PhD defense talk

**Title slide**

Welcome in my phd defense, in the next 20 minutes I will summarize my main results concerning the field of sound field synthesis.

**Slide 2**

So, first of all, several words about thebackground of my research, and generally about the aim of sound field synthesis: Generally speaking the aim of sound field reproduction is the recreation of sound scenes, containing several audio objects by driving an arrangement of loudspeakers, so that the superposition of waves, emerging from the loudspeakers create the impression of the desired audio scene.

Traditional techniques, like stereophony –which is actually still the audio rendering method for the state-of-the art commercially available sound systems nowadays---achive this by reconstructing „binaural cues”, like interaural time and level differences in the listener position.

As a consequence, correct localization of sound can be achieved with these techniques in one particular listener position, termed as the sweet spot.

Loosely speaking the aim of sound field synthesis is to extend this sweet spot, and ensure accurate localization over an extended region. Once it is achieved it is inherently ensured that the perfect acoustic illusion is created everywhere in the listening area.

**Slide 3/a**

In order to perfectly reproduce an arbitrary target, or so called virtual sound field over the listening region, a densely spaced loudspeaker array is employed, termed as the secondary source distribution, bounding the listening region.

In practical scenarios the listening region is a horizontal plane in the height of the listener’s ear, thus the secondary source distribution is a contour. The basic task in sound field synthesis is to find the driving signal, or the so called driving function for the SSD in order to reproduce the target sound field.

**Slide 3/b**

Mathematically the synthesized field inside the listening region can be written as the sum of the sound fields of the individual secondary source elements, weighted the driving function to be found. Supposing a theoretical continuous secondary source distribution the synthesized field is given by a convolution above the SSD. Therefore, if we know the target sound field and the field of the secondary source elements the general sound field synthesis problem is an inverse, or deconvolution problem.

**Slide 4**

There are several approaches in order to find the required driving functions.

One approach is the so called explicit solution, which aims at the direct solution of the inverse problem, by transforming the synthesis equation to the spectral, or wavenumber domain.

As a consequence, compact driving function formula in the spatial domain, that could be applied directly for sound field synthesis is rarely available.

Also, the required transform exist only in particular geometries, like for a theoretical infinite linear SSD, in which case the approach is termed as the Spectral Division Method, or for spherical or circular secondary source distribution, in which case the solution is refered to as Nearfield Compensated Higher Order Ambisonics

As an alternative, so called implicit solution exists, termed generally as Wave Field Synthesis, which loosley speaking is based on the Huygens principle, or more precisely relies on boundary integral representations of sound field. which boundary integrals implicitly contains the required driving functions.   
This technique is the basic topic of my dissertation.

**Slide 5**

So, after this short introduction now I summarize my results, presented in my four thesis groups, starting with the introcuction of my generalization of Wave Field Synthesis theory.

**Slide 6**

So, just to say a very few words about, how i got the results: My derivation started out from the 3 dimensional Kirchhoff approximation, or integral, describing an arbitrary 3 D sound field in terms of a surface integral in the high frequency region. Henc, the following WFS related results all assume high frequency conditons.

As we can see the Kirchhoff integral would implicitly contain the 3D driving function for a secondary source surface. Our aim now is to reduce this surface integral into a contour integral, containg the driving function for a secondary source contour.

This dimensionality reduction can be performed by applying the so-called stationary phase approximation, which serves as a central tool throughout my research. The SPA basically allows one to evalutae integrals asymptotically around critical points, termed as the stationary point.

**Slide 7**

In order to easily find this stationary point for integrals I introduced the so called local wavenumber concept.

The local wavenumber vector is well known quantity in the field of high frequency acoustics and ray acoustics, although there it is often known with different names, but has not been introduced in the field of sound field synthesis so far.

The vector is defined as the vector, pointing into the local propagation direction of the sound field, hence it is perpendicular to the wavefront at each position.

Also it constitutes a local plane wave approximation of sound fields, and at hih frequencies it satisfies a local dispersion relation, but what is more important in the aspect of my thesis is that it gives us a very simple interpretation for the location of this stationary position for the spa of boundary integrals and spectral integrals.

