AN INTRODUCTION TO THE FOUNDATIONS, THE TECHNOLOGIES AND THE POTENTIAL APPLICATIONS OF THE ACOUSTIC FIELD SYNTHESIS FOR AUDIO SPATIALIZATION ON LOUDSPEAKER ARRAYS

P.-A. Gauthier[†], A. Berry[†], W. Woszczyk[*]
philippe_aubert_gauthier@hotmail.com
[†] GAUS (Groupe d'Acoustique de l'Université de Sherbrooke), 2500 boul. de l'Université, Sherbrooke, Québec, Canada J1K 2R1
[*] CIRMMT (Centre for Interdisciplinary Research in Music, Media, and Technology), McGill University, 555 Sherbrooke Street West, Montréal, Quebec, Canada, H3A 1E3

Abstrct. Mainly dedicated to the artists or to the composers interested in the search and creation with networks of loudspeakers which can include up to hundred sources, this article introduces the technology of sound reproduction which is WFS (Wave Field Synthesis). A classification of the methods of spatial sound reproduction is also presented. Within the borders of this introductory text, I hope to expose an innovative technique of spatial sound reproduction, well-known in acoustics or in signal processing, which suffers regrettably from a lack of visibility at the artists or the composers. Such as presented in this review, the WFS adorns itself with many possibilities and openings for spatial compositions. The most fascinating aspects of this technology come from the fact that traditional spatial mixing (as with the case of "Surround 5.1") is no more realized by a sound engineer or the composer. Sometimes lengthy and fragile, this process is now automated – on the basis of physical principles – and creates a link between the virtual description of an acoustic scene, prescribed by the composer, and the network of loudspeakers, which is the reproduction system. Finally, this technique produces the reconstruction of the virtual sound field over a vast zone of the reproduction space. Because WFS is considered as a most promising solution for the near future, the composers or the artists interested by the broadcasting and the spatial composition on loudspeaker arrays, will surely be informed by this brief introduction to the subject.

INTRODUCTION

Monopolized by research activities on multimedia presentation and representation, the protagonist of such researches will be inevitably confronted with the very complex problematic of multisensory reproduction. The problem is complex in the sense that sensory modalities are coupled: subjected to a certain hierarchy and included in a structure of influence. This technological problem of multimedia reproduction can, to reduce the complexity level of implied parameters, be returned to its individual sensory constituents. So, according to this relaxation of the problem and as regards the technological objective of the spatial reproduction of the sound, many works were led by the researchers during the last decades.

At this stage, the definition of the audio spatialization to which we adhere should be introduced. This definition is not limited to the perfect reproduction of the sensation felt in a natural situation (to reproduce the sound quality of a place or event) recorded by some means, it rather takes its base in reproduction of the quality of the natural sensory immersion (envelopement, coherence, realism). Briefly stated, with sound spatialization, one will be able to say that one tries to create an auditive sensation which tries to utterly reach the quality of the natural sensory immersion.

Amid researches made on the subject, it is possible to introduce a first dichotomy for the main possible approaches. The first class of methods is the simulation of the perception and the second, according to a school of thought which answers the interest to reproduce a sound field on a more or less spreaded zone, is the simulation of sound fields. This first distinction of two general approaches is represented in the Figure 1 and can be easily illustrated by some practical examples.

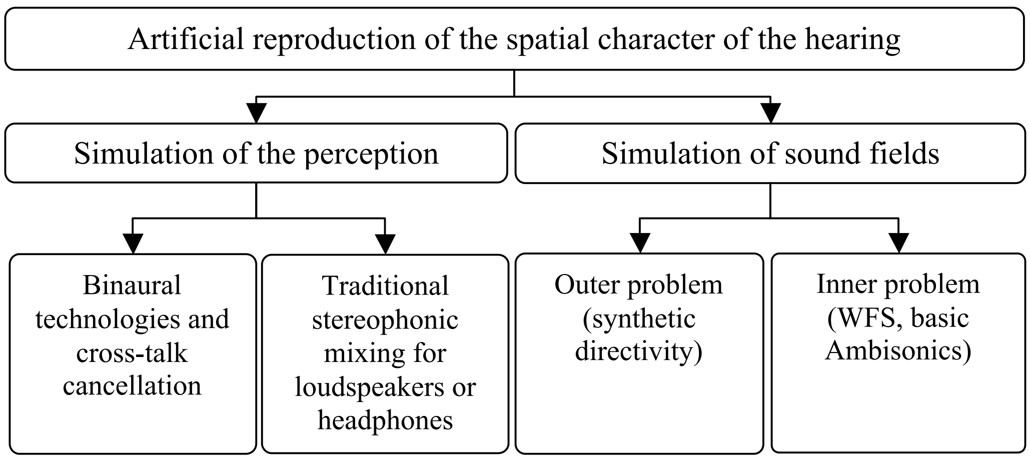

Fig. 1 – Classification of functional approaches and schools of thought in artificial reproduction of the spatial character of the hearing.

