An Exploration of a 4X4 Speaker Array

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Physics 406
May 11, 2012

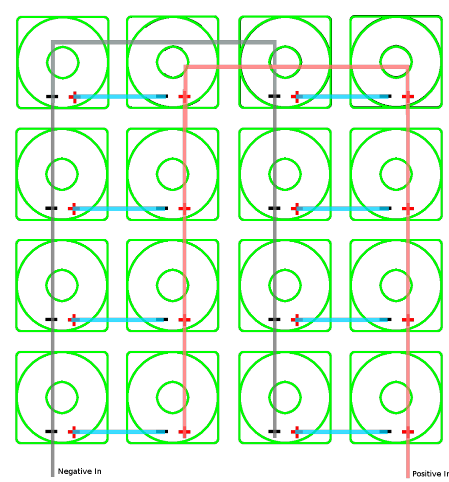
Overview

I am not a very musically inclined person so upon joining the "Physics of Music" class I needed to come up with an experiment that piqued my interest while fitting the bill for the class. Most other students built or modified instruments or something more along those lines, but I was looking for something more physical and less musical. One of my favorite experiments in my physics education is the double slit experiment done in introductory level quantum classes. Basically this consists of shining a laser on a piece of foil with two slits in it, and the resulting pattern is shined on a screen. What we see is a series of bright peaks separated by darkness caused by the interference of the light waves from emanating from each slit. This interference is caused by the phase difference between the waves that originated at each slit due to the path length difference to the point on the screen from the slits. If this difference is a full multiple of the wavelength then the interference will be wholly constructive and we see a bright peak; if it is an odd multiple of half the wavelength then we get destructive interference resulting in a dark spot. This experiment can be expanded to using a 2d mesh instead of a line of slits, and theoretically can be done with anything that exhibits wave like behavior, including sound. At the beginning of the semester as Professor Errede was outlining the equipment we had available and some of the experiments that had been done in previous semesters, he described an analogue to the multi-slit experiment using a linear array of speakers that sounded right up my alley. I didn't want to do the same experiment over again so instead I decided to go the 2D route and build a $4 X 4$ array. The original plan for this experiment was to compare the the theoretical results from the math to the actual experiment. After looking at some preliminary results it began to seem more practical to compare to the previous experiment than the theoretical data.

The previous experiment was run by two music students who wanted to investigate the properties of linear speaker systems that they had seen trending in many venues including, specifically the University of Illinois's Krannert Center for the Performing Arts. They experienced trouble in finding the time to run their experiment on the real deal in the auditorium so they built the first order approximation of the system they wanted to investigate, the 4 speaker linear array I mentioned earlier. Being something whose purpose is to fill a room with consistent, high quality sound, the array they wanted to find ideally would have a minimal interference pattern, the opposite goal of my experiment to specifically investigate this phenomena. Somewhat ironically however it seems I stumbled across a method of minimizing this interference, and their data clearly shows the lovely peaks and valleys that I was looking for.

Construction

The speaker cabinet is constructed of plywood and has overall dimensions of about $20\,X\,20\,X\,12$ in. The actual internal dimensions are $19\,1/4\,X\,19\,1/4\,X\,11\,7/8$ in due to the way the face board to which the speakers are mounted is inlaid. The walls were nailed together, then the corners were caulked to seal any gaps. The rig contains 16, 4 in diameter drivers mounted in a piece of 1/4 in plywood in a $4\,X\,4$ array. The holes the drivers are mounted in are all cut by hand using a hole saw then sanded to fit using a rotary tool. Each hole is centered 5 in away from its nearest neighbors. The drivers are then mounted with 4 self tapping screws each. The cabinet is filled with fiberglass insulation to damp the back pressure from the drivers. The drivers are rated at 16 Ohms and are wired in 8 parallel sets of 2 in series to achieve an overall impedance of 4 Ohms.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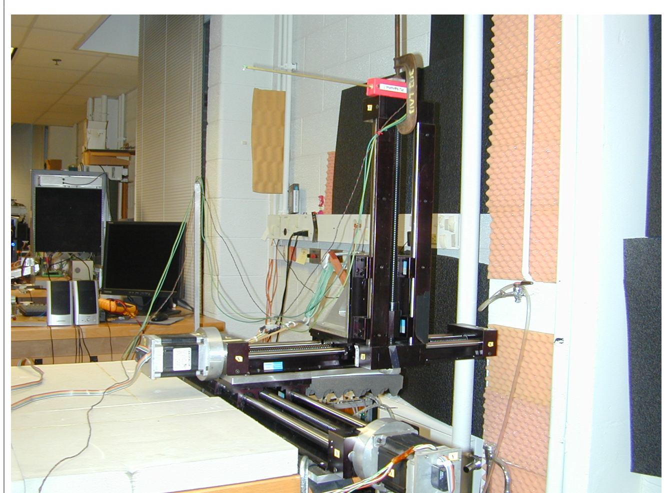