**Back to slide 6:**

So as the result we can reduce the 3D Kirchhoff integral to a contour integral, which contains the so called 2.5D WFS driving functions implicity, however, and that’s a key point: due to this dimensionality reduction this driving function can synthesize an arbitrary soundfield on at opne single receiver position amplitude correctly, termed the reference point.

Here the expression 2.5D refers to the fact that we use 3D point sources on a 2D contour of secondary source distribution to synthesize a 3D target sound field over a 2D receiver plane.

**Slide 8**

In order to arrive at driving functions ensuring optimal synthesis not only at one reference point, I applied the stationary phase approximation once again, now to the 2.5D Kirchhoff integral along the horizontal dimension. As a main result for my first thesis group I arrived at generalized, or unified Wave Field Synthesis driving functions that are capable of the synthesis of an arbitrary virtual sound field, propagating in the plane of synthesis using an arbitrary shaped convex SSD, and ensuring amplitude correct synthesis over a convex curve, I termed as the reference curve.

**Slide 9**

As a simple exampe we can see here the result of the synthesis of a 3D virtual point source, by applying a standard potato shaped SSD. The position of the virtual source is denoted by black dot. The left figure shows the real part of the synthesized field, while the right side shows the absoulte erre of the synthesis illustrated in a decibel scale.

We can see that inside the listening region the phase, therefore the shape of the wavefronts can be reconstructed perfectly. The figure, showng the error verifies that over the reference curve the error is minimal, therefore the amplitude of the synthesized field is optimized on this curve.

Obviously, one cannot ensure perfect synthesis over the entire reference curve, but on only that part, which is visible from the position of the virtual source.

**Slide 10**

So far I haven’t talked about previous approaches. Of course, there are several previous WFS theories, the most prominents often termed as the Traditional WFS and Revisited WFS theory.

The present table shows a comparison on the features of the WFS approaches under discussion.

What we can see here is that previous approaches could only synthesize specific virtual source models with specific SSD and reference curve shapes.

So, for example, the original, or traditional Wave Field Synthesis only considered 3D point sources, as virtual sources, by applying a linear secondary source distribution, and the reference curve wasa a line, paralllel with the SSD.

On the other hand, revisited Wave Field Synthesis allowed the synthesis of an arbitrary 2D wave field (invariant along the vertical dimension), by applying an arbitrary shaped SSD? Referencing the synthesis to a reference point.

Therefore, my generalized, unified WFS theory contains all these previous approaches as special cases.

**Slide 11**

To summarize my first thesis group with the subtheses I gave in my thesis booklet:

**Slide 12**

My second large thesis group discusses the spatial form of the explicit solution and it’s relation with the implicit solution, so with Wave Field Synthesis

**Slide 13**

First of all, several words about the basic idea behind the explicit solution for linear geometries, termed as the Spectral Division Method.

**Slide 14**

So, in order to arrive at a spatial form of the explicit solution that may be used directly for sound field synthesis, and allows the comparison with Wave Field Synthesis I applied the stationary phase approximation to the SDM driving functions.

The derivation consisted two main steps, first I had to approximate the forwards transforms, present in the spectral driving function, then I evaluated the inverse Fourier transform asymptotically.  
Again, the local wavenumber concep allowed us to find the stationary point for the involved integrals easily, and also it gave a simple connection between the forward transforms and inverse transform stationary points.

**Slide 15**

Again, as a simple example the synthesis of a virtual point source is illustrated by applying the novel spatial form of the explicit driving functions.

**Slide 16**

Now, besides that the novel explicit drivign functions can be directly used for sound field synthesis, it also allows us to compare Wave Field Synthesis and the Spectral Divison Method. Actually the relation of the explicit and implicit solution has been already discussed in the related literature, but only for particluar cases, for example for a virtual point source, with linear SSD.

In order bring the implicit and explicit driving functions into a similar form I expressed the novel explicit driving function in terms of the Rayleigh integral, or more precisely in terms of the stationary phase approximation of the Rayleigh integral. As a result I proved that the explicit and my generalized implicit solutions perfectly coincide in the high frequency region for arbitrary virtual sound fields and reference curves.

Besides its theoretical importance, or theoretical value also this equivalence has practical importance as well, because there are several artifacts, or phenomena that can be very efficiently described in the spectral domain, and now these results/descirption can be extended for Wave Field Synthesis in a unified manner.

