Higher order Ambisonic systems

*(abstracted from **"Space in Music - Music in Space**", an Mphil thesis by Dave Malham, submitted to the University of York in April 2003, revised and passed in December 2003. All rights reserved, copyright Dave Malham, 2003. Use for educational purposes is permitted and encouraged, so long as this copyright notice is retained)*

The simple, basic version of the Ambisonic system so far described can only (re)create an accurate soundfield at one central location. There is a gradual increase in the level of errors as the listener moves away from the centre and as the frequency increases (Bamford and Vanderkooy,1995). However, if carefully implemented, it has been shown to work reasonably effectively even over large areas (Malham and Orton, 1991; Malham, 1992; Vennonen, 1994). In order to improve the area over which low error soundfield reconstruction takes place, combining Ambisonics with either the Holophonic system (Nicol and Emerit,. 1999) or with Wavefield synthesis (Horbach and Boone, 1999) has been suggested. Unfortunately, these hybrid approaches, whilst interesting in their own right and perhaps appropriate for certain specific circumstances, lack the ease of implementation and control that Ambisonics can offer. Ambisonic systems are based on describing the soundfield using ***spherical harmonics*** with the system discussed above, as already indicated, being commonly referred to as a first order system, and it is well known that increasing the complexity of the description by increasing the order of the spherical harmonics used in that description reduces the errors for off-centre listeners (Bamford and Vanderkooy1995, Malham 1999b)

Spherical harmonics

Gerzon's original 1973 paper presented the spherical harmonics up to third order in terms of Cartesian coordinates (***x,y,z***) where ***x*** is the front-back axis, ***y*** is the left-right axis and ***z*** is the up-down axis. In his later published work the definitions are given in polar (***r,Θ,Φ***) coordinates (which has become the norm for Ambisonic system definitions) and the notation is somewhat different. This has left us with neither a defined terminology for higher order systems nor a spherical harmonic formulation for the higher order channels in a form which is consistent with the current practise for the first order ones. The well known ability of spherical harmonics to efficiently define a function on the surface of a sphere (Kaplan, 1981) has resulted in their extensive use in problems in Physics and Chemistry. Unfortunately, each of the groups of workers - physicists, chemists, mathematicians - using spherical harmonics have their own style and notation, of which none seem to match established Ambisonic practice. The best and most consistent presentation seems to be that of Daniel (Daniel, 2000) and, accordingly, that has been chosen as the basis for the notation used throughout the rest of this thesis, except where otherwise noted.

In this notation, spherical harmonics are described by:

$$Y_{mn}^{\varsigma}(\theta,\phi) = \tilde{P}_{mn}(\sin\phi) \times \begin{cases} \cos(n\theta) & if \quad \varsigma = 1 \\ \sin(n\theta) & if \quad \varsigma = -1 \end{cases} \qquad \textbf{(1)}$$

where $\tilde{P}_{mn}$ is the semi-normalised associated Legendre function of degree[1] ***m*** and order ***n***. Daniel calls this the ***SN3D*** Ambisonic encoding (or ***SN2D*** in the case of horizontal only variants). This corresponds to standard first order Ambisonics, with the exception of the 0.707 weighting applied to W for engineering reasons as discussed above. Although there are significant mathematical arguments for using this formulation (generality, availability of recursive functions for generating $\tilde{P}_{mn}$ (Press et al., 1997)) this author believes there are compelling real-world engineering reasons why the version called ***Max-Normalisation (MaxN)*** by Daniel should be used as the basis for expansion of the Ambisonic system to higher orders. This has been followed in the ***Furse-Malham (FuMa)*** version, with the inclusion of the standard 0.707 weighting of the ***W*** channel. It should be noted that the mathematically preferred spherical harmonic formulations usually include weighting factors which ensure that the result of integration of each harmonic over the sphere is 1. As the order ***M*** of the harmonics is increased, the maximum value that each harmonic may attain increases. For diffuse fields this does not, on average, represent a problem, but when dealing with point or near-point sound sources, such as those produced by panning, this can result in signals in higher order channels exceeding the signal handling capacity of the physical channel they are transmitted through (or stored in). Even this would not represent a serious problem if the channels all used floating point signal representations, but many systems still use 16, 20 or 24bit integers. ***MaxN*** representations have weighting factors applied to each component above the zeroth (***W***) component such that the maximum value each takes is limited to |1|. The factors for this can be obtained by inspection up to about third order but over this point it becomes more difficult and requires the maxima of each polynomial to be determined (either mathematically or numerically) explicitly and then inverted. Unlike the Legendre functions, no simple recurrence formula has so far been discovered for generating the required weighting factors automatically. The factors for converting the formal, mathematical***, SN3D*** representation into the ***FuMa*** engineering version used in practical systems are given up to third order in **table 1** below, together with the accepted channel designations.