As an example, the set of what is usually identified as binaural technologies belongs to the simulation of the perception. Such technologies suppose, with reason, that the sole reproduction of the acoustic pressure at the eardrums of the listener can be effective for the reproduction of an auditive spatial impression. The validity of this hypothesis rests on a well-known and verified fact. One knows indeed that a frequency-dependant filtering operates on the sounds which goes to the ears according to their direction of arrival (with regard to the external ear which includes the bust, the head and the pinna). This filtering, essentially attributable to the external ear, includes binaural indications which allow the auditive location of the acoustic sources because binaural signals are slightly colored according to the direction of arrival and according to the distance. This slight coloring allows to localize unconsciously the acoustic sources. Binaural technologies[1] for the spatial sound reproduction thus belongs to the simulation of the perception because this solution includes a part of the chain of the auditive perception, which is, in that case, the external ear. Cross-talk cancellation also belongs to the binaural techiques. Cross-talk cancellation, some time identified as transaural stereo, is requested while one wish to cancel the cross-talking between the left loudspeaker and the right ear of a listener. Once this is done, standard loudspeakers with cross-talk cancellation can act as a remote

[1] These can include: binaural recordings with manikin, binaural synthesis or binaural filtering of direct sound recordings by the measured impulse responses of external ears.

headphones for binaural reproduction. The conventional techniques of sound recordings and stereophony base themselves as for them on the observation, or the more or less empirical knowledge, of perceptive phenomena to establish guidelines for manual mixing (as for phantom imaging by means of intensity stereophony or time stereophony). Once again, a part of the chain of the spatial perception of sound is taken into account by means of perceptive experiments and observations resulting from a given set of "typical audio" actions (like gains or time delays). This also motivates the belonging of conventional stereophony to the broader simulation of the perception approach.

Few systems base themselves on sound field simulation because the technological and the implied physical concepts are usually more complex and require a fundamental background in acoustics and signal processing. In practical situation, the number of reproduction sources and the signal processing implied in sound field simulation are both more important than those evoked by the simulation of the perception. Such as mentioned quickly earlier, the appropriate hypothesis for the simulation of sound fields is the following one: by reproducing a sound field in the reproduction space (or in a more or less extended part of that space) with a faithful spatial distribution of the sound pressure, a complete hearing system (including natural filtering by the external ears) will be subjected to a physical stimulus which correspond to the virtual stimulus, that is the one that one tries to reproduce. Clearly, such a task presents a more physical nature and can not be reached by the sole theoretical or intuitive understanding of the spatial sound perception. Given the number of sources and the necessary signal processing, one can understand the lesser popularity of sound field simulation. "Wave Field Synthesis" (WFS), as its naming suggests, is a method intented for sound field simulation because the system tries to reproduce (objectively or, in a less ambiguous way, physically) a sound field prescribed for a zone surrounded with loudspeakers. Basic Ambisonic reproduction is also a sound field simulation since a sound field is partly recreated at the center of an Ambisonic surrounding loudspeaker array. The creation of a synthetic directivity pattern around a reproduction source, which can include several loudspeakers, is also an example of technology which belongs to the simulation of sound fields. It is important to note that these two problems present a fundamental complementarity. The first type (sound field reproduction inside a network of sources, as for the WFS) is an inner problem and the second type (synthetic directivity reproduction around a complex acoustical source) is a problem which one could qualify as outer. This new division, which may seems purely descriptive, has important repercussions on physics and technologies implied by these two additional objectives.

In this hierarchy, the place of the broadcasting on multi loudspeakers systems does not hold in a single specific compartment. The naming "multi loudspeakers" is, although conveniently and effectively used in many situations, too generic for it. It can indicate: a broadcasting on "Surround 5.1", the perception simulation or even the usage of synthetic directivity sources arranged on a stage for a loudspeaker concert. Going further, the simultaneous presentation of audionumeric material, varying according to respective canals, on a series of headphones, could receive this same naming of broadcasting over multi loudspeakers system. So, although it is difficult to exactly attribute parts of the organization of the Figure 1 to the presentation on several loudspeakers, this expression resonates for many musical practices and completely finds there its utility.

With the exception of certain combinations and possible hybridizations, the classification of approaches such as presented in Figure 1 regroups the set of possible, even conceivable, technologies in audio spatialization. One notes on the other hand that such a taxonomy is not massively used; so, according to the possible view points, other qualifiers can be used to build classifications which could focus on obtained results (system in two dimensions, three dimensions, homogeneous or heterogeneous distribution of reproducible directions, etc.).

PURPOSES AND PRACTICAL DEFINITION OF WAVE FIELD SYNTHESIS, AN EXAMPLE OF MULTI LOUDSPEAKERS SYSTEM

WFS is a specific application of the sound fields simulation. It is moreover this specificity which motivates here the usage of its acronym WFS rather than "wave field synthesis" to reduce confusion among WFS and sound fields simulation.