To see what am I talking about, as an example the so-called spatial aliasing artifacts can be very efficiently described analytically in the spectral, wavenumber domain, and this desription has been well known in the context of the Spectral Division Method.

**Slide 17**

The origin of the spatial aliasing artifacts is that instead of the theoretically continuous secondary source distribution, in practice we use an array of loudspeakers in discrete positions.

This „discretization of the driving functions” will result in echoes, following the intended wavefront of the virtual source originating from the individual secondary source elements. These echoes are hgh-pass filtered above the so-called aliasing frequency.

These alasing echoes can be seen on the present slide in case of an impulse virtual source excitation signal.

In order to eliminate these aliasing echoes I introduced a novel antialiasing strategy by identifying the positions of the sources of aliasing waves on given frequencies by applying the stationary phase approximation to the explicit driving functions.

**Slide 18**

As a result I showed that aliasing artifacts can be eliminated by simple low pass filtering of the driving functions, where the cutoff frequency of the low pass fitler is defined via the local wavenumber vector of the virtual field. So the cut off frequency for a given SSD element is defined by the local propagation direction of the virtual field on that SSD position. As it can be seen by using this antialaising strategy aliasing echoes can be suppressed at least into a particular direction. These remaining aliasing components can not be eliminated by preprocessing the driving functions, but can be only suppressed by applying directive sources as secondary sources,

**Slide 19**

As shown in this slide. Here we can see the result of synthesis by applying my antialiasing strategy and applying ideally directive secondary sources. The ideal secondary source directivity is also given in my dissertation.

**Slide 20.**

So, to conclude the second thesis group, I introduced analytical Spectral Division Method driving functions merely in the spatial domain, I showed that these driving functions are completely equivalent with my unified WFS driving functions for arbitrary virtual fields, and I introduced a novel anti-aliasing strategy.

**Slide 21.**

The third and the fourth thesis groups are both dealing with the synthesis of moving sources, so now I will briefly introduce the results in the two groups together.

**Slide 22.**

So, as a complex application example for generally sound field synthesis and for my unified Wave Field Synthesis framework, I investigated the possibilities for the synthesis of moving sound sources, or more specifically for moving 3D point sources.

For this dynamic case the primary challenge is the proper reconstruction of the Doppler effect, occuring due to the finite propagation speed of sound.

As we can see in the present slide, showing the sound field generated by a moving harmonic source, the Doppler effect affects both the phase and the amplitude of the virtual field.

**Slide 23.**

In order to arrive at an implicit solution, and to extend my unified WFS framework for moving sources as well the starting point was again, the 3D Kirchhoff integral, but this the time-domain Kirchhoff integral.

Again, our aim is to reduce the 3D surface integral to a contour integral in the plane of synthesis, which describes sources, moving with an arbitrary trajectory and velocity profile, but of course with the trajectory restricted to the plane of interest, and which integral may contain the required driving functions implicitly.

This dimensionality reduction can be again, performed by the stationary phase approximation. I extended the local wavenumber vector concept for time variant fields, so again, it gave us a simple method to find the stationary position for the involved integral.

As an important result, I arrived at 2.5D Wave Field Synthesis driving functions, that are capable of the synthesis of sources, moving on an arbtirary trajectry and may radiate with an arbitrary excitation signal.

**Slide 24.**

Again, as a simple application example we can see here the result of synthesizing a point source moving on a straight trajectory, by using an arbitrary secondary source distribution.

As a result we can see, that the phase of the sound field (hence the shape of the wavefronts) can be resynthesized perfectly in the listening region, and the driving functions ensure an amplitude correct synthesis on the prescribed reference curve.

It should be noted here that for arbitrary source trajectories the main challenge in calculating the driving function is that it requires the knowledge of the propagation time delay. So we have to know for each secondary source element at each time instant that when was the wavefront emitted by the virtual source that arrives to the given posiition at the receiving time. And of course we also have to know, where was the virtual source at this emission time.

Now to calculate this is a challenging task, and is of large computational complexity, I gave a simple numerical approximation for the task in my dissertation.

