Guitars with Ambisonic Spatial Performance (GASP) An immersive guitar system[1]

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The GASP project investigates the design and realisation of an Immersive Guitar System. It brings together a range of sound processing and spatialising technologies and applies them to a specific musical instrument – the Electric Guitar. GASP is an ongoing innovative audio project, fusing the musical with the technical, combining the processing of each string's output (which we called *timbralisation*) with spatial sound. It is also an artistic musical project, where space becomes a performance parameter, providing new experimental immersive sound production techniques for the guitarist and music producer. Several ways of reimagining the electric guitar as an immersive sounding instrument have been considered, the primary method using Ambisonics. However, additionally, some complementary performance and production techniques have emerged from the use of divided pickups, supporting both immersive live performance and studio post-production.

GASP Live offers performers and audiences new real-time sonic-spatial perspectives, where the guitarist or a Live GASP producer can have real-time control of timbral, spatial, and other performance features, such as: timbral crossfading, switching of split-timbres across strings, spatial movement where Spatial Patterns may be selected and modulated, control of Spatial Tempo, and real-time performance re-tuning. For GASP recording and post-production, individual string note patterns may be visualised in Reaper DAW,[2] from which, analyses and judgements can be made to inform post-production decisions for timbralisation and spatialisation. An appreciation of auditory grouping and perceptual streaming (Bregman, 1994) has informed GASP production ideas. For performance monitoring or recorded playback, the immersive audio would typically be heard over a circular array of loudspeakers, or over headphones with head-tracked binaural reproduction. This paper discusses the design of the system and its elements, investigates other applications of divided pickups, namely GASP's Guitarpeggiator, and reflects on productions made so far.

Why Spatialisation?

In addition to pitch, timbre, intensity, and duration, an understanding of space is a significant musical parameter, and as such, musical instruments with spatial sound control should be regarded as instruments of musical expression (Pysiewicz and Weinzierl, 2016). The term *sound spatialisation* refers to a group of techniques for organising and manipulating the spatial projection and movement of sound in a physical or virtual listening environment (Valiquet, 2011). Suggested design features for spatialisation systems (Perez-Lopez, 2015) have helped inform the GASP project development, in particular, considerations such as: is the performer exclusively controlling spatial parameters (in contrast to one who controls both spatialisation

[1] Lecture given at The 21st century Guitar Conference 2021.

[2] Available from http://www.reaper.fm

and sound generation); is the spatial control made by an individual, or shared by a group of performers; what is the required level of expertise for expressivity and virtuosity; and does the system provide a graphical user interface for real-time visual feedback?

An Overview of GASP

A spatially immersive guitar system has been devised and realised, with the project name GASP: Guitars with Ambisonic Spatial Performance. The GASP project is a guitar-based 2D Ambisonic instrument and performance system. GASP is an ongoing research project, where our interest in Ambisonic algorithmic research and guitar sound production is combined with off-the-shelf hardware and bespoke software to create an Ambisonic based, spatially immersive guitar system. The system may have applications within the live performance domain in medium or large-format theatre/concert systems. Additionally, in post-production, the audio may be downmixed to work with traditional stereo sound installations or personal playback over headphones, i.e., binaural or google 360° Virtual Reality via web streaming. The current hardware configuration, as shown in Figure 1, consists of two interconnected computers (Mac Pro and iMac), three visual monitors, eight loudspeakers, audio interfacing, and three guitars (two Strat type and an electro-acoustic) retrofitted with divided pickups (i.e., an assembly containing a separate pickup and discrete output for each string, so called in this case hexaphonic or hex pickups).

Figure 1 GASP System Hardware excluding Ambisonic loudspeaker system. Copyright 2019 by R. Johnson. Reprinted with permission.

System Key Features

- Electric guitars have been retrofitted with divided pickups, to facilitate the processing of individual strings, for timbre, spatial location, and other processing.
- Each string's sound processing (which we call *timbralisation*) is achieved with commercial sound processing software Line 6 Helix Native,[3] configured in a bespoke fashion for individual string processing.
- Spatial positioning and dynamic spatial movement of individual strings are achieved using bespoke WigWare Ambisonic plugins (Wiggins, 2017).
- Arpeggiation effects with TrackGate[4] audio gate switching on individual strings, facilitating simple or complex polyrhythms as part of the guitar performance.
- A range of GASP Auditory Scenes, which combine Spatial, Timbral, and Guitarpeggiator pre-sets, as Ableton Live Clips.[5]
- A circular array of loudspeakers supporting 2D, 360° spatial representation.
- Configuration over headphones for head-tracked binaural, and VR-based applications.

Guitars and Pickups

The GASP system is based around guitars retrofitted with divided pickups. Compared with traditional all-strings pickups, divided pickups facilitate independent processing for each string, and as a function of their separation, each string is individually processed with its full bandwidth and dynamic range, resulting in enhanced sonic detail of the guitar performance. We have three guitars retrofitted with this type of pickup: a Yamaha APX500 electro-acoustic and a Fender Stratocaster, both of which have Ubertar hex passive pickups;[6] and a second Stratocaster fitted with Cycfi Nu-Series Modular Active Pickups.[7] The Stratocasters were chosen as they enable straightforward installation of the multichannel pickup, as it simply replaces the bridge pickup. This positioning has the advantage of generating minimal signal cross-over into the pickup area of the neighbouring string when string bending occurs. Both types of pickup are very good. However, as they operate with different operating principles (passive vs active), they have different tonal qualities. To route the individual signal from each string to the computer for processing, a Focusrite Scarlett 18i20 multichannel interface is used,[8] where individual gain levels for each string can be independently set. The Scarlett interface receives the six discrete string signals from the divided pickup and sends them to Reaper,[9] hosted on a 2013 Apple Mac Pro with 6 core and 64 GB RAM.

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[3] Available from http://uk.line6.com/helix/helixnative.html

[4] Available from https://dmgaudio.com/products_trackgate.php

[5] Available from http://www.ableton.com

[6] Available from http://www.ubertar.com/hexaphonic

[7] Available from https://www.cycfi.com

[8] Available from https://focusrite.com/en/usb-audio-interface/scarlett/scarlett-18i20

[9] Available from http://www.reaper.fm

Reaper, Ableton Live, and Routing

The workstation for the GASP project is Reaper, chosen as it has exceptionally versatile signal routing, with its track-channel design approach, where each track may be assigned up to 64 channels. The current GASP configuration hosts Reaper and it's plugins on the 2013 Mac Pro. Additionally, a second computer, a standard 2017 iMac, hosts Ableton Live and provides user control for timbralisation, spatialisation, and arpeggiation features.

The signal path begins with the guitar and hexaphonic pickup; the guitar has six discrete line outputs, that is, one per string, which in turn connects to the Scarlett computer interface. This converts the guitar signals into a digital format, which is then connected by USB to the Reaper DAW. Within Reaper there are several audio plugins on each string's track. Firstly, Helix Native guitar sound processor, which is our *Timbraliser*, providing amp simulation and other guitar effects, followed by TrackGate, which is a MIDI-controlled audio gate used for the Guitarpeggiator effects, then comes the Spatialiser, our bespoke Wigware Ambisonic panning software. The plugins are controlled through Clips in Ableton Live, which in turn may be selected through the pedalboard, this allows timbral, spatial, and arpeggiation patterns to be selected, and for variable parameters to be modulated in real-time. The signal routing overview can be seen in Figure 2. The master bus sends these processed signals to the Ambisonic decoder plugin, and then to the circle of loudspeakers, or head-tracked binaural headphones, where we hear the immersive output.

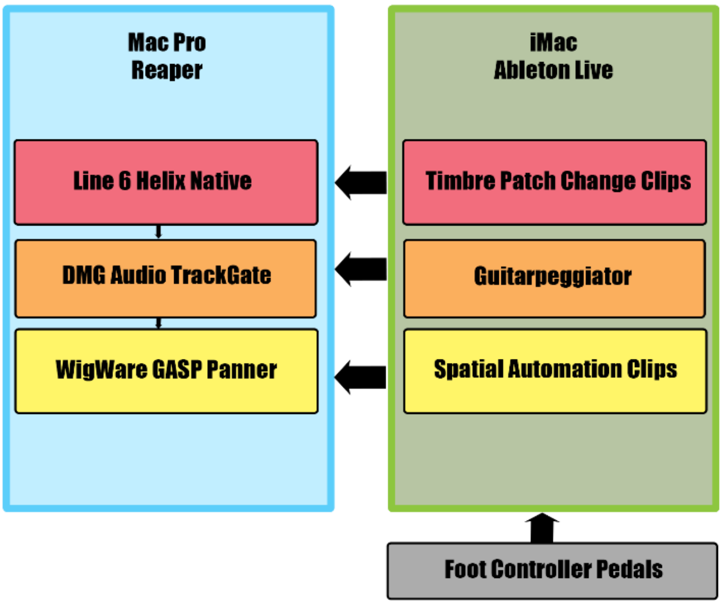

Figure 2 GASP signal routing overview across Mac Pro and iMac. Copyright 2019 by E. Fitzmaurice.