Before even revealing the details of WFS, let us suppose a priori that it would be sought to reproduce a progressive spherical wave[2] which would emanate from a prescribed position. This simple definition, a source of spherical type in such a position, would be so the virtual scene. This virtual source should be fed with an audionumeric stream. It is the physics of the waves which is going to allow one to establish the core of WFS. This core is the treatment of digital signal which has to connect, automatically and in real time, a monophonic audionumeric stream with an important series of loudspeakers to obtain the sound field attributable to the wished virtual source. Although these remarks are formulated for an unique virtual source, a complex scene is obtained with the simple accumulation of virtual sources.

It is to reproduce a sound field on a vast zone, which could include an audience in movement, that WFS was initially introduced. In the original formulation and according to the most simple usage, WFS supposes that the reproduction space (where is the sound system and the audience) is an anechoic space, that is without echo or acoustic reflection by walls or objects in the reproduction room. This simplification, which obviously does not correspond to the reality of a studio, a concert hall or a listening room, simplify enormously, but in a necessary way, the development of the theoretical bases of WFS technologies. In spite of the important approximation attributable to the supposition that the space of reproduction is anechoic, this hypothesis of free field (that is a reproduction space without obstacle or reflection) is justifiable due to an observation concerning spatial perception of sound. What is named the precedence effect in auditive localization shows us that the spatial construction of an auditiry scene[3] can cancel the influence of reflections (auditory localization operates according to the direction of arrival of the first

[2] One could define this type of wave by means of a more or less exact but nevertheless illustrative analogy: as circular waves in the surface of the water leaving a point where an object would be thrown.
[3] The definition of an auditory event corresponds here to that introduced by Blauert [1]. An auditory event is the sensory results of an acoustic event.

wave front in a coherent series of fronts[4]), as far as these last ones are not too delayed in time [1]. During the reproduction on WFS system, the hearing system compensates and cancels perceptive effect attributable to reflections by means of this precedence effect. But in practical situation, these reflections, which still physically exist, can damage the objective and subjective reproduction, notably about the reproduction of the acoustic reflections of a virtual place using WFS. A part of current researches on WFS concerns this aspect of spatial sound reproduction, it is the room compensation.

Again from a practical view point, the listening zone is surrounded with a linear loudspeaker array (within the horizontal plane for two-dimensional reproduction) separated by a small distance to finally reach such a spatial reconstruction of a virtual field by means of WFS. For a listening zone covering 12 square meters (a circle of about 5.5 meters in diameter), one could have 100 loudspeakers which would form a belt around the audience. In practice, this distance of separation is simply limited by the size of transducers. The more sources will be putted closer, the more WFS will be spatially effective at high frequencies. In fact, at least two sources have to be used by the smallest wavelength of interest. In the previous example of 100 sources, WFS would be effective only below about 1kHz. It, demonstrating itself with some mechanisms of sound perception which go beyond the scope of this introduction, is sufficient – from subjective point of view – in qualitative terms of reproduction.

This first section reviewed the tangible and visible part of WFS. The next section presents the evoked principles to carry out the synthesis.

THEORETICAL FOUNDATIONS OF WFS

Such as mentioned earlier, the functioning of WFS is based on waves physics to achieve spatial sound reproduction. The problem of the spatial reproduction is exactly defined as follows for WFS (or for any other method of sound fields simulation): the objective is to reproduce the detail (both amplitude and phase in the space) of a virtual sound field (it is usually defined virtually) on a vast space.

Let us see now how the WFS leans on physical notions to realize the reconstruction of a virtual field. Let us first revisit quickly the physical notion of the sound. Sound propagates in air as waves, sound waves in that case. These waves are small oscillations of the medium which are passed on from particles to particles until the wave reaches our ears. Sound waves propagate in three dimensions and not in two dimensions as waves at the surface of water. In spite of the fact that images presented in this article are essentially sections in two dimensions, it is necessary to not forget this tridimensional reality. Waves propagate at the speed of sound, this is not the case of the vibrating air. The oscillations of the medium are passed on from neighbour to neighbour without any transport of matter from the acoustic source to the listener. As a starting point, it is the

[4] A coherent series of wave fronts would correspond for example to the arrival of a first impulse (directly from the source of impulse) and a series of other fronts (delayed in time and of reduced amplitude) arising from the reflections of the original impulse on walls and objects. This series of wave fronts would form a coherent series of wave fronts.

Huygens's principle (or the secondary sources principle) which suggests the idea to reproduce a sound field by surrounding the listening zone with reproduction sources.

Of course, Huygens's reasoning (which have been formulated sometime in 17-th century [2]) does not directly concern spatial sound reproduction, it stipulates simply that it is possible to recreate a wave field by replacing a wave front to be reproduced (originally created with a primary source) by a continuous distribution of sources (the secondary sources) on the original wave front. By acting so, by means of this mental experiment, it swould be possible to drop the primary source because the cumulative contribution of the secondary sources recreates the wave front originally attributable to the primary source. "Every particle (P) of the medium crossed by a wave communicates its movement, not only to the nearby particle (P') which is aligned with (P) and the source [of the wave] (A), but also to the other particle (P'') which touches (P) and which opposes to its movement. So that it is necessary that around every particle there is a wave of which this particle will be the centre [3]." This was Huygens's original proposition which, conjugated with Figures 2 and 3, is more easily understood. In Huygens's proposition, particle (P) corresponds to the secondary sources and the source (A) is in fact the primary source.