Experiment

We placed the cabinet on a stool on a table in the lab then fed a monotonic sine wave to it. Placed 1m away from the face of the cabinet is a pair of microphones; one of which measures pressure, the other velocity. These microphones are attached to a rig consisting of stepper motors turning worm screws which allow us to move them in a plane. For this experiment the X axis measures the perpendicular distance from the face, and the Y axis measures distance parallel to the horizontal axis of the cabinet. The microphones sweep out the plane between these axes 1cm at a time in a serpentine fashion, taking measurements of the air pressure and velocity at each point. This data is displayed graphically in the plots of Real Pressure and Real Velocity later. Using this data we can also calculate many other things. A matlab script was used to read the data and calculate many different things such as the imaginary pressure and velocities, the intensity, sound pressure level, phase data for all of these, and much more. In total the script outputs about 90 different plots for each run of the experiment. This was run at 10Khz, 5Khz, 2Khz, and 1Khz. We also used this script to interpret data from a previous experiment by Robert Dagit and Beth Parthum which consisted of running basically the same experiment for a linear array of 4 speakers. Data from an individual speaker is used as well, and both of these data sets are extremely valuable for comparison.

We also collected frequency response data for the cabinet using the same setup with the microphones centered 1m away from the rig. We also measured the electrical response of the cabinet itself while feeding in a wide range of frequencies. We collected data for a range of frequencies between 0 to 2Khz in 1Hz steps and 0 to 10Khz in 10Hz steps. This experiment allowed us to collect data for the pressure and velocity response as a function of frequencies as well as things like the electrical voltage, current, impedance, capacitance, and inductance for the cabinet. This experiment yielded over 100 plots per run.

Data

Without taking specific measurements for things like the speed of sound in the lab, and the output power of the drivers, the absolute numerical data often does not actually mean much. The relative numbers from the same experiments, and the qualitative spatial structure, however, can still tell us a lot, especially when comparing data across the various number of speakers.

The first set of data to look at comes from another matlab script. This script emulated a 4x4 speaker array to get a theoretical model of the sound intensity level we should expect from the array. As I mentioned, the actual value of the SIL on these graphs is pretty much meaningless, but the location of the peaks and dips should be a good approximation. I have included the two most useful graphs. The first of which, Fig 1a, shows the cross section of the Y axis interference pattern at the vertical center, Z=0, of the cabinet. The second, 3D plot, 1b, shows the pattern I was originally looking for when I decided on this experiment. Basically we see a grid pattern which is strongest on the central axes, culminating to a large peak in the center. If we were to emulate this in 3D, as we gain distance from the cabinet on the perpendicular direction, the X axis, we would see the overall grid pattern quickly die out and be left mostly with just the crosshairs. Progressing even further into the far field we will continue to hear. the central peak after the crosshair approaches the lower threshold of hearing. Looking ahead to the actual measured results we can clearly see this sort of pattern in the higher frequencies of the linear array, but in the square array this pattern is severely weakened if present at all.

For the multi-slit experiment what we expect to observe purely from interference is many, evenly spaced peaks, but the amount of peaks is mitigated by an envelop of the approximately gaussian intensity pattern that would be seen from a single slit. If however, we have an infinite number of slits this gaussian intensity distribution disappears because each peak corresponds to a most direct path to a slit. 4 speakers is not nearly infinite so we would expect this envelope to be present in both experiments using multiple sources. As we can see from the plots for both experiments, regardless of whether or not the interference pattern was clear we can usually observe this envelope effect.

We can also compare the curvature of the wavefronts. A point sound source would of course radiate a spherical wave from its origin. The single speaker, the closest approximation in this experiment, clearly displays a very curved wave front. Since they are composed of similar sources the two arrays should be able to be expressed as a linear combination of these sorts of waves. We see the line array displays a flat wavefront with curved edges. The square array, however, displays what is, over the area measured, an apparently entirely flat wavefront. It is a bit larger than the previous array, but the plot shown covers an area greater than that of the cabinet which leads one to infer that the additional dimension in the array is leading to further flattening of the wave front.

We also performed frequency response tests on the cabinet. While not directly pertaining to the phenomenon we are looking for it could provide some insight into any apparently anomalous data that disagrees with the theory. Figure 5 a) displays the pressure output as a function of frequency and from that we see an approximate gaussian best fit approaching zero near 100Hz and 10Khz. This breakdown in high frequencies probably helps explain the messiness of the 10Khz plots for the 4x4 arrays. The frequency response test produced far more plots than is practical to actually publish and discuss, but one specific frequency seemed to keep popping up unexplained. Showin in Figure 5 b) we kept finding either maxima or minima, depending on the particular function, at 165.5 Hz. I believe this to be explained by the setup of the experiment, the cabinet is placed about 2m away from a wall that sits behind the microphones, which corresponds with the wavelength of that frequency. Thankfully, it seems there were no prevalent harmonics present with this standing wave and since our lowest frequency test was run at 1Khz this probably did not have a big effect on the data.