How do we hear it?

The immersive output is ideally heard through a loudspeaker system, however binaural reproduction with head-tracking headphones retains many of the spatial qualities. The project was originally conceived to be experienced over loudspeakers in a real space, as increased speaker radius distance from the listener enhances the sense of spatiality perceived. The current set-up is based on an eight-loudspeaker circular array supporting a 2D, 360º spatial representation, using 3rd order Wigware Ambisonic encoding/decoding. The circular speaker array as shown in Figure 3 may be arranged for a studio environment or within a large theatre/auditorium.

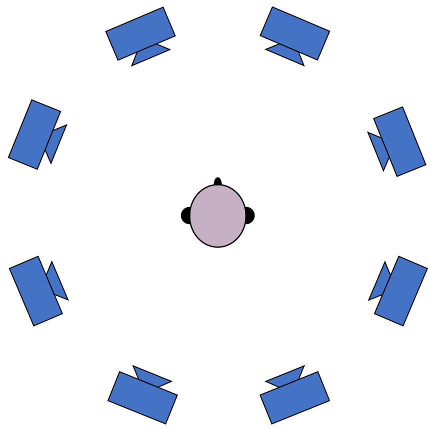

Figure 3 Depiction of an eight-loudspeaker circular array supporting a 2D, 360º spatial representation.

Timbralisation

Timbralisation is the term we have assigned to the process of applying sound processing to each string. It is carried out using six independent installations of Helix Native guitar processor, that is one Helix sound processor for each string as shown in Figure 4. Helix Native is a high-quality plugin, enabling the simulation of a large range of guitar (and other) effects. This creates the core timbre of the sound for each string. Six independent strings, processed by six independent Helixes (as opposed to one Helix processing all strings), provides a highly transparent sonic output, as the full bandwidth and dynamics of each string are independently processed. Each Helix processor generates a two-channel simulated stereo or *pseudo stereo* output for each string. The Timbralising Clips in Ableton Live select six independent Helix pre-sets simultaneously; around thirty Timbral Clips have been created where each Clip selects a new bank of six Helix processors (see Figure 12). The stereo outputs from each of the Helix processors are then routed to the two-channel inputs of GASP's bespoke Wigware Ambisonic spatialisers, that is, an independent spatialiser for each Helix, as shown in Figure 9.

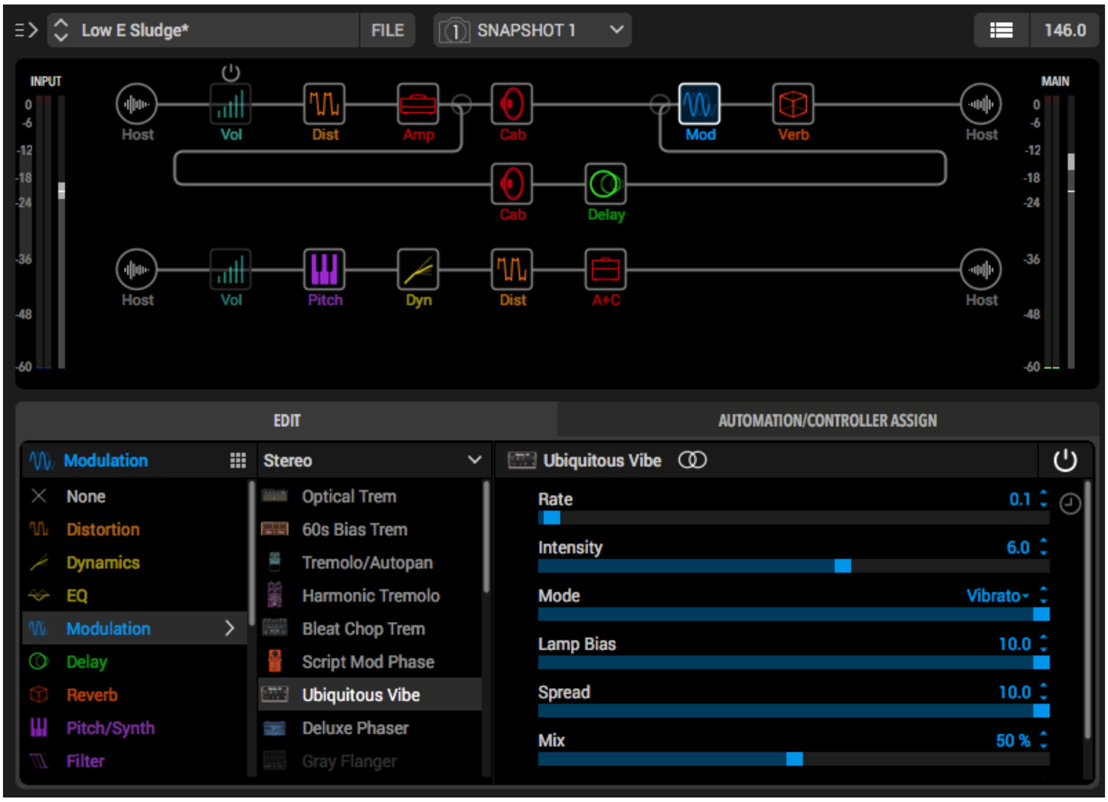

Figure 4 One of the six Helix Native guitar processors for GASP system's Timbralisation (i.e., one of the six discrete processors for each individual guitar string).

Ambisonics and Spatialisation

Spatially, the GASP system is based around Ambisonics, pioneered by Michael Gerzon in the 1970s (Gerzon, 1983). Ambisonics is a system based around the spherical harmonic decomposition of a sound field in two, or three dimensions and the reconstruction of this sound field using loudspeakers or headphones. The GASP system currently operates in two dimensions (using circular, rather than spherical harmonics) and uses panners of up to 3rd order (although we have software and panners written up to 35th order). With increasing Ambisonic order, the accuracy of the spatial reproduction improves but more loudspeakers and channels per track are required. Reproducing Ambisonics to 3rd order in two dimensions requires eight speakers arranged in an octagon as a minimum and needs sixteen channels per track for the encoding of the full 3D sound field. For 2D encoding and reproduction at 3rd order, only seven channels will actually contain audio, but the full sixteen channels are used in the system to allow for future expansion to 3D.

Currently, the GASP system has the following playback modes:

- Minimum of 8 speakers arranged in an octagon (for 3rd order playback)
- Minimum of 6 speakers arranged in a hexagon (for 2nd order playback)
- Minimum of 4 speakers arranged in a square (for 1st order playback)
- 5.1 or 7.1 decoders (3rd order using irregular optimised decoders [Wiggins, 2007])

- Two-channel stereo mix-down using the UHJ format (Gerzon, 1985)
- Binaural output (with or without head-tracking, up to 3rd order resolution)

Ambisonics differs from many other formats in that the encoding of the sound field is separated from the decoding, or presentation, of that sound field to the listener. To encode an audio source in a particular direction, the audio signal is multiplied by the coefficient of each spherical harmonic channel at the required angle (although the panners graphical user interface shows a 2-dimensional plane, the plug-in implements panning in three dimensions, allowing for future expansion). The GASP panner uses the Furse-Malham Ambisonic normalisation and channel ordering scheme (Malham, 2003) as it pre-dates Ambisonics being standardised for virtual reality and 360° video, which use ambiX channel ordering and normalisation (Nachbar et al, 2011). Conversion to the newer ambiX scheme is simply a change of channel order and gain, and can be realised using free plug-ins (Wiggins, 2016).

The GASP system has been developed for presentation over loudspeakers, but the flexibility of Ambisonics means it may also be presented with good spatial accuracy, over headphones. This makes it ideal for publishing on the web and using head-mounted displays (HMDs) or systems incorporating head tracking, providing a more immersive representation which preserves the psycho-acoustically important dynamic interaural cues when compared to standard headphone listening.