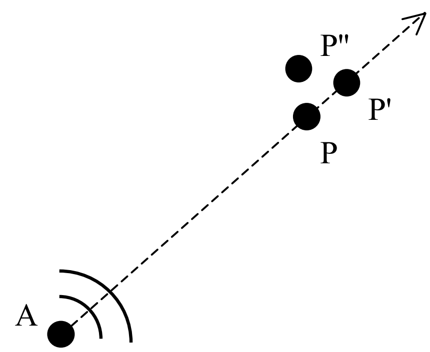

Fig. 2 – Illustration of Huygens's statement.

Although the secondary sources principle lets suppose that its validity is only verifiable when the secondary sources are placed on the wave front to be reproduced (see the left part of Figure 3), it is also possible to place the secondary sources on any surface. This could be a line, such as shown in the right part of Figure 3. This type of configuration is obviously more practical and flexible for real technological applications. In practice, the continuously distributed secondary sources are thus replaced by a finite number of real sources, electrodynamic loudspeakers for example.

Knowing that the possibility of replacing a real source by a network of reproduction sources is valid, we are entitled to wonder how, practically, can one reproduces an audionumeric recording with such an application. To obtain an answer, it would be at first necessary to know how to feed the secondary sources which have to replace the primary source. One finds the essence of the answer to this problem by using the mathematical formulation of the Huygens's principle. The principle shows itself by means of a integral formulation: the Kirchhoff-Helmholtz's formula which allows one to find which amplitudes and phases of the reproduction sources (the secondary sources)[5]. Knowing these amplitudes and these phases as function of frequency for the position of a given virtual source and the position of a given secondary source, this couple (amplitude and phase) defined in the frequency domain is transformed in the time domain to finally define a filter which could be realized by means of conventional digital signal processing being able to be realized on a personnal computer. A complete WFS system could so includes between two and ten conventional PC, depending on the size of the loudspeaker array. Between every virtual source and every loudspeaker, a synthesis operator must be implanted such as illustrated in Figure 4 where *WFSi* represents the synthesis operator (who handles an audio stream from a wave file defining the sound to be reproduced in a prescribed virtual position) for the loudspeaker *i*.

WFS includes some supplementary hypotheses in this seemingly very simple development. Here introduced explanation is in fact very summary, even rough, but illustrates the physics behind WFS. The reader interested in great detail by the development is invited to consult references.

WFS can be related with other spatial sound technologies. Historically, WFS was introduced by Berkhout in the late 80s and at the beginning of the following decade [4]. The idea was not new since the concept of the "holophonie" had been introduced by Jessel in 1973 [3]. WFS proposition by Berkhout is in fact a specific application of holophony which is a theoretical concept which we silently touched earlier during the evocation of the Kirchhoff-Helmholtz formulation. Besides, it was demonstrated in the late 90s that Ambisonic reproduction and its equations (for basic encoding and decoding) could be derived from holophony. This establishes a considerable link betwen holophony, WFS and Ambisonics, because basic Abisonics is a particular case of the holophony, in the same way as WFS is another particular case of holophony [5].

[5] In fact, Kirchhoff-Helmholtz allows to replace an acoustic universe beyond a surface (S) closed around a listener by a similar surface covered with sources with omnidirectional and bidirectional radiation pattern. It is exactly the theoretical idea of holophony.

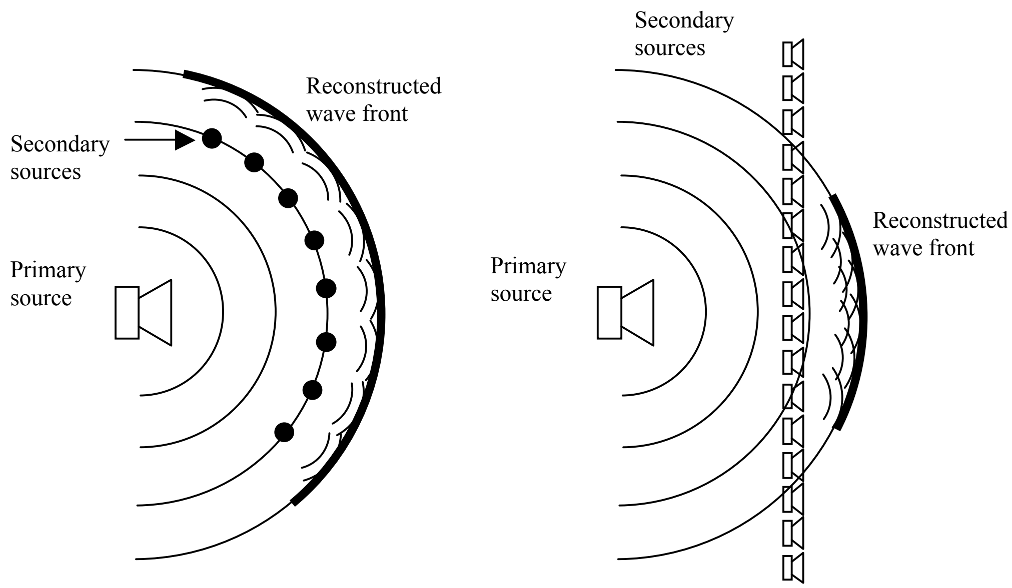

Fig. 3 – On left, the Huygens's principle of construction. On right, the principle of construction applied to sound fields reproduction by means of practical and real sources.

