate as possible. Though not symmetrical in depth, using true Doppler modulation still produces more partials in the resulting spectra for greater timbral variation. For simplicity, the following equations will consider the symmetrical Doppler approximation that shows similar relationships between velocity, bounds, modulation depth, and frequency.

2.1.1 SM Square Modulation

Consider the scenario of a single sound source with frequency f_s moving on the x-axis at a constant velocity, v_s , past a listener at $x = 0$. If the motion of the sound source oscillates such that the direction of its velocity is inverted at a bounds at distance B in either direction from the listener then the resulting Doppler shift becomes periodic. For this back and forth motion at constant velocity, the resulting Doppler curve will resemble a square wave.

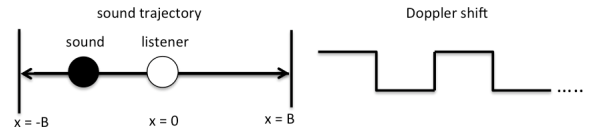


Figure 4. Oscillating Doppler Shift for Constant Velocity

Now, considering the Doppler curve as a frequency modulator for our source with a rate of modulation determined by the time it takes the source to move a distance of $2B$ and a modulation depth directly related to the sound source's velocity, the modulation depth (Δf), frequency (f_m), and index (I) are given by

$$\Delta f = \frac{v_s}{c} f_s \quad (3)$$

$$f_m = \frac{v_s}{2B} \quad (4)$$

$$I = \frac{\Delta f}{f_m} = \frac{2B f_s}{c} \quad (5)$$

The speed of the moving sound source, v_s , is directly proportional to both the frequency and depth of modulation. The size of the bounds, B is inversely proportional to the frequency of modulation, but directly proportional to the index of modulation. The frequency of the moving sound, or carrier, is directly related to the depth and index of modulation. This is a departure from classic FM in which the carrier frequency is a separate control from the depth and index. Similarly, this unique relationship between carrier frequency and index of modulation was observed by Lazzarini et. al [8] in their delay-line phase modulation implementation.

A fundamental concept of FM synthesis is that integer ratios of the carrier to modulator frequencies will produce harmonic spectra. In the case of SM square wave modulation the ratio appears as

$$\frac{f_s}{f_m} = \frac{2B f_s}{v_s} \quad (6)$$

Thus, proportions of bounding space and velocity become critical to shape the harmonic content of a sound.

2.1.2 SM Sinusoidal Modulation

The equation for classic FM synthesis involves a sinusoidal modulator and the instantaneous frequency is given as

$$f(t) = f_s + \Delta f \sin(2\pi f_m t) \quad (7)$$

By applying time-varying velocity (acceleration) to Equation 2 we can derive the acceleration required of our sound source to produce a sinusoidal Doppler curve.

$$v_s(t) = \frac{\Delta f \sin(2\pi f_m t) c}{f_s} \quad (8)$$

This sinusoidal velocity implies acceleration from rest at the position of both boundaries and at the listener. The depth of modulation will remain the same as for square modulation, but the frequency of modulation is divided by a factor of $\frac{\pi}{2}$.



Figure 5. Sinusoidal Doppler FM from Accelerating Motion

In addition to the square and sinusoidal frequency modulators produced by linear velocity and sinusoidal acceleration respectively, linear accelerations can produce triangle

and sawtooth modulators. Also, asymmetrical bounds may be used to further shape the modulation.

2.2 Multi-dimensional Motion

Expanding source velocity to a 3-dimensional vector, $\langle v_{sx}, v_{sy}, v_{sz} \rangle$, produces complex modulation similar to parallel multiple modulator frequency modulation (MMFM) [14]. Not only are the timbres more complex, but the resulting 3D orbits can produce beautiful Lissajous trajectories that modulate in correlation with the changing FM parameters.