Ambisonics works by sampling the sound field at a point using different directional patterns. These can then be recombined to reconstruct the sound field based on the locations of the loudspeakers (somewhat like an extension of Blumlein Stereo). Converting Ambisonics B-Format to binaural audio for headphones is well documented with McKeag and McGrath using 1st order Ambisonic recordings to feed head-tracked binaural audio over headphones in the 1990s (McKeag & McGrath, 1996). Headphone playback makes use of head-related transfer functions (HRTFs), which are filters that model how the ears, head and torso modify the audio before it reaches the eardrum from various locations. The benefit of using Ambisonic binaural decoding is that it can easily incorporate head-tracking *after* mixing, with the audio reacting to head rotations in real-time for a more immersive and accurate experience. For this reason, Ambisonics has been utilised as one of the standard playback formats for virtual reality and 360° videos, further expanding the possibilities of the system (Wiggins, 2017). Several systems are currently available on the web, which can present audio encoded in this way and incorporate head tracking (if compatible hardware is available from the user). Notable examples are from YouTube (which uses Google Spatial Media[10]), Facebook (Facebook Spatial Workstation[11]) and the HOAST (Higher Order Ambisonics STreaming) Library[12]. An example implementation using webcam head tracking is also available online,[13] which was developed to require only headphones and a webcam to present the audio and track the head orientation of the listener (Dring & Wiggins, 2020). For a more technical look at the details of spherical

[10] https://github.com/google/spatial-media (Spatial Media - Google)

[11] https://facebookincubator.github.io/facebook-360-spatial-workstation (Facebook Audio 360 Documentation)

[12] https://hoast.iem.at (Higher Order Ambisonics Streaming [HOAST] Library)

[13] https://www.brucewiggins.co.uk/WHAM (head tracking implementation using webcam)

harmonics/Ambisonics and their use with binaural audio, the reader is directed to the concise summary given by Politis and Poirier-Quinot (2016).

Wigware Panners as GASP Spatialisers

The signal processing elements of the system are hosted in Reaper DAW and utilise the Jesusonic (JSFX) effect engine built into Reaper. These plugins are written in the EEL2 language, and compiled on the fly, which enables rapid prototyping compared with other plug-in architectures. Reaper is utilised to manage routing and sequencing of the audio due to its flexibility in terms of channel count, routing possibilities and its support for multiple plug-in standards (Wiggins, 2008). Each track requires sixteen channels for the 3rd order Ambisonic signals that are created by the spatialising panner, as shown in Figure 5.

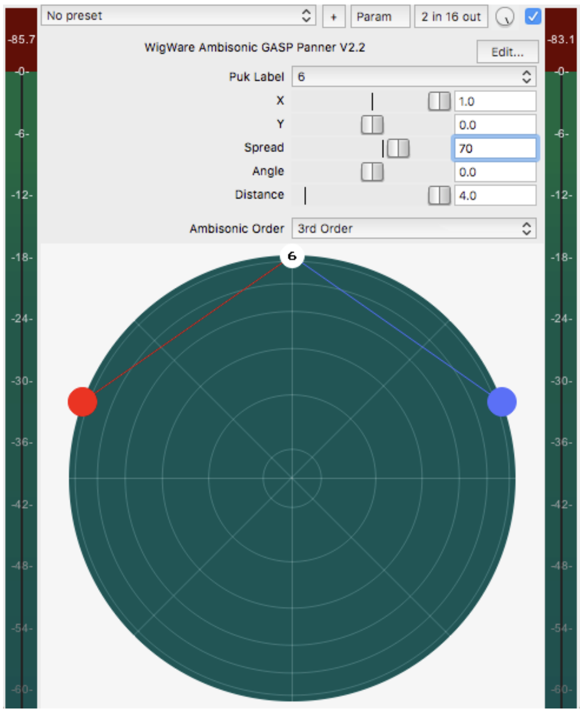

Figure 5 A single string Spatialiser from the GASP system with stereo image shown as red and blue dots.

The variable parameters of GASP's WigWare panners are Spread, Angle and Distance, now referred to as *spatialisers*. After the individual string's Helix timbral processing, each string of the guitar is allocated its own individual spatialiser.

Each spatialiser has a two-channel input (usually a stereo pair) and sixteen outputs (3^{rd} order Ambisonic), this allows the user independent control of the Spread, Angle and Distance parameters for each output from the Helix timbralisation stage. More specifically:

- Spread controls the angle between the two channels of the stereo Helix signal (see Figure 6).
- Angle controls the position of the centre of the stereo image, defined anticlockwise from the front (see Figure 7).
- Distance controls the spatial definition of each of the two signals being spatialised, with value 4 being as close to a point source as possible, and value 0 meaning coming equally from all directions (see Figure 8).

Examples of changing the Spread, Angle and Distance parameters on the plug-ins graphical user interface (GUI) are shown below. The white circle represents the position for Angle and Distance. The blue and red dots are the locations of the two input channels with the angular distance between them affected by the Spread control.

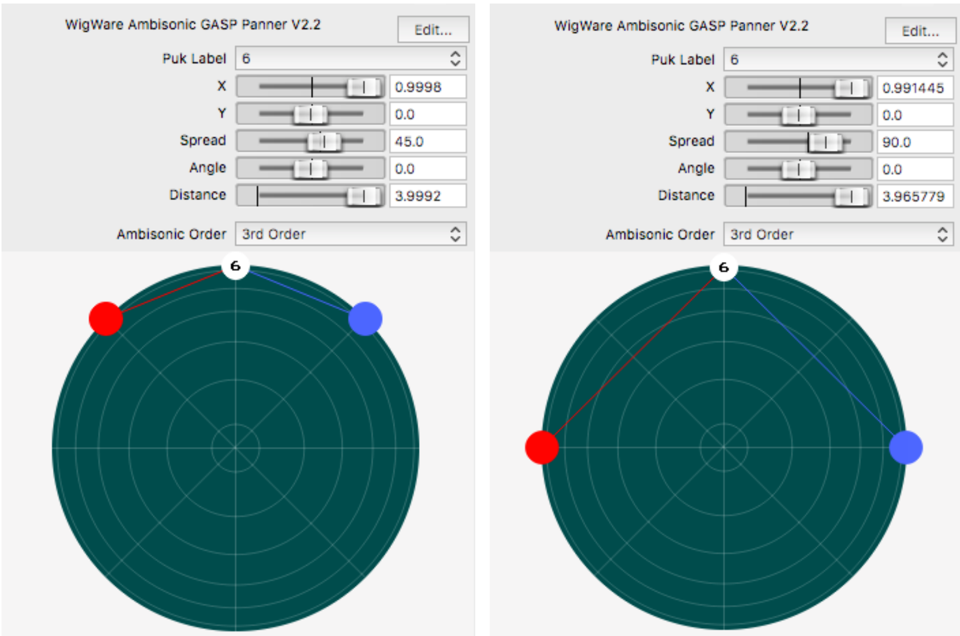

Figure 6 The effect of changing only the Spread control in the GASP system.

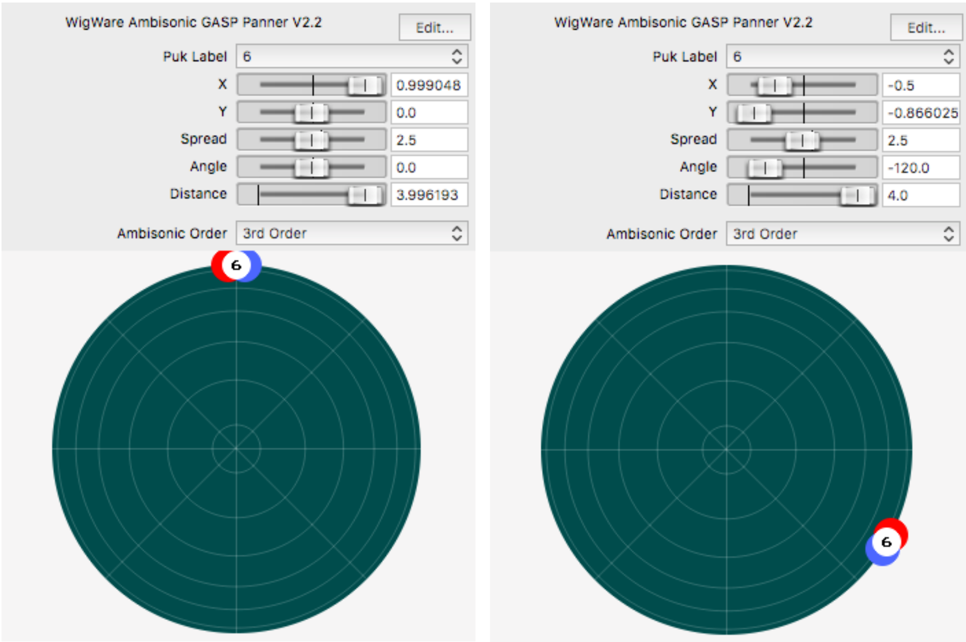

Figure 7 The effect of changing only the Angle control in the GASP system.