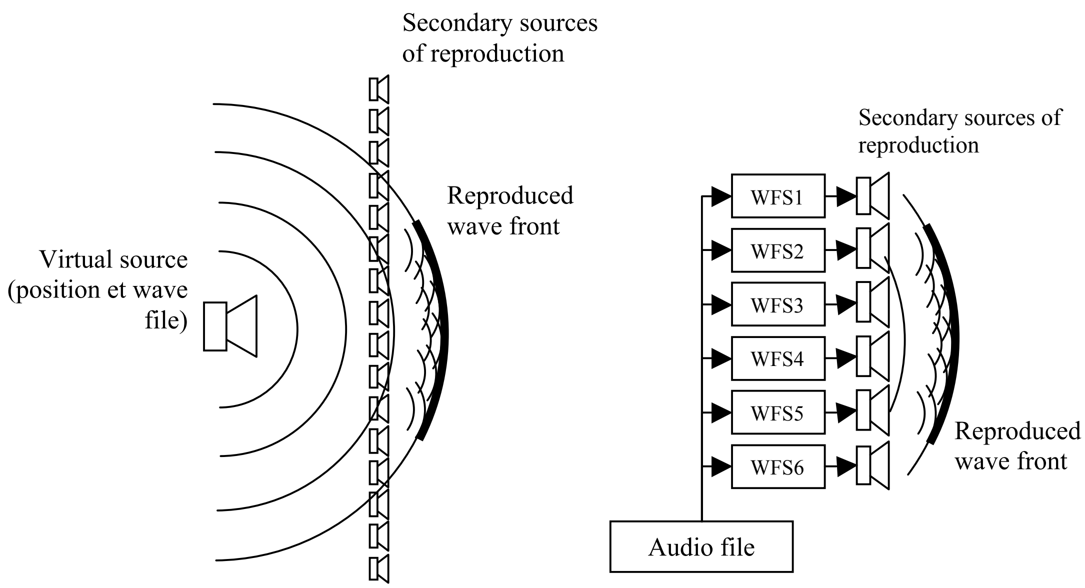

Fig. 4 – On left, the principle of construction of Huygens applied to the reproduction. On right, a simplification of the realization of WFS for a single virtual source.

Conventional stereophony can even, under the exercise of some limitations, be considered as a version of the WFS. So, by placing two omnidirectional sources (loudspeaker cabinet at low frequency) in the same relative positions which were used during the sound recording with bidirectional microphones, a sparse version of WFS or holophony would be reached. By pursuing this exercise by adding more and more sources and corresponding microphones, this experiment would aim gradually towards WFS and holophony.

REVIEW OF POTENTIAL APPLICATIONS FOR WFS

Now that physical and technological notions supporting WFS were briefly reviewed, let us see what is the main interest while reproducing simple virtual sources (spherical waves or plane waves). Figure 5 proposes an example of virtual scene formed with three sources of different type. As one can see, the movement of the listener engenders a change of perspective – of the view point – on the scene. This possibility forms one of the main interests of the sound fields reproduction because the virtual scene and the movements of the listener are now coherent. There is no region of optimal listening (the sweet spot) and the audience is from then on subjected to a substantial virtual world correctly distributed in space. With the spherical sources (S1 and S2; S2 is a spherical wave reconstructed in front of the real sources, that is the focus of the acoustic energy), it is possible to create perceptible effects of distance and direction. The possibility of reconstructing a virtual source in front of the real sources introduces an other one of the most attractive aspects for spatial sound creation, notably about the dynamism in the time which can be radically modulated from intimacy to long distance. With plane wave S3, only the direction of incidence is definite. It does not change with movements of the listener. So, a movement of A towards B will always give a source perceived at +30 degrees in that case. An example of typical application requires the usage of a virtual spherical source in front fed by a direct sound recording of an acoustical instrument and eight plane waves (spreading on 360 degrees) fed by an artificial or natural reverberation to recreate an effect of virtual room which is certainly different of the acoustical character of the reproduction room.