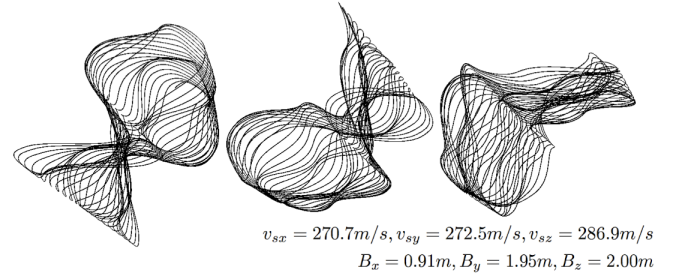


Figure 6. 3D Asymmetrical SM Orbit

2.3 Morphing Tones to Spatial Grains

Sounds resulting from SM can replicate classic FM timbres, but have the ability to morph into completely different modulating or granular timbres by changing only a two spatial controls, namely velocity and bounds. The novelty of SM lies in its simple, visual control paradigm which creates a continuum between spatial choreography, tone, and granulation.

Within bounds of ± 1 meter, Doppler FM can occur with minimal amplitude modulation due to distance based gain attenuation and panning. Using sinusoidal velocity along a single axis to produce a sinusoidal modulator, Doppler produced vibrato begins to morph into FM-like timbres starting at about 125 m/s (≈ 280 mph). Currently, sources can be simulated up to the speed of sound, 340 m/s, within a minimum bounds of 0.1 m (depending on sampling rate). By simply extending the boundary of a Doppler FM tone, it can morph into a series of spatial sound particles. With larger boundaries imposing greater gain attenuation with distance, AM effects increase in depth, eventually becoming short duration amplitude envelopes. When the velocity of source movement is sufficiently high, the duration of the resulting amplitude envelopes can enter the granular domain (≤ 100 ms). Oscillating movement within a bounds produces a train of these envelopes that varies in duration, shape, and spatial location as the source moves in multiple dimensions.

3. IMPLEMENTATION

While a plethora of tools exist for simulating moving sound sources such as GRM Tools Doppler¹, the novelty of an SM

¹ <http://www.inagrm.com/doppler>

implementation lies in the ability to have a simple control continuum between a tool for spatialization, tonal synthesis, and granulation. Unlike other spatialization toolsets, the goal of an SM implementation is to create a complete instrument unifying space and timbre.

Spatial modulation synthesis is currently realized as a VST plug-in using the open-source AlloSystem C++ suite². Implementation as a VST allows for timeline automation of all parameters via the host DAW. The current parameters are source type (sine/square/triangle/saw waveform or audio input from DAW track), motion type (square, sine, saw, triangle), Doppler type (symmetrical, physical), gain-attenuation curve (inverse distance and distance squared), spatialization type (stereo, DBAP, VBAP, Ambisonics), $x/y/z$ upper and lower bounds, $x/y/z$ velocity, $x/y/z$ carrier to modulation ratio, visual trail length, and an adjustable ADSR envelope. OpenGL orbits are displayed in the plug-in interface, and an accompanying synchronized graphics application allows the rendering of orbits over a cluster of machines in fully immersive stereo 3D graphics within the AlloSphere³ laboratory. The plug-in is capable of outputting to an arbitrary number of output channels and implements a unique rendering paradigm to compute sound trajectories and their corresponding graphics at audio-sample rate. A dynamic anti-aliasing filter adjusts its cutoff to match the predicted bandwidth of the signal using Carson's rule and prevent modulating delay line artifacts. In addition to using arbitrary source input, the plug-in is capable of scanning (audifying) its spatialization orbit as the source used for spatialization, creating feedback SM. When connected to a MIDI keyboard the plug-in features a carrier-to-modulator ratio lock that results in dynamically changing size and velocity of the orbits with different notes, creating an intrinsic visual music accompaniment. Video examples and a free stereo-only demo VST are available online⁴.

4. CONCLUSION

Spatial modulation synthesis is a novel, spatial way to control complex frequency modulation, amplitude modulation, and granular synthesis. Looking back to Chowning's work with increasing vibrato rates to realize FM synthesis, SM takes sound spatialization into the realm of timbre by increasing speeds. Unlike other techniques that spatialize a series of given sound grains, SM produces grains through the spatialization of a non-granular source at high-speeds within a large boundary. Using parameters of space and motion to fuse and decompose sound timbre expands Stockhausen's Concept of Unity to include spatialization alongside timbre, pitch, intensity, and duration. Visualization of SM trajectories also provides a physical, intrinsic correlation between visual space and timbre.

² <https://github.com/AlloSphere-Research-Group/AlloSystem>

³ <http://www.allosphere.ucsb.edu>

⁴ <http://www.spatialmodulation.com>

Acknowledgments

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