[1] Although not strictly mathematically correct, since ***m*** is the degree and ***n*** the order of the Legendre functions, and despite the confusion this can cause, it is accepted practice to refer to the ***order M*** of spherical harmonics in terms of ***m***

Table 1 Ambisonic B Format Channels to 3rd. Order

Order	m,n,ς	Channel	SN3D definition	FuMa weight
0	0,0,1	W	1	$1/\sqrt{2}$
1	1,1,1	X	$\cos\theta\cos\phi$	1
	1,1,-1	Y	$\sin\theta\cos\phi$	1
	1,0,1	Z	$\sin\phi$	1
2	2,0,1	R	$(3\sin^2\phi - 1)/2$	1
	2,1,1	S	$(\sqrt{3}/2)\cos\theta\sin(2\phi)$	$2/\sqrt{3}$
	2,1,-1	T	$(\sqrt{3}/2)\sin\theta\sin(2\phi)$	$2/\sqrt{3}$
	2,2,1	U	$(\sqrt{3}/2)\cos(2\theta)\cos^2\phi$	$2/\sqrt{3}$
	2,2,-1	V	$(\sqrt{3}/2)\sin(2\theta)\cos^2\phi$	$2/\sqrt{3}$
3	3,0,1	K	$\sin\phi(5\sin^2\phi - 3)/2$	1
	3,1,1	L	$(\sqrt{3}/8)\cos\theta\cos\phi(5\sin^2\phi - 1)$	$\sqrt{45}/32$
	3,1,-1	M	$(\sqrt{3}/8)\sin\theta\cos\phi(5\sin^2\phi - 1)$	$\sqrt{45}/32$
	3,2,1	N	$(\sqrt{15}/2)\cos(2\theta)\sin\phi\cos^2\phi$	$3/\sqrt{5}$
	3,2,-1	O	$(\sqrt{15}/2)\sin(2\theta)\sin\phi\cos^2\phi$	$3/\sqrt{5}$
	3,3,1	P	$(\sqrt{5}/8)\cos(3\theta)\cos^3\phi$	$\sqrt{8}/5$
	3,3,-1	Q	$(\sqrt{5}/8)\sin(3\theta)\cos^3\phi$	$\sqrt{8}/5$

I do not, in general, think it worth continuing the use of the letter based nomenclature for channel names above the third order, although the English alphabet would actually accommodate the nine channels of fourth order, preferring instead to use the m,n,ς system used in table 1. This system is slightly different from the normal mathematical convention, in that sigma is not superscripted above the other two. This convention has been adopted for future typographic convenience.

Rotation around the Z-axis as described in the section on basic Ambisonics can be easily extended to these higher orders. Both Daniel (Daniel 2000:165) and Furse (WWW[6]) have published the matrices for first and second order, albeit with slight differences in conventions. Since the table covers third order systems, the rotation matrices up to third order are presented here. The W matrix is trivial, being the identity matrix under all these transforms and so is not included.

Rotation matrices.

For a rotation around the Z axis by an angle $\boldsymbol{\beta}$ the matrices are given by the following;

First order components
Row (input) order ***X,Y,Z***
Column (output) order ***X´,Y´,Z´***

$$\begin{bmatrix} \cos\beta & -\sin\beta & 0 \\ \sin\beta & \cos\beta & 0 \\ 0 & 0 & 1 \end{bmatrix} \qquad \textbf{(2)}$$

Second order components
Row (input) order ***R,S,T,U,V***
Column (output) order ***R´,S´,T´,U´,V´***

$$\begin{bmatrix} 1 & 0 & 0 & 0 & 0 \\ 0 & \cos\beta & \sin\beta & 0 & 0 \\ 0 & -\sin\beta & \cos\beta & 0 & 0 \\ 0 & 0 & 0 & \cos 2\beta & -\sin 2\beta \\ 0 & 0 & 0 & \sin 2\beta & \cos 2\beta \end{bmatrix} \qquad \textbf{(3)}$$

Third order components
Row (input) order ***K,L,M,N,O,P,Q***
Column (output) order ***K´,L´,M´,N´,O´,P´,Q´***

$$\begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & \cos\beta & \sin\beta & 0 & 0 & 0 & 0 \\ 0 & \sin\beta & \cos\beta & 0 & 0 & 0 & 0 \\ -0 & 0 & 0 & \cos 2\beta & \sin 2\beta & 0 & 0 \\ 0 & 0 & 0 & \sin 2\beta & \cos 2\beta & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & \cos 3\beta & \sin 3\beta \\ 0 & 0 & 0 & 0 & 0 & -\sin 3\beta & \cos 3\beta \end{bmatrix} \qquad \textbf{(4)}$$

Tilt and tumble.