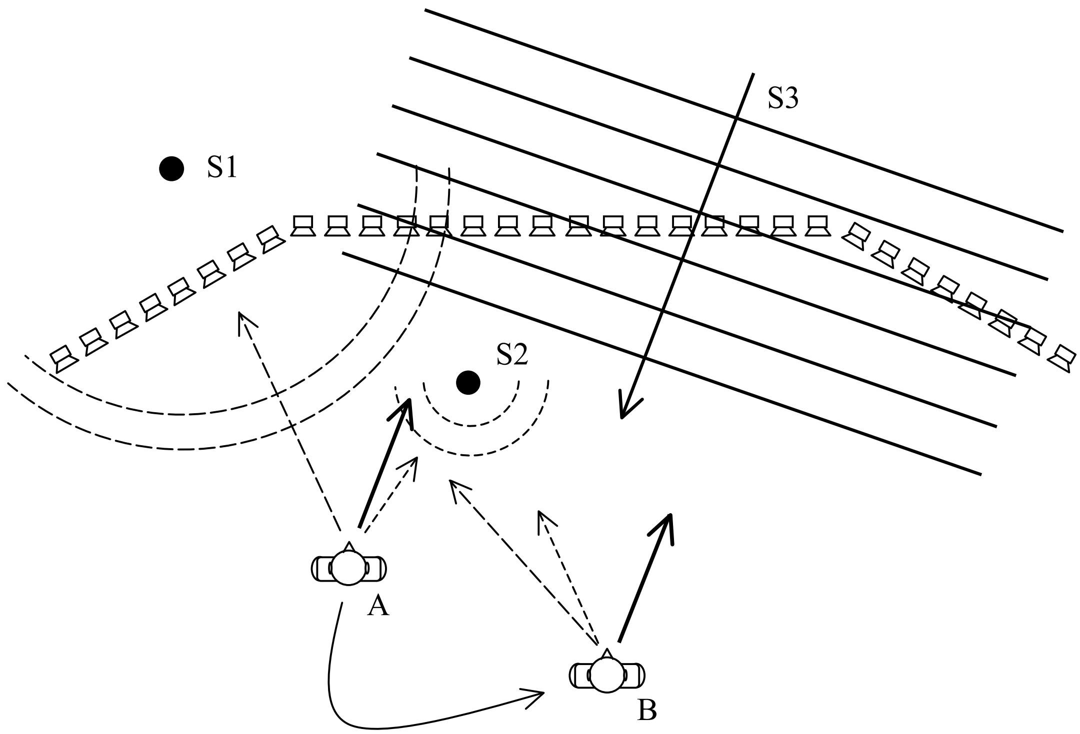

Fig. 5 – Illustration of a virtual scene formed with a spherical source S1, a spherical source focused in S2 (in front of the loudspeaker array) and from a source of plane waves S3. The listener can be in two positions (A or B) for which the perceived directions of the virtual sources are represented with arrows with graphical displays corresponding to the virtual sources.

The fact that plane progressive waves do not imply a change of direction of the auditory event with the movement of the listener reveals a latent and interesting application of WFS: that is the easy recovery and improved broadcast of stereophonic material (two-channel stereo, "Surround", etc.) by means of plane virtual sources representing loudspeakers in a standard angular configuration (2-0.0 , 3-2.1, etc.)[6]. For which an art work would have been initially created. Figures 6 and 7 present two solutions for such a broadcast of multitrack programs. While the first offers similar sensations for the entire audience, the second proposes appreciably the same effects as with a real multi loudspeakers system (an optimal listening zone of limited extent also known as the "sweet spot"). In both cases, this type of approach introduces what is sometimes called "Virtual PANning" or VPAN. Conventional audio mixing (stereophony, stereo sound recording techniques, etc.) is virtually applicable by means of the VPAN with WFS. The conventional techniques of mixing, skilfully mastered for years, are not dilapidated but propelled well towards the flourish of their known current usages. Obviously, it is also easy to represent a 3-2.1 system or even another of generic type *x-y.z*. The compatibility of WFS with the other multichannel formats is so very flexible.

[6] We adhere to the following notation: *x-y.z* where *x* is the number of front channels, *y* the number of ambiance channels ("Surround" or back channels) and *z* the number of low frequency channels [6].

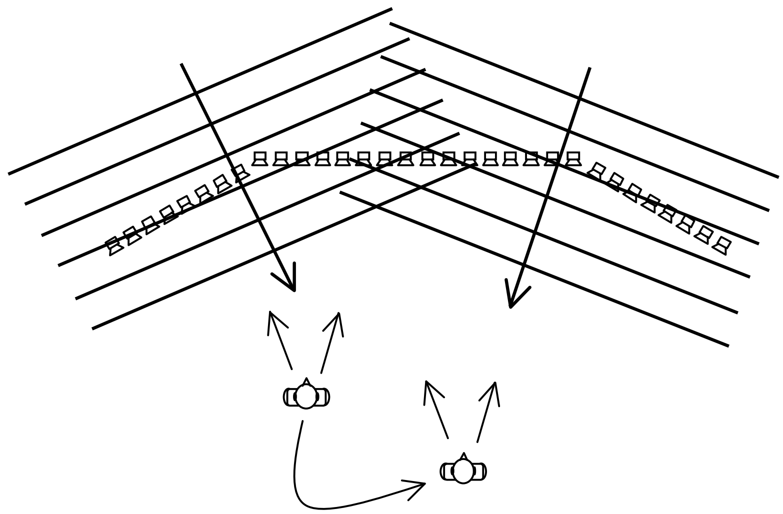

Fig. 6 - Realization of a virtual scene presenting a compatibility with stereophony 2-0.0 by means of virtual plane waves. The two auditors perceive the same directions of incidence.