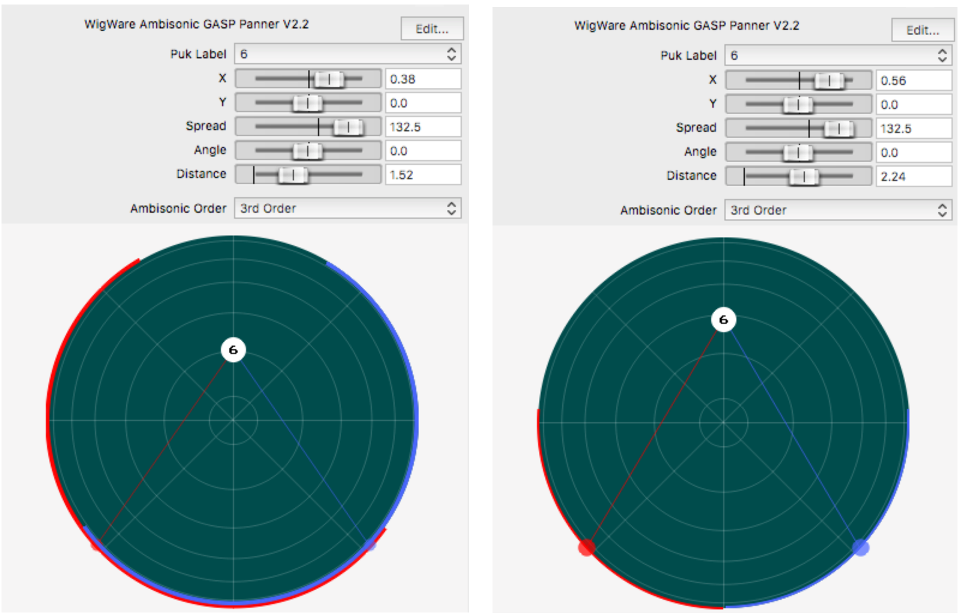

Figure 8 The effect of changing only the Distance control in the GASP system. The red and blue lines on the circumference denote how wide the spatial definition of each source is.

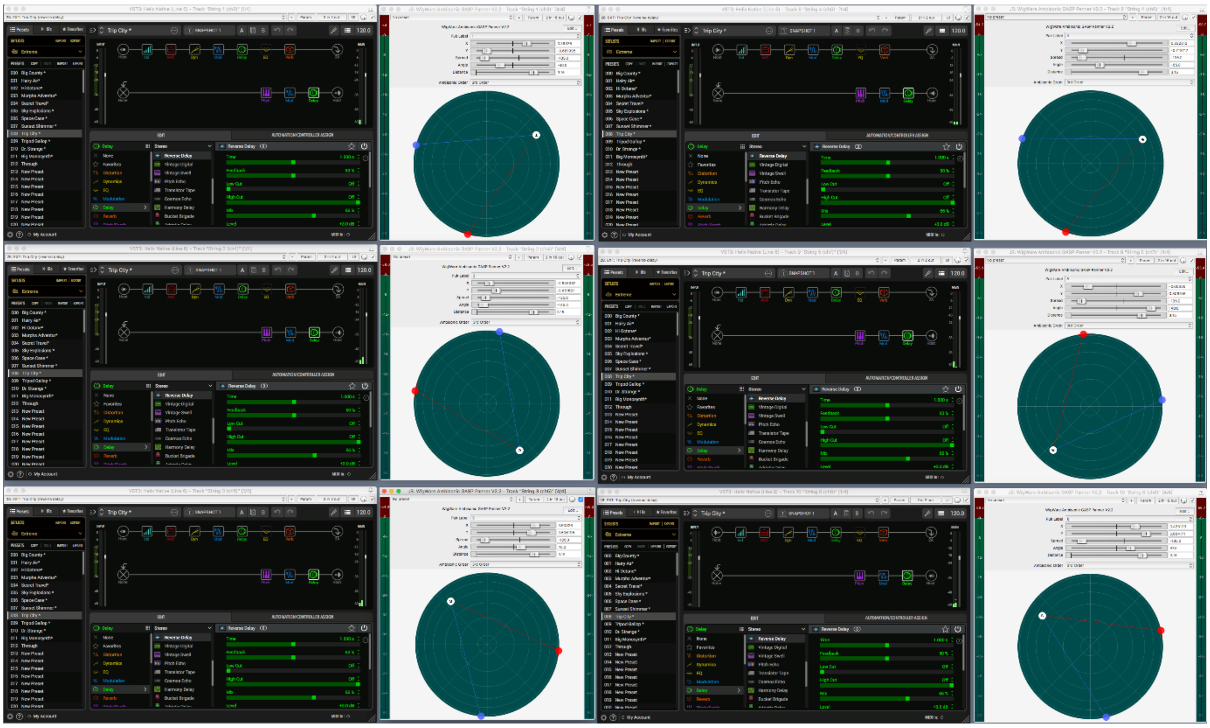

Figure 9 Six Helix Timbralisers and Wigware Spatialisers from the GASP system, one for each string of the guitar.

Ableton Live Spatialiser Clips

To easily select one of the Spread/Angle/Distance Spatialisers, several pre-set *Spatialiser Clips* have been created in Ableton Live. Spatialiser Clips contain the spatial arrangements for that Clip, which may range from simple static positioning of each string in its own space, to complex movement and interactions of the three variable spatial parameters. Investigation of some of the possible combinations and interactions of the spatialising parameters has led to the creation of 20 pre-set Spatialiser Clips, which may be individually selected from within Ableton, or by using the foot controller. The static positioning or movement associated with the Spread/Angle/Distance parameters may also be automated within the Spatialiser Clip. Examples of Spatialiser Clips include: Simple static angular offsets between string locations; Rotation of individual strings around the listener; Stepped rotational arrangements where the step tempo may be synchronised with the music performance tempo; Modulation of enveloping stereo spread, and more. Descriptions and animated GIFs of dynamic spatialiser movement can be viewed on the GASP project page.[14]

GASP's Guitarpeggiator

It's useful to restate that at the heart of the GASP system is an electric guitar fitted with a hexaphonic, or divided, pickup. The divided pickup generates six signal outputs, one for each string, and as each individual string's signal may be accessed, then further processing in the form of audio-gate switching may be

[14]http://gaspproject.xyz/21st-century-guitar (Animated GIFs of dynamic spatialiser movement)

employed, to create what we have termed GASP's *Guitarapeggiator*.[15] This arrangement can be configured to create a musical effect similar to arpeggiation found on many synthesisers.

It is based around MIDI-controlled audio gates on individual strings, such that a sustained chord will have individual strings fast-switching on and off in a pre-defined rhythmic sequence, enabling simple or complex rhythmic arpeggiation-like effects to be realised. It works by using six individually MIDI-triggered audio gates in software; TrackGate facilitates the programmable rhythmic muting and unmuting of individual strings. The arpeggiation effect is achieved through the use of MIDI note-on/note-off patterns in Ableton Live, where each string is associated with a MIDI note value and responds to its own gated on/off pattern, as shown in Figure 10. Once a string is plucked, the rhythmic pattern for that string is set in motion. As each string can have its own unique on-off rhythmic sequence, then simple or complex polyrhythmic performance patterns may be realised. The performer or producer may use this as a creative device for composition, or in post-production on a pre-recorded performance. Each pattern is saved as an Ableton Live Clip. We have created around 20 Guitarpeggiator Clips within Ableton, where each Clip has a unique pattern, and may also have its own tempo and/or time signature.

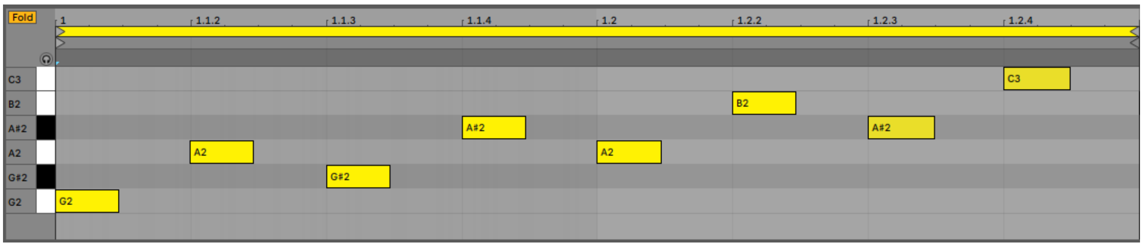

Figure 10 Selection of GASP system's Guitarpeggiator patterns as Ableton Clips. MIDI notes represent on-off switching of TrackGate for arpeggiation effects. Each on-off event corresponds to gate switching for an individual string.

The Guitarpeggiator creates a rhythmic effect which is heard during the Sustain and Release elements of an individual string's ADSR (Attack, Decay, Sustain, Release) envelope. Increased Sustain levels may be achieved through a series of delay lines; for example, the Helix preset Secret Travel works particularly well, having eight delay lines on each string as shown in Figure 11. The arpeggiation effect may also be blended with the output from the non-hex (standard) mono guitar pickups, whilst at the same time, the MIDI-sequence controlling the on-off gating enhances the selected rhythmic notes from the divided pickup.