Anyways, in case that the source moves uniformly along a straight trajectory, like in this case, an analytical solution can be given for the propagation time delay, so using this expression I gave closed form driving functions for virtual sources under uniform motion.

**Slide 25.**

Also the importance of the case of sources under uniform motion is given by the fact that in this case the wavenumber content of a source pass-by can be expressed analytically.   
This spectral description allows us to formulate analytical spectral division method driving functions in the geometry that can be seen on the present slide. Furthermore, in this particular geometry, when the source moves parallel to the secondary source distribution, even the spatial inverse Fourier transform of the spectral driving function can be evaluated analytically, so we could formulate analytical Spectral Division Method driving functions in the spatial domain.

The figure in the bottom illustrates the result of synthesis using these explicit driving functions. We can see that indeed, the explicit driving functions allow perfect synthesis of the moving source field along the reference line, being parllel with the secondary source distribution.

**Slide 26.**

Similarly to the stationary case I also proved that these explicit driving functions coincide with the Wave Field Synthesis driving functions in the same setup, therefore in case of sources, moving uniformly parallel to a linear SSD and optimizing the field on a parallel reference line.  
This fact again allowed me to investigate spatial aliasing, described in the wavenumber domain in a unified manner.

The figure on the present slide illustrates spatial aliasing echoes in case of a moving source.  
What we can see here is that in case of a virtual source under motion in a given receiver position the arriving aliasing echoes suffer a different Doppler shift, than the original, intended wavefront. Therefore in this dynamic case aliasing artifacts are even more enhanced than in the stationary case, resulting in strong frequency distortion. So avoiding spatial aliasing is even more crucial in the present case.

**Slide 27.**

So, finally in order to suppress aliasing artifacts I extended my anti-aliasing strategy to include the synthesis of moving sources.   
In this case antialiasing can be performed by time variant low pass filtering of the driving function, so again the driving functions are simply low pass filtered, but this time the cut-off frequency is time dependent. Otherwise the formula is the same as in the stationary case.

The result of antialiasing is shown in the present slide for a source, moving on a curved trajectory, emitting an impulse train. The SSD is a circular one, because I showed that this geometry is optimal in the aspect of aliasing and referencing the synthesis.

As a result into one particular direction the aliasing wavefronts could be suppressed.  
We can also watch the result of synthesis and the result of antialasing in video as well.

**Slide 28.**

To summarize my third and fourth thesis groups:  
In thesis groupd III I gave 3D and 2.5D Wave Field Synthesis driving functions for sources, moving on arbitrary trajectory, the latter one was obtained by adapting the stationary phase approximation to time variant fields.  
In case of sources under uniform motion I gave closed form time domain driving functions, opposed to the general case, when of course the driving functions are closed form, but in order to calculate them first one has to calculate the propagation time delay.

I did not mention it in this presentation, but also for sources under uniform motion I gave merely frequency domain Wave Field Synthesis driving functions.

**Slide 29.**

As parts of my last thesis groups I gave explicit driving functions for sources under uniform motion, and I proved that these driving functions coincide with the WFS solution.

Finally besides an analytical treatment of spatial aliasing artifacts I extended my antialiasing strategy to include moving sources as well.

**Slide 30.**

So. To conlcude my presentation: as the main results of my dissertation, I intrudced a unified Wave Field Synthesis framework, valid for arbitrary virtual fields, secondary source shapes and reference curves.

I formulated a spatial form of the explicit driving functions, valid in the high-frequency region, proven to be equivalent with the Wave Field Synthesis solution.

I extended both methods to include sources, moving on arbitrary trajectories.

Finally I gave a novel antialiasing strategy for both static and dynamic sound field.

As an outlook: during my research I only considered so called diverging sound field and did not formulate driving functions for converging or focused sources. These types of virtual source models allow the synthesis of sources, located inside the listening region, so this is a straightforward direction to go with my research.

Also, as mr Bilicz stated it in his review, the dissertation mainly deals with the theoretical aspects of sound field synthesis and the implementation of the results is not discussed. So it may be again a way to continue to investigate the real-time implementation possibilities for example the synthesis using an arbitrary SSD and arbitrary reference curve.

**Slide 30.**

And jap, in this final slide you can find the journal papers, related to the content of my dissertation. And it concludes my presentation ,so, thank you for you attention!