Since, starting with second order, the harmonic shapes involved in either tilt or tumble are no longer simple, generating the matrices involved is not trivial. Deriving the second order matrices is not too difficult, although it does require a significant amount of manipulation of trigonometrical equations to arrive at the results given in Furse or Daniel. However, third and higher order harmonics is "a rather intricate task", to quote a web page (WWW[7]) related to the European Union ***Similugen*** Esprit Open Long Term Research project (WWW[8]). In this project they have investigated the use of spherical harmonics for defining directional illumination if visual rendering systems, a clearly related task. They note that no solution to the problem of simple generation of the required rotational matrices had been found in 1995, but that this had been solved by 2000,the date of the web page. Unfortunately they give no further details, either on the web page or in the publically available documentation from the project.However, a search of the literature in another field which uses spherical harmonics extensively, Chemical Physics, yielded a paper by Choi, Ivanic, Gordon and Ruedenberg, (Choi et al, 1999) which gives a stable recursive formula for rotations of spherical harmonics which appears to be adaptable to the conventions used in Ambisonics. Work is ongoing to apply this to software capable of working at arbitrary order.

Dominance

Daniel states (Daniel, 2000:166), without giving a proof, that it is not possible to implement versions of the dominance effect above first order using Lorentz transforms without disrupting the wavefront reconstruction process. A numerical proof of this statement is given by Cotterell in his doctoral thesis (Cotterell, 2002:123). Further work is required to identify a suitable transform to provide this useful function for higher order systems. In his section on the topic, Daniel suggests searching for a linear transformation matrix based on the relationships between the associated Legendre functions. Richard Furse, in a private communication, has suggested using a numerical approach to this. He has developed a spreadsheet based method for investigating this although at the time of writing no listening tests had been conducted. One further possibility which would bear investigation would be to spatially oversample the soundfield using a sufficient number of sampling points to avoid spatial aliasing and then to produce a new soundfield by resampling the points using a suitable warping function.

Higher order systems - recent developments.

In a recent development (March 2003), Daniel, Nicol and Moreau (Daniel et Al, 2003) have proposed reformulating Ambisonic B format to remove the limitation implicit in the fact that it is constrained to reconstructing plane waves. The plane wave restriction means that the system cannot deal well with close sources, especially when they are effectively inside the speaker array. The approach taken was arrived at as a result of examining the Fourier-Bessel expression for the pressure field on the spherical surface surrounding a point.

$$p(\vec{r}) = \sum_{m=0}^{\infty} j^m j_m(kr) \sum_{0\le n\le m,\varsigma=\pm 1} B_{mn}^{\varsigma} Y_{mn}^{\varsigma}(\theta,\phi) + \sum_{m=0}^{\infty} j^m h_m(kr) \sum_{0\le n\le m,\varsigma=\pm 1} A_{mn}^{\varsigma} Y_{mn}^{\varsigma}(\theta,\phi) \quad \textbf{(5)}$$

with the wave number $k=2\pi f/c$, where $\boldsymbol{j_m(kr)}$ are the first series spherical Bessel functions and $\boldsymbol{h_m(kr)}$ are the divergent spherical Hankel functions.

The right hand side of the first line of the equation is equivalent to the current Ambisonic formulation for sources external to the loudspeaker array expressed in the frequency domain. The ***B*** coefficients become the gains of the spherical harmonic components if plane wave sources are assumed. The second line describes wavefronts from sources inside the array which are inherently curved and frequency dependent.

$$B_{mn}^{\varsigma} = S \cdot F_m^{R/c}(\omega) Y_{mn}^{\varsigma}(\theta, \delta) \qquad \textbf{(6)}$$

Daniel et Al go on to derive a formula describing nearfield sources with a distance ***R*** from the centre; where the Ambisonic components (or spherical harmonic) ***B*** are given by:where ***S*** is the pressure field at the centre, $\boldsymbol{Y^{\varsigma}_{mn}}$ are spherical harmonics as defined in **(26)** and

$$F_m^{\rho/c}(\omega) = \sum_{n=0}^{m} \frac{(m+n)!}{(m-n)!n!} \left(\frac{-jc}{\omega\rho} \right)^n, with \omega = 2\pi f \qquad \textbf{(7)}$$

The filtering ***F*** indicated by **(32)** is an integration and so has infinite gain at low frequencies. The impracticability of this has meant that this formulation was ignored in the past. However, they go on to show that the spherical wavefront compensation filtering previously discussed in the context of compensating for the effect of loudspeakers being too close to the central listening position (as described by equation **(20)**) can be combined with ***F*** when encoding the soundfield. This produces the desirable result that the filtering no longer has an infinite gain at low frequencies. With this formulation, sources both inside and outside the array can be produced since concave, plane and convex wavefronts can all be (re)produced. The price paid is that the speaker array size has theoretically to be known at the time of encoding. Fortunately, so long as the array size assumed during encoding is known, it is possible to apply a compensating filter prior to decoding which corrects for the difference between assumed and actual array size. This discovery is too new for the current author to have experimented with, but if it proves to be a practicable technology, it will hugely enhance the functionality of Ambisonic systems and provide new opportunities for electroacoustic composers.

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