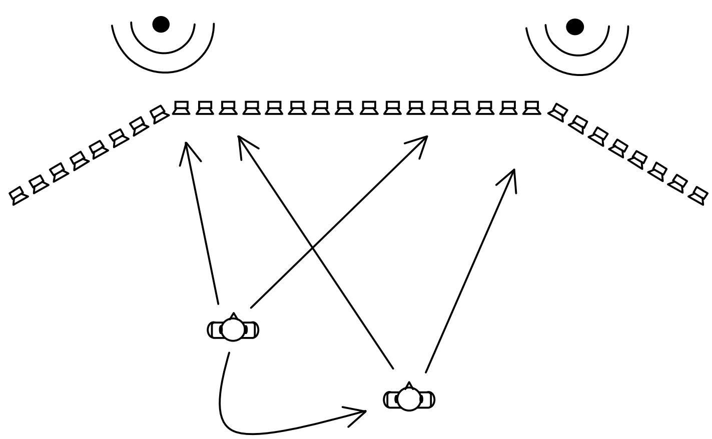

Fig. 7 - Realization of a virtual scene presenting a compatibility with stereophony 2-0.0 by means of spherical waves. The "sweet spot" arise: according to the position of the listener, the perceived effect varies.

As it is possible to imagine, the potential applications of WFS are vast. In concert hall, cinema, audio presentation with more or less big display and, obviously or even especially, in music broadcasting, the acquired latitude by the use of such technology is well beyond the simple realism of reproduction and immersion: it offers an access to expressive novelties as moving virtual sources in two dimensions, sources which not correspond to real sources, virtual room atmospheres (a diffuse or reverberating field is approached, or at least its sensation, by adding for example about ten plane waves) and the artistic search for the spatial perspective or for the relative character of the view point of the audience on the scene. WFS and the group of sound fields simulation is gone, if it is not already begun, to modify profoundly the bases of the spatial sound composition.

RESEARCH, DEVELOPMENT AND TECHNOLOGY

Since the theoretical formulation of the technological concept of WFS, many researchers have worked on the reproduction of sound fields. It is necessary so to admit that this brief introduction to the concept of WFS was not exhaustive: many other technical details characterize the WFS some of which reduce the quality of the reproduction, notably to what is connected with the effect of the reproduction room and with the spatial distribution of the reproduction quality in listening zone. It is for correcting these gaps that are engaged a good part of current researches on WFS or the reproduction of sound fields. These obstacles do not compromise the quality of the classic WFS, such as it is here described, but establish the tangentes of research for the improvement of the spatial reproduction over loudspeaker arrays.

So, as example, we published the first results of our researches on the reproduction of progressive sound fields in room [7]. Among important results, it was demonstrated that it is in theory possible to recreate progressive sound fields in a lightly damped place which presents so a strongly modal dynamics at low frequencies. To reach such a reproduction, two physical mechanisms were identified: acoustical power absorption by certain sources and the rearrangement of the room's modal response. This type of observations suggests new technological avenues for the future.

A big part of recent researches in WFS were realized in Europe by the research consortium CARROUSO which included Delft Polytechnic University (the place of birth of WFS), IRCAM, the Fraunhofer institute and other groups which are maybe less known in North America [8]. The researches covered a considerable number of subjects: signal processing, synthetic directivity of virtual sources, movement of the virtual sources, visual computer interfaces, various reproduction sources (electrodynamics, directivity, invisibility, panel sources), subjective evaluation of the spatial perception of WFS and room compensation. According to the set of technological developments proposed by CARROUSO, commercial applications are eminent and will be certainly launched by protagonists of the ancient consortium. Fraunhofer proposes a commercial application of WFS baptized IOSONO. Many effort are also devoted to value the idea of WFS, notably by means of frequent demonstrations and presentations in international conferences and conventions of the AES ("Audio Engineering Society").

This brief outline demonstrates activity and liveliness of the research and the development of WFS or sound fields simulations. Such an activity lets hope for a multitude of debates and real applications for the years to come. It is likely so as technology succeeds in settling down profitably in some domains of application.

FUTURE OF SPATIAL DESCRIPTION

Advent and standardization of new formats of structured multimedia data as MPEG-4 will be also one of the key operators in the development and the blooming of the spatial sound reproduction. This type of data formats, which can obviously contain audio tracks without any data compression, allows to include instructions of signal processing and descriptions of virtual scenes. For this reason, MPEG-4 formats held attention of those that are concerned by the interaction with a virtuality [9-11]. With such an approach one speaks of *spatial encoding* and not of *channel encoding*. Contrary to the time when traditional methods of stereophony (channel encoding) where used (this implied mixing operations on a variable number of channels to manually reach the wished scene), the composer who will work from then on with spatial encoding will be a lot closer of the virtual scene which he tries to describe. Contact between the work and his creator should be more immediate with the spatial encoding. Finally, it is the reproduction system which will handle the virtual scene decoding to present it to the audience.