Conclusions

A picture is supposed to be worth 1000 words so the 40 plots accompanying this report will say much more than I ever could, but I will attempt to present what I have learned from this experiment. In case I failed to make it clear at any point already, the humps lying on a constant X, sweeping through Y seen most prevalently in the SIL plots are the interference pattern I was looking for. Those running on a constant Y sweeping through X on the Pressure and Velocity plots are simply a product of basic wave behavior. It seems in my attempt to explore acoustical interference patterns I have inadvertently come up with a way to minimize them. As best as I can infer from the data I've collected, and the knowledge of how cheap the drivers I decided to use are, random manufacturing differences in each of the individual drivers is causing them to play ever so slightly out of phase. When arranged into a two dimensional array these phase differences of the drivers in the same column will at least partially cancel out the interference of the rows, and vice versa. This leads to relatively consistent, flat wavefronts. It may be possible to actually apply this idea by design rather than as an accident of poor quality control that one expects to find when buying $2 speaker drivers. Hopefully this could also lead to a more "interesting" sound if the necessary dissidence is not so much that it overwhelms the listener.

I need to thank my Father, Tony Boehme, for helping me construct the cabinet. Thanks also to Robert Dagit and Beth Parthum for all the data from the linear array without which I would lack much to actually compare to and say about my experiment. Their final paper is published here: http://online.physics.uiuc.edu/courses/phys406/Student_Projects/Spring11/Robt_Dagit_Beth_Parthum/Robt_Dagit_Beth_Parthum_P498POM_Final_Report_Sp11.pdf

And a huge thanks to Professor Steve Errede for essentially running the experiment for me and being the one to make this a proverbial "we." I will publish all 1500 or so plots along with the scripts used to create and analyze them online at:

https://netfiles.uiuc.edu/boehme1/shared/Phys%20406/

Fig 1 a) Matlab modeled Sound Intensity Level of a 4x4 array at 10 Khz

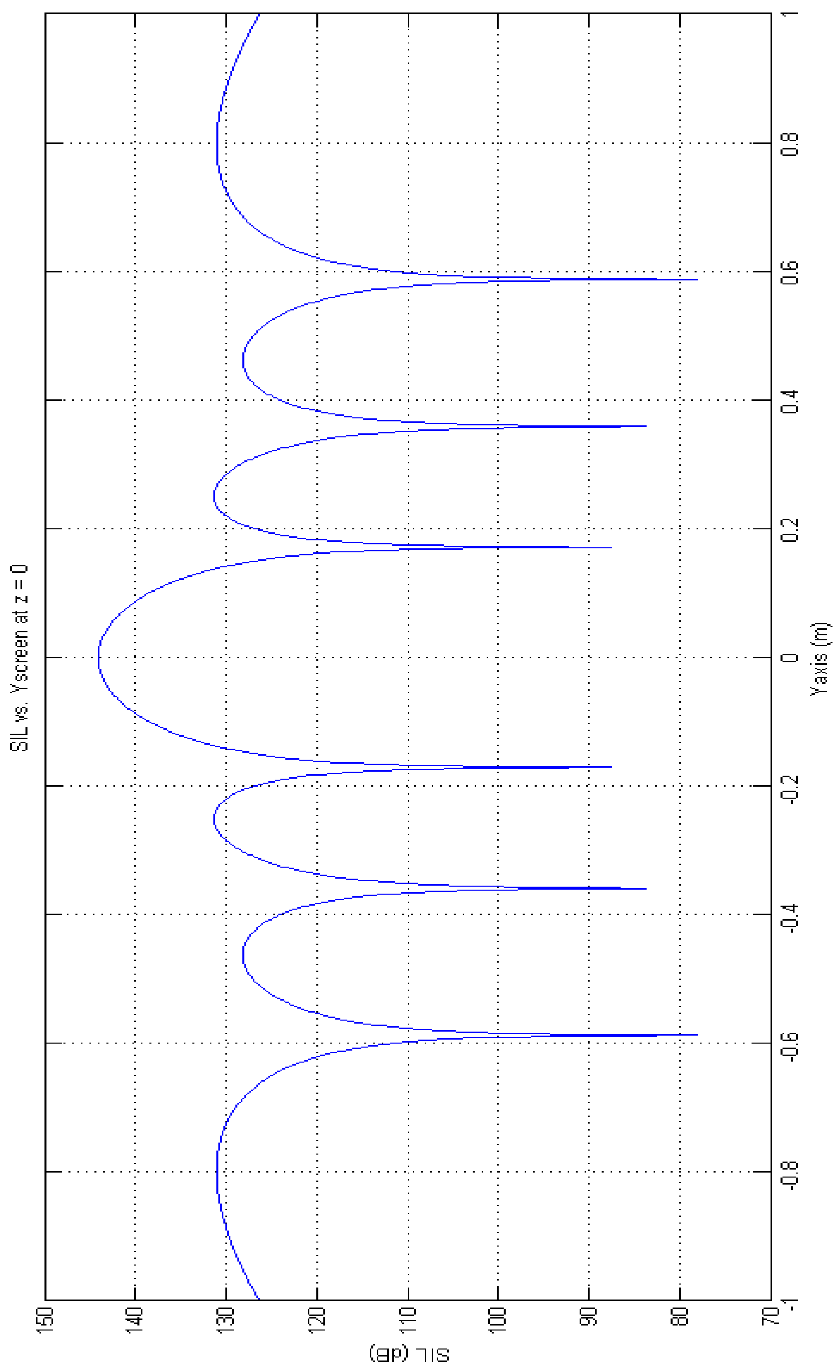


Fig 1 b) Matlab modeled Sound Intensity Level of a plane parallel to face of array at 10Khz.