[15] http://gaspproject.xyz/guitarpeggiator (example of GASP's Guitarpeggiator)

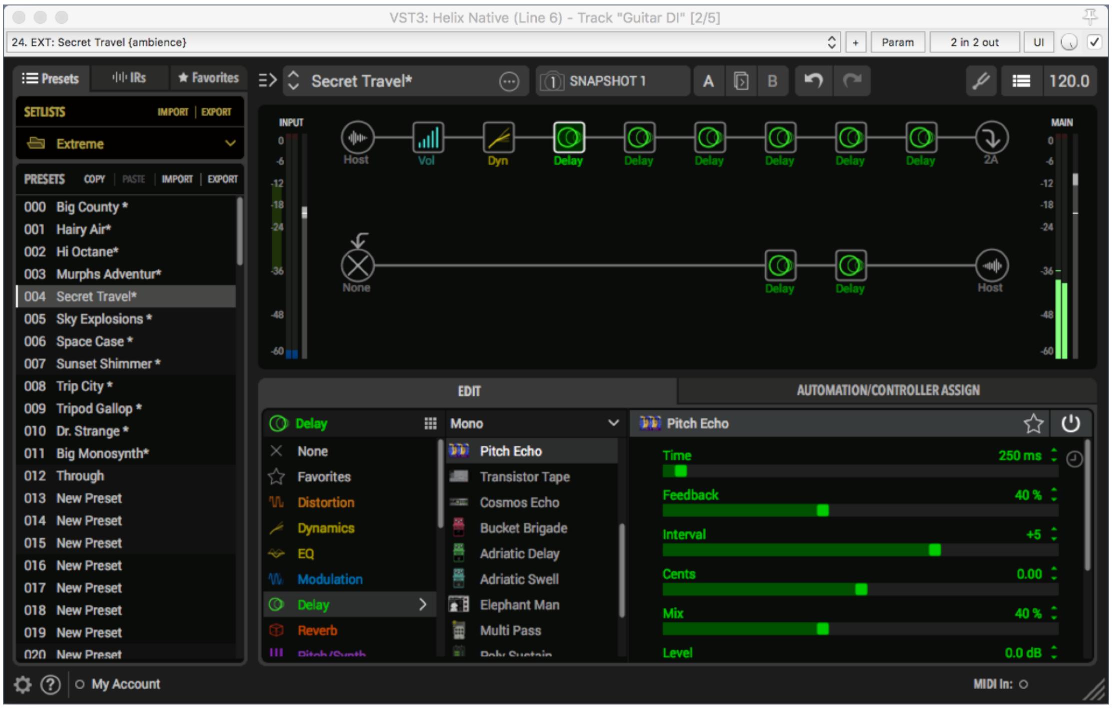

Figure 11 Extended sustain for GASP's Guitarpeggiator using Helix's preset Secret Travel with eight delay lines per string.

Other features which have been developed include the modulation of attack and release times of the arpeggiated notes. This is made available to the player through two performance expression pedals, where two Audiofront MIDI expression pedals are configured,[16] enabling real-time envelope-shaping of the arpeggiations.

A particularly interesting and creative application is when the player's rhythmic performance interacts with the arpeggiation rhythmic pattern, enabling cross-rhythms and non-standard time signatures to emerge. This may be considered a form of performance feedback loop between the player and Guitarpeggiator pattern. There are parallels here with guitar performances that interact with a delay line, where the repetition of a phrase from the delay line can inspire the rhythmic performance of the player. Some examples of GASP's Guitarpeggiator may be heard on the GASP project page.[17] Future work includes the investigation of plugins that auto-generate arpeggiation patterns, for real-time performance applications.

GASP control: Ableton Live

Ableton Live Clips as shown in Figure 12 are used for the selection of GASP's timbralising, spatialising, and Guitarpeggiator pre-sets. Clips may be selected from within Ableton, or from a foot pedal. The BPM tempo control in Ableton Live simultaneously controls both the spatial tempo and the Guitarpeggiator tempo; this

[16] Available from https://www.audiofront.net/MIDIExpression.php

[17] http://gaspproject.xyz/guitarpeggiator (example of GASP's Guitarpeggiator)

is independent of Reaper's project tempo unless purposefully synchronised via MIDI clock or Midi Time Code (MTC).

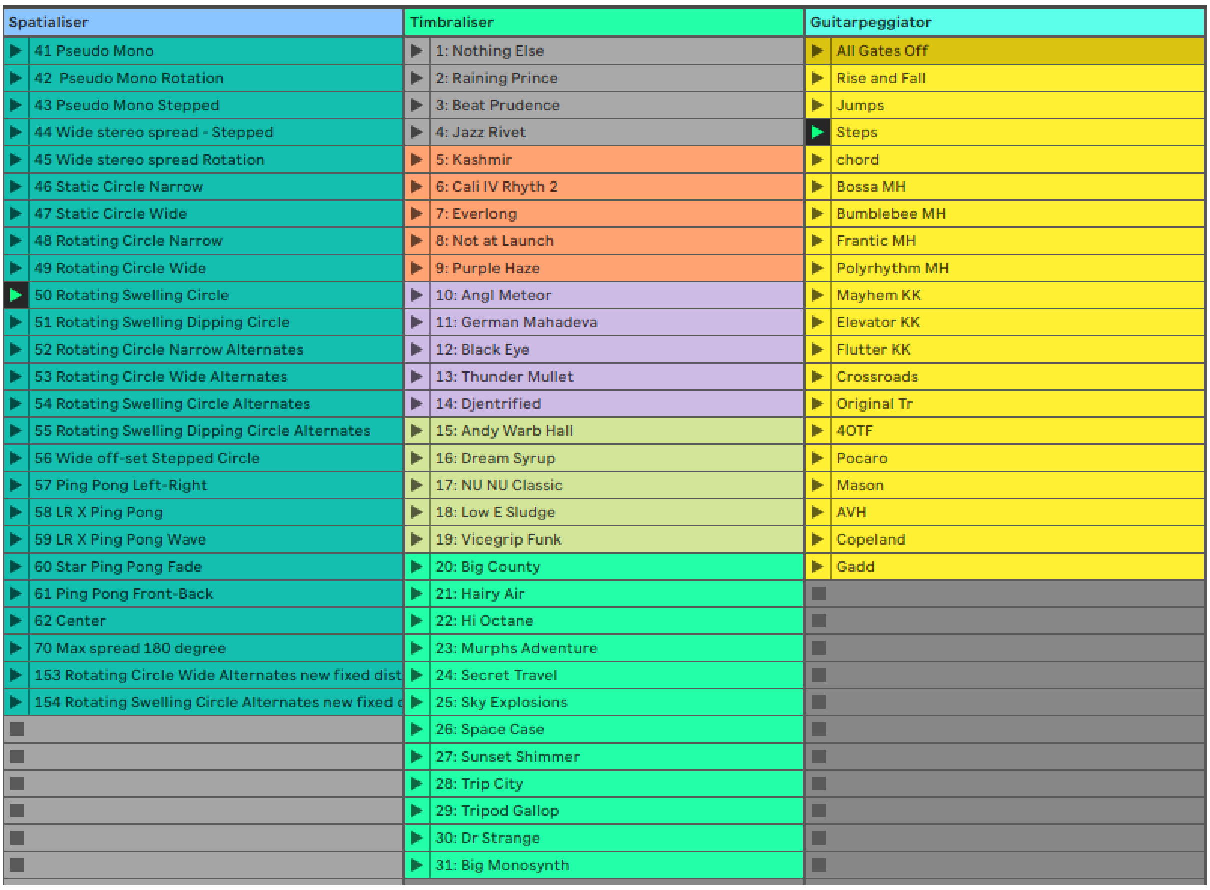

Figure 12 View of Ableton Live in GASP system, showing Spatialiser, Timbraliser, and Guitarpeggiator Clips.

Spatial Tempo and Perceptual Judgements

Wigware Spatialisers, in combination with the Clip control features in Ableton Live, enable some interesting spatial monitoring and perceptual observations. These relate to what we have termed *spatial tempo*, and also to some extent the *spatial pattern* of sonic movement. A Spatialiser Clip can be assigned to have a spatial tempo, this may be a fixed or modulating value, or controlled with an expression pedal, or alternatively manipulated by a live-performance producer. A simple definition of spatial tempo may be considered to be the rate of movement of sound within the ambisonic circle; this is controlled by the BPM value of the Spatialiser Clip control in Ableton Live. The spatial movement itself may be rotational or any other defined spatial pattern; some links to example Clips are cited below.

It's important to reiterate, two tempi are being referred to here. Firstly, the usual musical tempo of the piece, as denoted in the Reaper Project, and secondly, the tempo of the spatial movement in Ableton Live. The spatial tempo may range from a minimum value of 20 BPM, up to a very high tempo of 999 BPM, and may be synchronised with the actual tempo of the music performance, in real-time or during recorded playback. This facilitates some interesting production techniques enabling the matching of spatial tempo with the music tempo, or any multiples or sub-multiples thereof, including alternative time signatures, and other variables such as dotted or triplet rhythms. This provides some interesting creative rhythmic opportunities for the composer, player, or producer.