It is now interesting to return back to Figure 1 which had initially put a certain classification on the possible methods for the reproduction of the spatial character of the auditory experience. So, about the future of such technologies, one can question about the compatibility, about the complementarity or even about the competitive fight between simulation of sound fields and simulation of the perception. At this time, opinions are various. Some preach only by the simulation of the perception while the others believe only in sound fields simulation. Roughly, when a sound system addresses a single listener, the simulation of the perception is surely the most attractive because it remains simple to realize with a minimum of equipment and specialized knowledge. Obviously, for a system addressing a complete audience, it would be more effective to seek for sound field simulation. Knowing that the major benefit in favour of the simulation of the perception is essentially the simplicity of its implementation and that in presence of a complete audience such a type of simulation should inevitably include a tracking device to take into account the movements of each auditors (here making reference to binaural technologies), it is clear that a threshold of complexity equivalent to that of the simulation of sound fields is fast reached. As an example, it is an argument in favour of the reproduction of sound fields for concert applications.

CONCLUSION

It is now necessary to admit that WFS is neither a utter or perfect solution. This brief statement was not a simple favoritism for this specific technology – which appears as one of the most important for the near future – but rather its simple presentation. Forgetting the interest and the utility of real sources (acoustical or electroacoustical) and the power of sound installations would be very distressing since representation, and even the meaning, of real sources can play an original role for some artistic works [12,13]. In the big family of broadcasting over multi loudspeakers systems, WFS presents on the other hand advantages of the most considerable: the possibility of creating complex virtual scenes by means of the spatial encoding and the consequent opening towards the compatibility with well-known loudspeaker layouts (2-0.0, 3-2.1) on which already depends a considerable amout of electroacoustic works.

In fact, the detail of the technologies matters little in a context of creation. Flexibility, expressiveness, immateriality or transparency of the media and immortality of art works are maybe the most appreciated and valuable characters. The future should supply such characteristics because researches abound in these ways, and the synthesis of sound fields called WFS is one of the convincing means to lead us towards these characteristics.

This introduction should be taken as a very general and rough presentation of the subject, the reader is so asked to relate to references for more information about WFS. Verheijen's thesis is an excellent and complete work on the topics [14]. Other references are introduced as additional resources [15-18].

REFERENCES

1. J. Blauert, *Spatial Hearing, The psychophysics of human sound localization*, The MIT Press, 1999.
2. W.W. Rouse Ball, *A Short Account of the History of Mathematics*, Dover publications, 1960.
3. M. Jessel, *Acoustique Théorique : Propagation et Holophonie*, Masson et cie, Paris, 1973.
4. A.J. Berkhout, D. de vries, P. Vogel, Acoustic control by wave field synthesis, *Journal of the Acoustical Society of America*, 1993, vol. 93, no 5, p. 2764-2778.
5. R. Nicol, M. Emerit, 3D-sound reproduction over an extensive listening area: A hybrid method derived from holophony and ambisonic, *Proceedings of the AES 16th international conference*, 1999, p. 436-453.
6. F. Rumsey, *Spatial Audio*, Focal Press, 2001.
7. P.-A. Gauthier, A. Berry, W. Woszczyk, Sound field reproduction using active control techniques: Simulations in the frequency domain, présentation invitée et cahier des actes, *International Congress on Acoustics*, Kyoto, Japon, 2004.
8. S. Brix, T. Sporer, J. Plogsties, CARROUSO – An European Approach to 3D audio, *AES Convention paper*, 2001.
9. P.R. Cook, *Real Sound Synthesis for Interactive Applications*, A K Peters, 2002.
10. J. Plegsties, O. Baum, B. Grill, Conveying spatial sound using MPEG-4, *Proceedings of the AES 24th international conference*, 2003, p. 58-65.
11. E.D. Scheirer, Structured audio and effects processing in the MPEG-4 multimedia standard, *Multimedia Systems*, 1999, vol. 7, p. 11-22.
12. M. Trochimczyk, From Circles to Nets: On the Signification of Spatial Sound Imagery in New Music, *Computer Music Journal*, 2001, vol. 25, no 4, p. 39-56.
13. S. Wilson, *Information Arts – Intersections of Art, Science, and Technology*, The MIT Press, 2002.
14. E.N.G. Verheijen, *Sound Reproduction by Wave Field Synthesis*, thèse de doctorat, Université Technique de Delft, 1998.
15. M.F. Davis, History of spatial coding, *Journal of the AES*, 2003, vol. 51, no 6, p. 554-569.
16. E. van der Heide, *A world beyond the loudspeaker*, http://utopia.ision.nl/users/heide/world_beyond.html.
17. G. Theile, H. Wittek, M. Reisinger, Potential wave field synthesis application in the multichannel stereophonic world, *Proceedings of the AES 24th international conference*, 2003, p. 43-57.
18. D. de Vries, R.Boone, Wave field synthesis: new improvements and extensions, *Proc. of the 18th International Congress on Acoustics*, 2004.