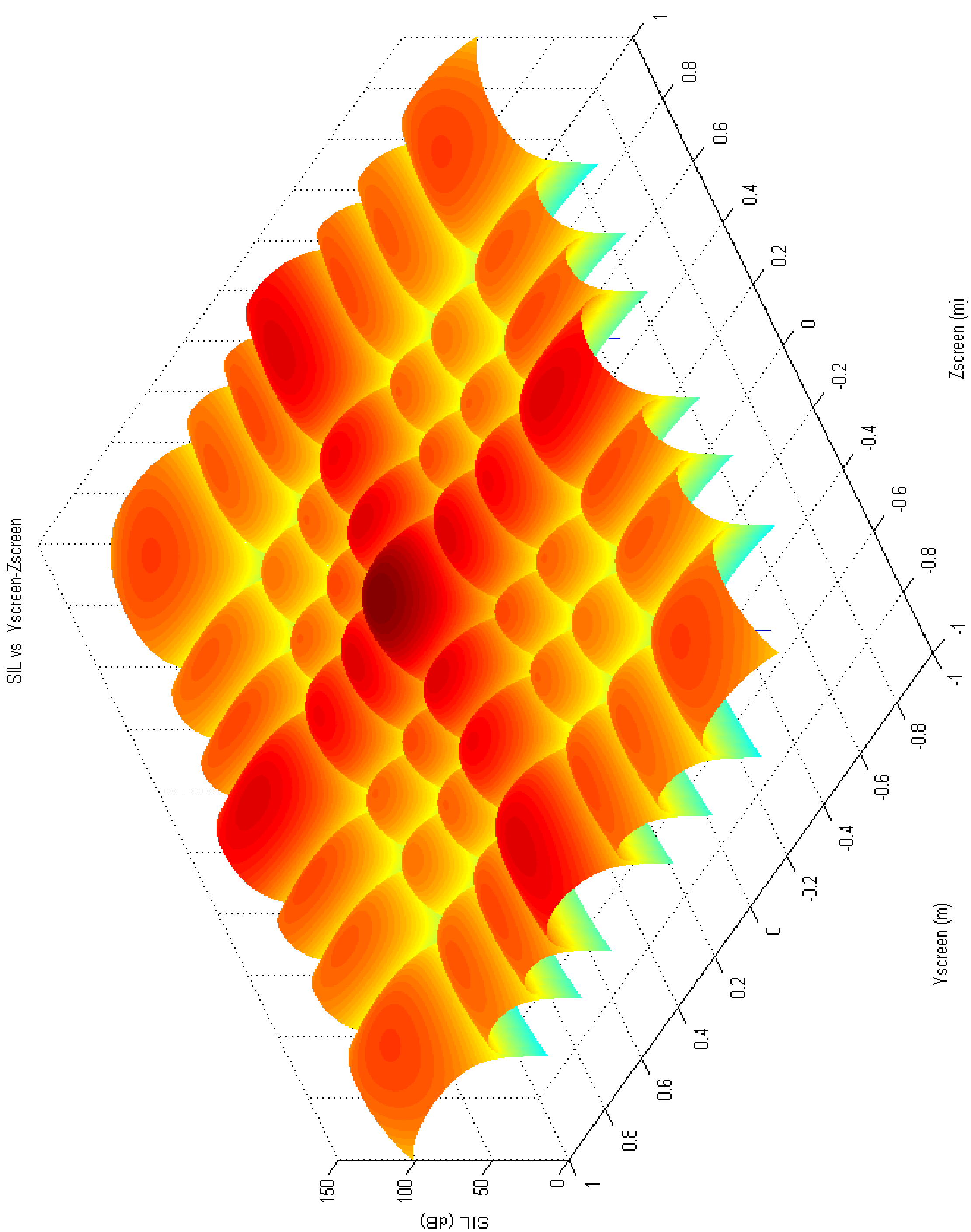


Fig 2 a) i. Real Pressure measurement for 1 speaker at 1Khz

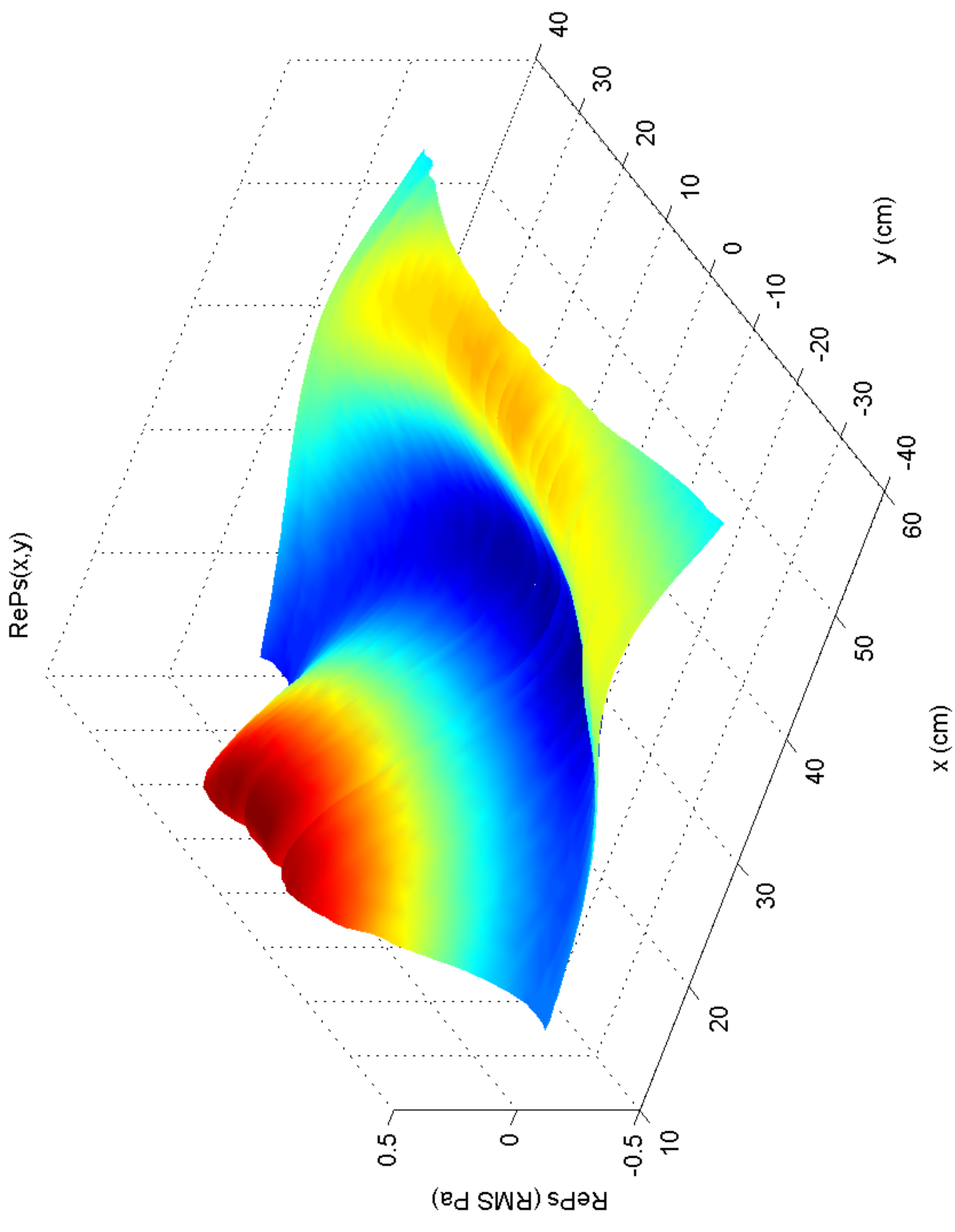