For analysis, a Clip named "Mono rotation variable tempo" may be observed. In this example, the spatial tempo modulation, is controlled with an expression pedal, see animated "Clip 52a" on the GASP project page.[18] Clip 52a displays variations in spatial tempo, and associated with this, there appears to be a band of spatial tempos up to around 150-200 BPM where listeners of our project have commented (anecdotally) they can comfortably follow the movement of the sound location. When the spatial tempo increases beyond this range, listeners have then commented on perceiving a fuller sense of immersion. However, comparisons with other spatial clips with different spatial patterns create differing perceptions regarding the awareness of sound tracking and sense of immersion, as some spatial patterns appear to give a greater sense of immersion. More rigorous listening tests are required to provide an evidenced-based analysis of these phenomena.

A useful term here is Eversion which is "the state of being turned inside out" (Merriam-Webster, n.d. a). It is an appropriate descriptor, as some listeners of our project have described the perception associated with listening at higher spatial tempo values as being inside the sound of the guitar – this presents as a new and unique sound description of the instrument. Additionally, it was observed that around the lower mid-range values of spatial tempo (200–300 BPM) there appear some particularly interesting spatial effects worthy of further investigation, this is currently a work in progress.

Other notable spatial effects include what may be referred to as *spatial wobble* or *moving waves*; where the frequency of the so-called spatial wobble is related to the spatial tempo of Clips that use Distance parameter modulation (Figure 13). This is particularly apparent for Clips 51 and 51b (Rotating Swelling Dipping Circle), see animations on the GASP project page.[19] Clip 51 is shown with a fixed tempo, whereas Clip 51b has its spatial tempo modulated. These effects are associated with modulation of the Distance parameter, such that a form of dynamic amplitude modulation is perceived. This appears to occur as a result of the dynamic overlapping of the left and right spreading function of the Distance parameter modulation, resulting in spatially dynamic peaks and troughs.

A further interesting consideration is associated with variations of spatial tempo in small vs larger performance spaces. As an example, consider the situation where the loudspeaker array is positioned around the periphery of a large room and one rotation of a spatial cycle occurs; this will have a greater circular distance (i.e., a larger circumference) than the same speaker set-up in a smaller room. The peripheral movement in the large space must be faster, as it has a greater distance to move in one rotation time frame. Whilst this may seem obvious, it suggests there is a relationship between the perception of

[18] http://gaspproject.xyz/21st-century-guitar (see clip 52a: 'Mono rotation variable tempo')

[19] http://gaspproject.xyz/21st-century-guitar (see animated Clips 51 and 51b: Rotating Swelling Dipping Circle)

spatial tempo with the size of the room. However, of course, the angular velocity in both cases remains the same. Clip 71: "Circumferential rotation comparison" may be viewed on the GASP project page.[20] Comparisons with other spatial patterns may reveal other perceptual insights, this is future work.

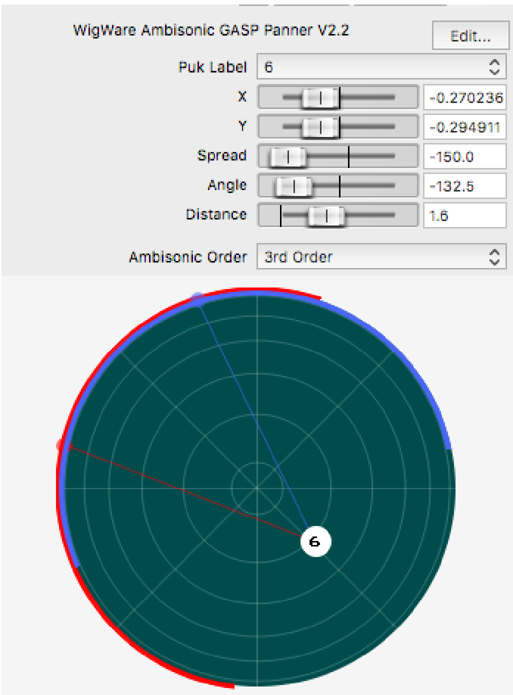

Figure 13 GASP system's Spatialiser with Distance parameter modulation: see animated Clips 51 and 51b on GASP project page.[21]

Ambisonic Reverb and Spatial Delay

Two further Ambisonic effects are set up on the output bus sends after Timbralisation and Spatialisation. These are WigWare AmbiFreeVerb 2 (Wiggins & Dring, 2016), and Blue Ripple 03A Spatial Delay.[22] AmbiFreeVerb2 provides a full 3D spatial reverb operating at 1st order. The reverb processing is novel as the processing in the spatial domain allows the reverb to be applied to the entire sound field, but processing different areas of the sound field separately, demonstrating good spatial and immersive properties that react to the spatial panning and information contained within the sound field. Although the reverb works at 1st order resolution, the 3rd order direct sound (supplied by the panners) provides the higher directional impression of the dry audio. The other Ambisonic plugin used on the output bus is Blue Ripple 03A Spatial Delay, this provides a delay effect for the whole 2D sound field with a rotation effect in the feedback loop,

[20] http://gaspproject.xyz/21st-century-guitar (see Clip 71: Circumferential rotation comparison)

[21] http://gaspproject.xyz/21st-century-guitar (see animated Clips 51 and 51b: Rotating Swelling Dipping Circle)

[22] Available from http://www.blueripplesound.com/products/o3a-core

so every repeat from the delay can come at a different angle. This has a particularly interesting effect in conjunction with specific GASP spatialisation patterns.

Interactive Live Performance

In the live performance environment, the GASP system may be controlled by a dedicated live-producer. The live-producer could provide control over the timbral, spatial and other performance parameters, either as pre-agreed musical arrangements, or entirely independent of the guitarist. This may be considered as an interactive sound-arts performance, where the guitarist responds to any changes initiated by the live-producer, the outcome being potentially unpredictable. Further, the live-production control parameters could be made available to an audience through a pre-programmed phone-based application of GASP performance variables, to realise an audience/guitarist interactive performance.

GASP Post-Production and Demonstrations

Some demonstration productions have been made, each seeking to demonstrate alternative post-production methods. This is ongoing work where there remain many production ideas yet to be tested. GASP post-production affords much versatility and may be applied to any style of guitar performance technique. An interesting observation relating to GASP post-production is that differing guitar performance styles (an example could be acoustic picking vs progressive metal), may utilise potentially extreme variations of timbral and spatial production, such that the more complex the guitar performance, the greater the creative potential for GASP post-production.

There were four demonstration pieces included in our presentation at The 21st Century Guitar Conference. These were originally mixed for, and intended to be heard over an eight-speaker circular array in a real space, e.g., in a medium-sized or large room. However, for the online presentation, which remains available, they were rendered to binaural sound, so can be heard over headphones.[23]

Pale Aura (extract, 1 min 20 sec) Performed by Dominic Dallali: Post-Production by Jack Hooley and Dominic Dallali. This demo starts with the original unprocessed guitar which then develops to demonstrate various timbral and spatial production techniques. The recording has no overdubs, that is, the final production is derived from one single guitar performance. This track is the guitar part of the progressive metal song *Pale Aura* by the band Periphery.[24] It turned out to be quite a dramatic production, with rapid changes in spatial location for close temporal events. The guitar part consists of some highly syncopated timing elements, which have been mapped to rapid location switching. A range of amplifier distortion timbres are employed for different parts of the performance. A low kick drum was included to provide the listener with a sense of meter as the guitar performance includes syncopated elements. The full GASP demo of *Pale Aura* may also be heard on HOAST (Higher-Order Ambisonics STreaming Library), where

[23] https://youtu.be/liDcWAm31EA?t=6778 (link to all GASP demonstrations as binaural sound in The 21st Century Guitar Conference presentation)

[24] Song available at https://www.youtube.com/watch?v=-ydpiDs2i0Q

you can drag the video around with the mouse to change the field-of-listening, or experience head tracked binaural audio if you have a compatible VR device.[25]

Cat Fantastic (extract, 1 min 10 sec) Performed by Jack Hooley: Post-Production by Duncan Werner and Emma Fitzmaurice. Again, this demo begins with the original unprocessed guitar, which then crossfades through timbral and spatial variations, and then returns to the unprocessed sound. This track is a section of the guitar part of the song *Cat Fantastic* by the band TTNG.[26] The GASP recording has no overdubs, that is, the final production is derived from one single guitar performance. Post-production includes timbral crossfading and dynamic spatialisation. Post-production also includes experimentation with timbral crossfades, where multiple versions of each string, each with different timbres, were printed on time-synchronized parallel tracks, thus allowing crossfading between individual string timbres, then mixing the respective tracks. The timbral crossfading works well (*Cat Fantastic* real-time timbral crossfading process, n.d.), and we have now made templates for live performance real-time timbral crossfades. The full demo of *Cat Fantastic* may also be heard on HOAST.[27]

Prelude to Life (extract, 1 min 10 sec): Composed and performed by Fred T. Baker,[28] post-production by Charlie Box and Duncan Werner.[29] This single guitar performance begins with the original unprocessed sound, and then develops to demonstrate various timbral and spatial production techniques. Post-production timbralisation is supplemented with other instrument sound samples where Melodyne's pitch-to-MIDI conversion is used; where the MIDI note events then trigger various instrument samples e.g., orchestral strings with other sampled and synthetic sounds. Upon reflection, the timing of pitch to MIDI conversion works very well, such that the nuances of the guitar performance have been precisely captured by the MIDI conversion. The full demo of *Prelude to Life* may also be heard on HOAST.[30]

Question/Answer (duration, 1 min): Lead Guitar composed and performed by Emiliano Bonanomi, post-production by Harry Dale and Duncan Werner. The main guitar line has no overdubs, that is, the final production is derived from one single guitar performance. The backing track is a mono mix placed in the centre of the Ambisonic sound stage. In post-production, the lead guitar part has been divided into several time sections for production experimentation, with both timbral and spatial processing on each section. In places you may hear what sounds like audio phasing, this is a spatial artefact resulting from Ambisonic to Binaural conversion.

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[25] https://hoast.iem.at/play/pale_aura_o2 (link to Pale Aura binaural GASP demonstration, where you can drag the 360° video around)

[26] Song available at https://www.youtube.com/watch?v=mT-fjYFqPOk

[27] https://hoast.iem.at/play/cat_fantastic_o3 (link to 'Cat Fantastic' binaural GASP demonstration, where you can drag the 360° video around)

[28] Original track included in Baker, F. T. (2014). Prelude to life. In Life Suite [CD]. First Hand Records.

[29] A preview of the album is available at https://www.youtube.com/watch?v=hDJfv-Hft_s

[30] https://hoast.iem.at/play/prelude_to_life_o2 (link to 'Prelude to Life' binaural GASP demonstration, where you can drag the 360° video around)

Other factors for GASP Production: An appreciation of Bregman's writings on Auditory Scene Analysis (ASA) (e.g., Bregman, 1994) has inspired some GASP production techniques. By contrasting ASA perceptual grouping and streaming with GASP post-production possibilities, the notion of resynthesised grouping and streaming is introduced (Appendices, 2021). For example, one mode of ASA perception (say, a melody stream from a static location), may be supplemented using GASP production by generating an additional (and possibly stronger) perceptual mechanism of spatial movement, i.e. the introduction of a synthesised spatial stream.

Music Producer David Ward, Executive Director of JAMES - Joint Audio Media Educational Support[31] commented:

> …of particular interest, on our (University of Derby accreditation) visit, was the Guitar-based Ambisonic Spatial Performance project where we became aware of the myriad commercial, theatrical, performance and educational potentials of this project. (personal communication, June 11, 2018)

Real-time crossfading for *Cat Fantastic*

The GASP post-production of *Cat Fantastic* applied several individual Helix timbres across strings that were crossfaded into and out of one another. This process involved timbral-crossfading with variables of six strings, four timbres, and several spatial arrangements, all requiring precise dynamic control for the production to work. However, the intention now is to realise this as a real-time process, such that a potential live performance with individual-string, timbral cross-fading may be achieved.

The approach taken is to route the signal from each string to four separate signal paths inside Helix, now referred to as *lines*, with the original post-production timbral processing applied to each line as shown in Figure 14. MIDI continuous controller (CC) messages may then be assigned to the volume level of each line such that we can apply CC curves to control the crossfades between lines. The four signals from each string are then recombined at the output across six Reaper tracks, which are then be routed to the GASP spatialisers. A detailed description of this process is posted on the GASP project page.[32]

[31] http://www.jamesonline.org.uk

[32] http://gaspproject.xyz/wp-content/uploads/2021/08/CatFan-real-time-Timbral-Morphing-Process.pdf (Cat Fantastic real-time Timbral Crossfading Process)

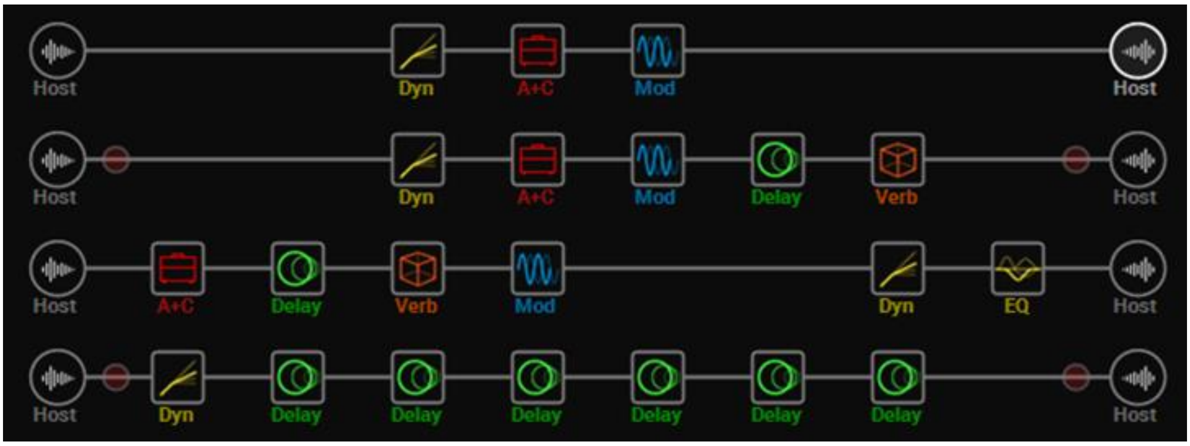

Figure 14 Processing of each string by four timbral lines in GASP system, crossfading into one another at different times.

Remixing *Gone Sailing* for GASP post-production

Another element of the project is investigating the re-spatialisation of existing mastered stereo recordings, where our research question may be stated as: Can pre-recorded music be successfully processed by the GASP immersive production system to create new and interesting reimagined immersive sound mixes? This process employs Melodyne's DNA note-extraction tools,[33] coupled with Bregman's ASA visual grouping and streaming ideas, then spatialising using GASP-based production.

Specialist music production software Celemony Melodyne with its Direct Note Access (DNA) feature, may be used to identify individual notes from a complex musical arrangement, the musical notes may be observed visually, and heard individually. A typical use for DNA analysis would be for post-production editing to edit bad or out-of-tune notes from a recording.

For test purposes, we have chosen the guitar piece *Gone Sailing* by Allan Holdsworth from the 1975 Bundles album by Soft Machine.[34] This was initially extracted from CD to create a standard .wav file. Importing this into Melodyne's DNA analysis programme, enables the piece to be visualised in detail, showing note values on the vertical axis, and time, horizontally. A screenshot example is shown in Figure 15, where you can see the highlighted top notes, which were then routed to one of GASP's string spatialisers.

[33] Available from https://www.celemony.com/en/melodyne/what-is-melodyne

[34] Piece available at https://www.youtube.com/watch?v=7gQVQ6ArHnE

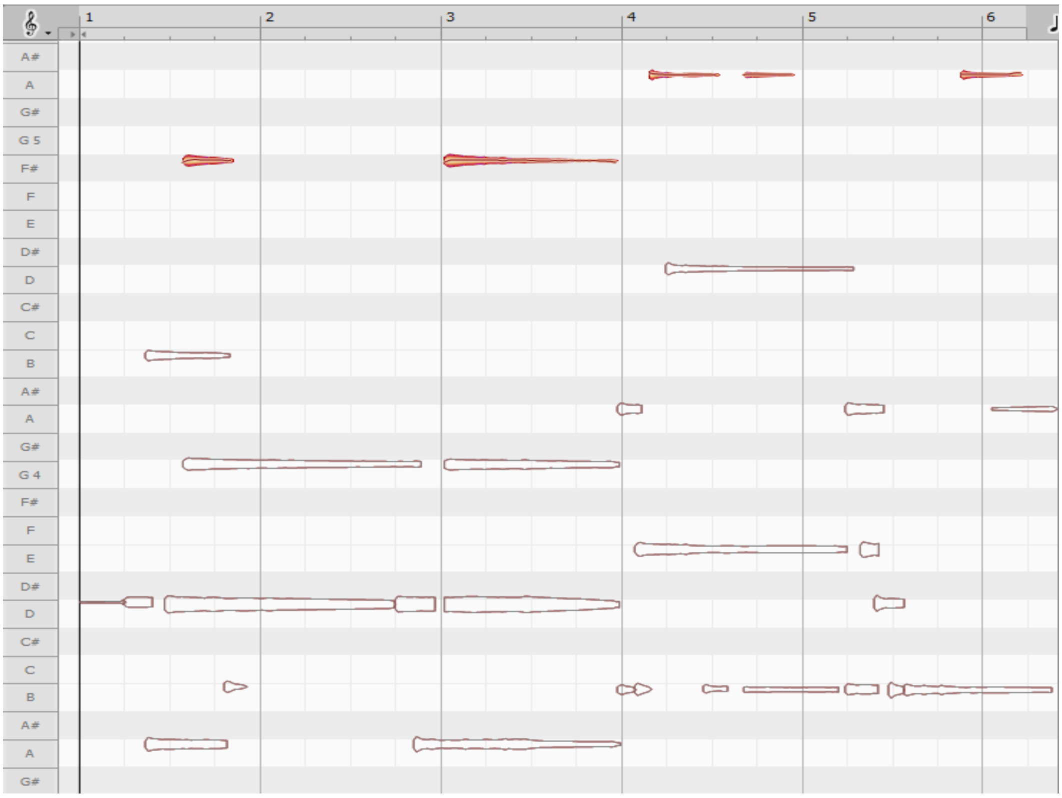

Figure 15 Part of Melodyne's DNA analysis of Gone Sailing, showing highlighted top notes which were then routed to one of GASP's string spatialisers.