Fig 2 a) ii. Real Air Velocity measurement for 1 speaker at 1 Khz

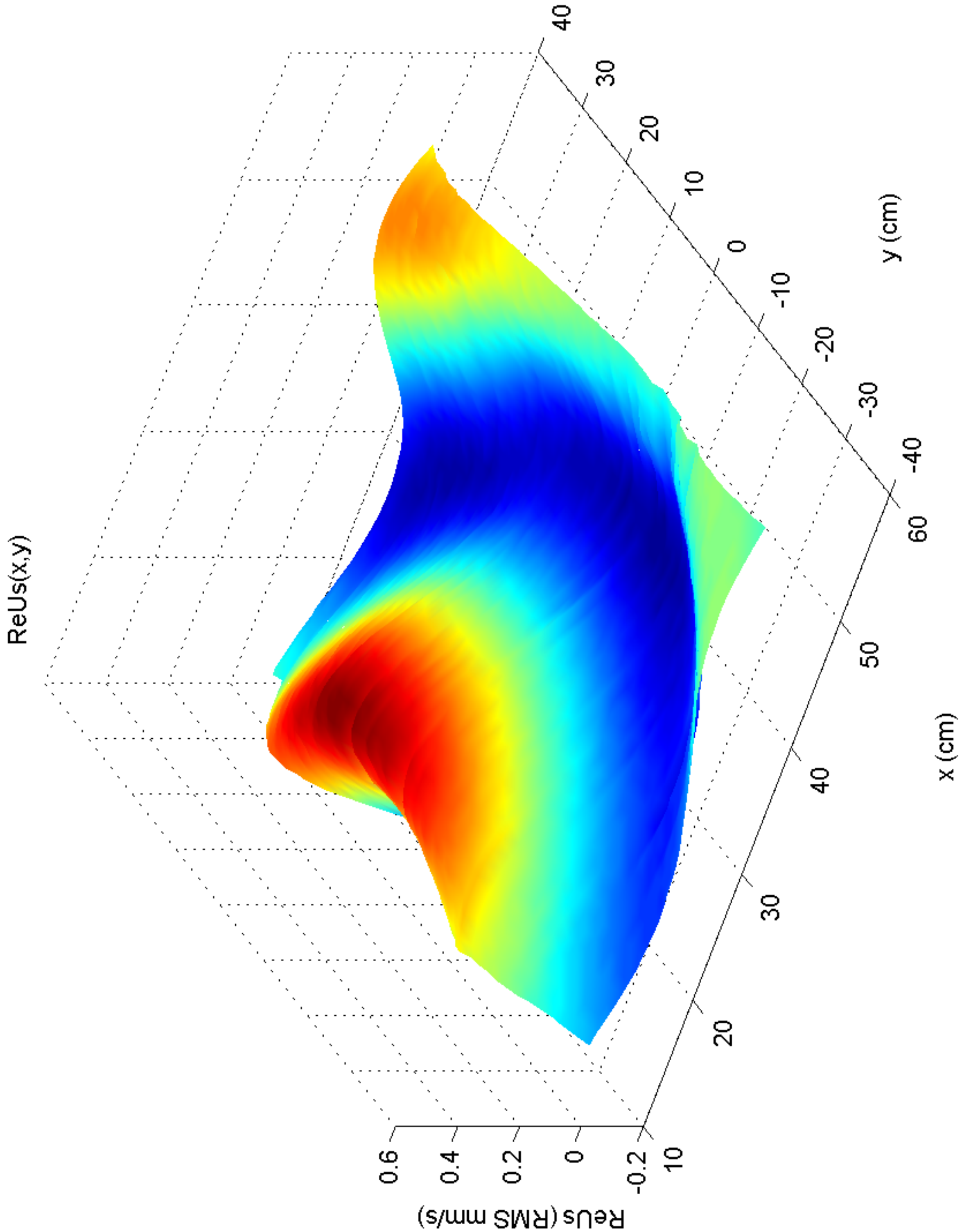


Fig 2 a) iii. Calculated Sound Intensity level for 1 speaker at 1Khz

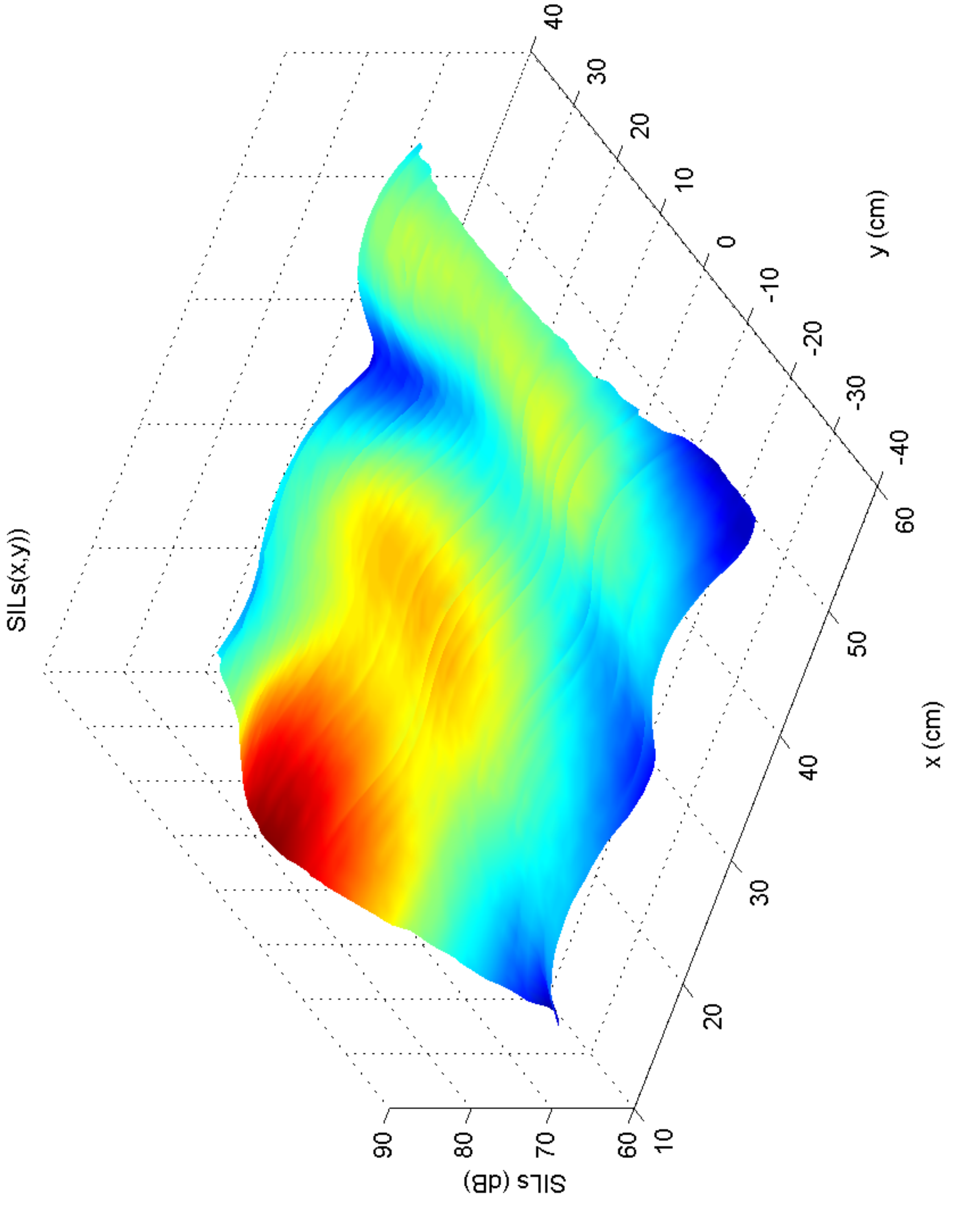


Fig 2 b) i. Real Pressure measurement for 1 speaker at 2Khz

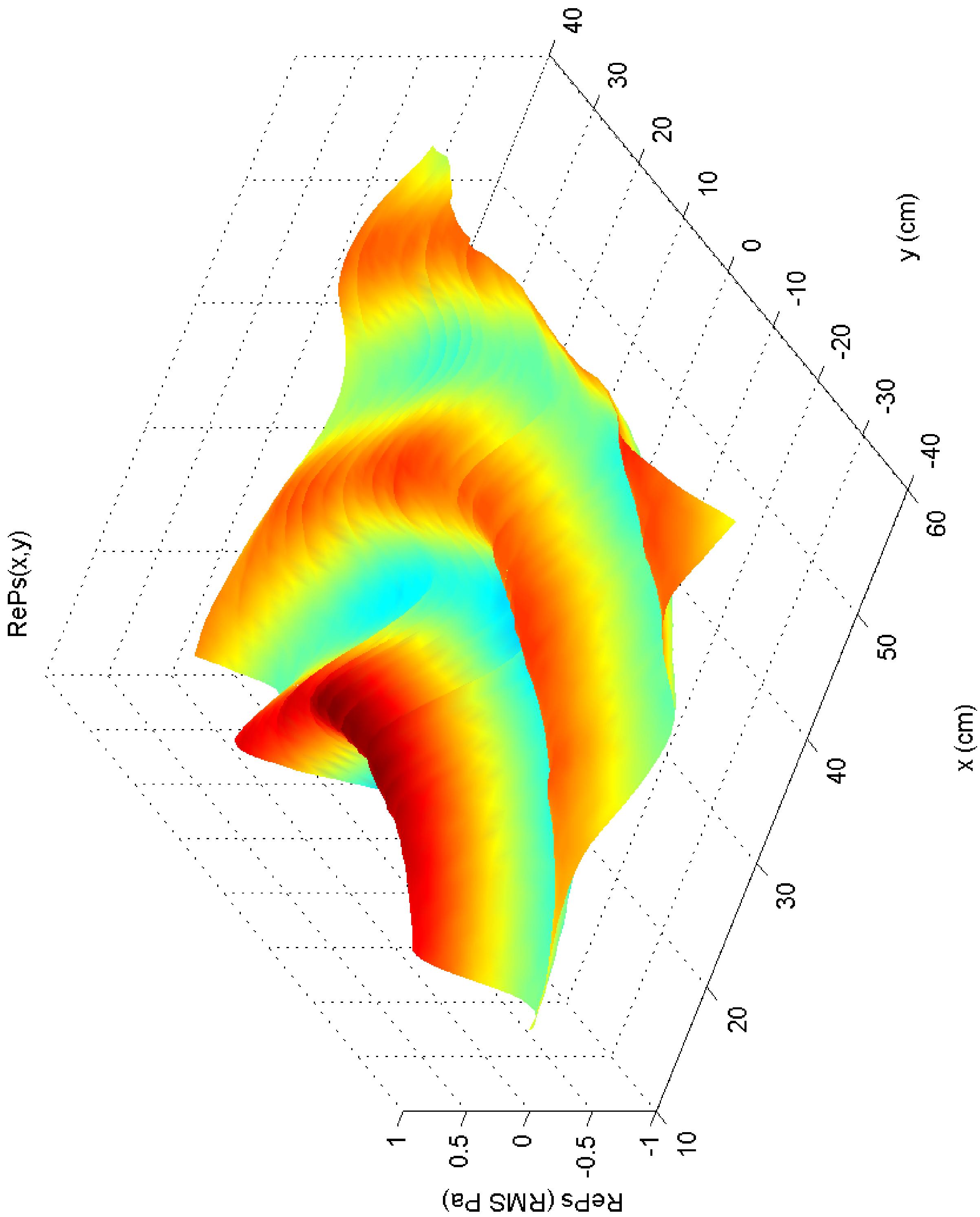