The process is to separate the musical notes into a series of sequential visual streams through time; in the case of this guitar piece, five streams were identified. Each visual stream now effectively becomes a stem, in much the same way as in a traditional multitrack recording. The decision as to what constitutes a new stem (visual stream) is derived from ASA perceptual auditory streaming and grouping rules of Bregman (Bregman, 1994). The newly separated stems may then be independently processed by the GASP system, the resulting production being an immersive re-mix of the piece.[35]

Investigating real-time re-tuning: Scordatura

At The 21st Century Guitar online conference in March 2021, discussions regarding other possible applications of the GASP project took place. In particular, scordatura, which is defined as "tunings that are different from the normal, standard tuning" (Merriam-Webster, n.d. b). We have identified two ways in which this may be realised for live performance:

35 A more detailed description of the process is available at http://gaspproject.xyz/wp-content/uploads/2021/09/Gone-Sailing-Melodyne-DNA-Process.pdf

Firstly, through the use of Helix Snapshots, where up to eight alternative tunings may be stored for a given performance and recalled with a foot pedal switch by the performer, or by a live producer. This Snapshot method would be useful for instant re-tuning, where pre-set pitch-shift blocks on individual strings will (almost) instantly generate an alternative tuning of the guitar.

And secondly, through the use of slowly-modulated Helix pitch-shift blocks (each associated with individual strings), where alternative tunings may be morphed over time during the guitar performance. This method would require pre-knowledge of the piece in terms of the initial tuning conditions, how the tunings would change within the piece, and over what time durations. Multiple re-tunings could be accommodated, including non-standard tunings, such as quarter tones, or specific cents values tunings. The real-time morphing re-tuning may then become a feature of the guitar performance; classical guitarist Sam Cave commented:

> When combined with the previously established properties of the GASP system, these methods of independently manipulating the tuning of each guitar string represent very fertile ground for the creation of new guitar music. Collaboration is underway to investigate these possibilities and, whilst still in its infancy, we hope that some results can be presented shortly. In terms of pre-existing repertoire, this research has the potential to minimise the amount of retuning required of the performer during a concert programme, and thereby ensuring absolute stability of each tuning used and negating the cumbersome burden of preparing and transporting multiple guitars to accommodate the use of multiple, highly specific tunings. (personal communication, August 16, 2021).

GASP2: Improvements and Rationalisation

GASP2 is a work in progress, investigating the realisation of the system running on one single computer. It is based around a 2018 Mac mini, 3.2GHz 6-core i7 processor with 32GB RAM.

GASP2 was partly instigated to investigate ways of enabling more flexible control of the spatialisation parameters. A limitation of the current system is the conflated spatial tempo associated with the Spread, Angle, and Distance parameters, as controlled by the Session tempo in Ableton Live. In the current GASP implementation, the Spatial Tempo (Ableton's Session tempo), is linked to all spatialiser parameters simultaneously, that is Spread, Angle, and Distance parameters are all modulated together when the Spatial Tempo is increased or decreased. However, ideally, these parameters would be configured such that they can be independently modulated. To take forward this idea, GASP2 seeks to implement the separation of the current overarching spatial parameter control, such that more flexible configurations may be realised. The combinations being: 1) Spread, Angle, and Distance, each with independent spatial parameter control; 2) Spread/Angle, Spread/Distance, and Angle/Distance, to give combined control of two parameters linked together; and 3) Spread/Angle/Distance with all parameters linked, as in the original GASP configuration, that is, seven combinations in all. As stated previously, the current GASP control system for Wigware Spatialisers relies on the use of Ableton Live Clips, where LFO shapes are drawn into automation lanes, with the Clips then looping. This can be an awkward and time-consuming programming process, particularly when seeking to create some of the more complex spatial movements of the spatialising parameters. To facilitate the ideas above, alternative controller programs have been investigated, with Bitwig being a potentially good alternative to Ableton Live.[36]

Bitwig offers several readily available alternative configurations for creating control over the spatialisation parameters. Multiple configurable LFOs are available, providing easier and more flexible control for GASP spatialisation. The Clip launching system in Bitwig is much the same as within Ableton, where Clips may be aligned to form Scenes, or triggered individually either from within the programme, or an external MIDI controller. However, a key benefit of Bitwig over Ableton is the ability to set up control of individual LFO devices, which in turn may be controlled from an external expression pedal, thus facilitating user control of individual spatialisation parameters. Additionally, this also enables an external controller for each parameter, either singularly, or in groups with two or three linked parameters.

Bitwig's Classic LFO is shown in Figure 16, where the parameters of Frequency (Hz) can be assigned to define the speed of motion, Amount to control the modulation range for the given spatial parameter, and Waveshape to control the pattern of the motion. The Phase value may be used to offset the LFO movement relative to other strings, that is, if the strings are to chase each other around a playback circle (see Clip 48)[37], then the Phase value for each string may be staggered by a percentage value. Another potentially interesting feature is a Quantiser, which can take its input from the Angle LFO and convert the smooth rotational motion to a stepped motion.

The work for GASP2 is ongoing, and preliminary findings are encouraging. These developments will offer a range of new opportunities for spatial experimentation and the creative immersive possibilities for the GASP project.

Figure 16 Bitwig's Classic LFO configured for a single string in GASP system, to provide control for the multiple parameters of Spread, Angle and Distance spatialization.

[36] Available from https://www.bitwig.com

[37] http://gaspproject.xyz/21st-century-guitar (see Clip 48: Rotational Chasing Strings)

Future work

Our objectives for the future are:

- To expand the current 2D circular representation to implement true 3D spherical representation, i.e., to include spatial height. There are several considerations, including re-routing of existing 2D spatial pathways, include additional implementation of Helix Timbralisation, or apply spatial filtering using equalisation on height information.
- To investigate the implementation of GASP within Dolby Atmos as Reaper DAW now supports Dolby Atmos rendering;[38] this offers avenues for further exploitation.
- To enhance the differences in the timbre of the Left and Right pseudo stereo Helix pre-sets, to provide a deeper sense of immersion, post-spatialisation.
- To investigate alternative techniques of spatialisation: by introducing an additional three pre-spatialisers with outputs assigned to three pairs of strings, alternative spatial effects may be created: I.e., routing strings 1&2 to pre-spatialiser#1, strings 3&4 to pre-spatialiser#2, and strings 5&6 to pre-spatialiser#3.
- To further develop GASP's Guitarpeggiator to include plugins that auto-generate arpeggiation patterns, for real-time performance applications.
- To design listening tests for an analysis of the sense of immersion experienced by listeners. Programmed variations of Spatial Tempo and choice of Spatial Pattern would form the basis of this investigation. This would require a spatial lexicon for the description of immersive perceptions.
- To investigate system control by a dedicated Live-Producer. And potentially, the live-production control parameters could be made available through a phone-based application of GASP performance variables, to realise an audience/guitarist interactive performance.

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Bruce Wiggins completed his PhD in 2004 where he solved the problem of generating Ambisonic decoders for irregular speaker arrays and looked at the optimisation of binaural and transaural systems. His research into Ambisonics has been featured as an impact case study in the national Research Excellence Framework in 2014 and will be again in 2021. His latest work is based around the auralisation of rooms to very high order Ambisonics with head-tracking.

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Emma Fitzmaurice graduated from the University of Derby UK in 2019, after completing BSc(Hons) Music Technology and Production, then followed by MSc Audio Engineering. It was here she gained an interest in spatial audio and the GASP project, making significant contributions to GASP's spatial control system. She now works in QA on Novation products at Focusrite and continues to work on the development of the GASP project in her spare time.

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