Fig 2 b) ii. Real Air Velocity measurement for 1 speaker at 2Khz

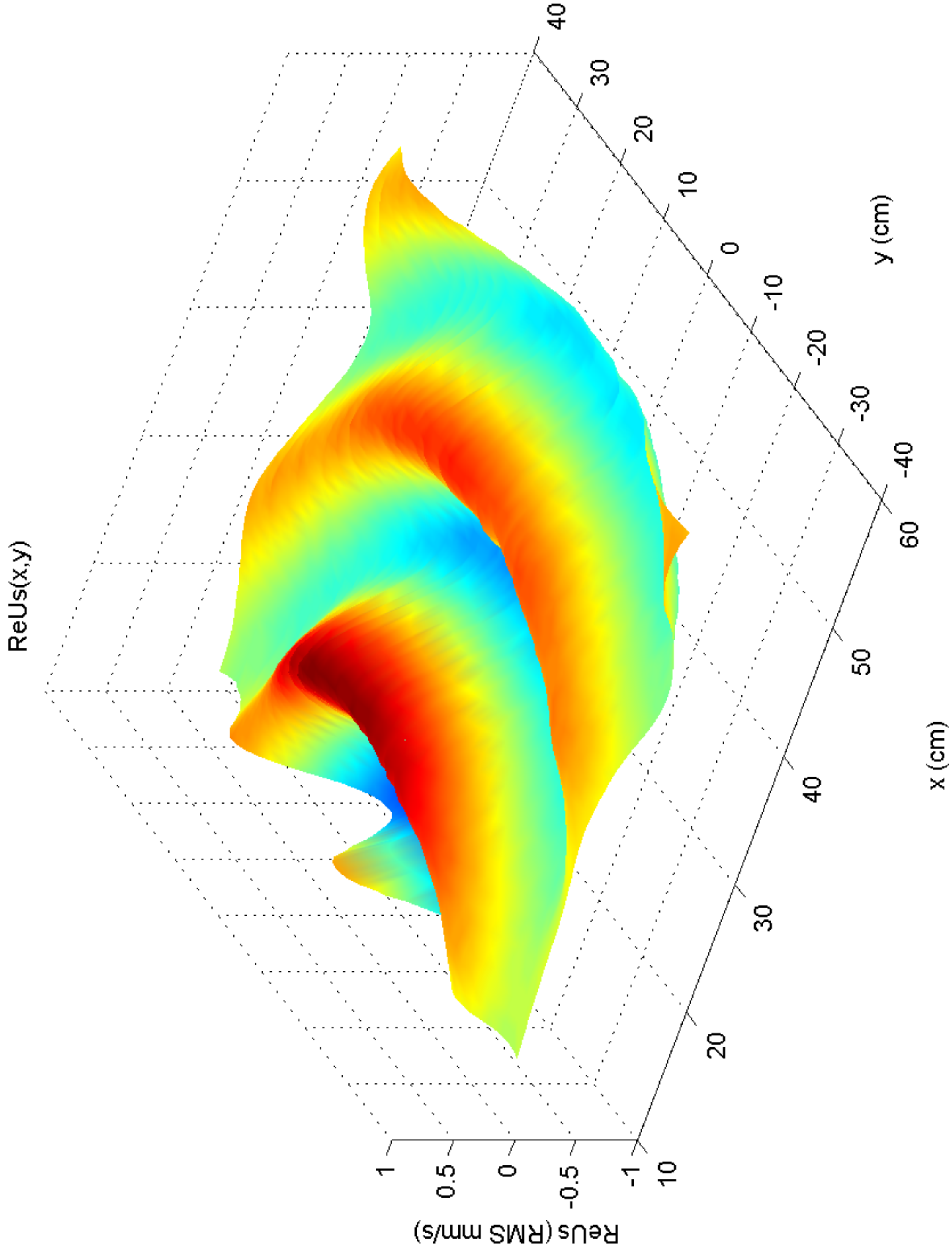


Fig 2 b) iii. Calculated Sound Intensity Level for 1 speaker at 2Khz

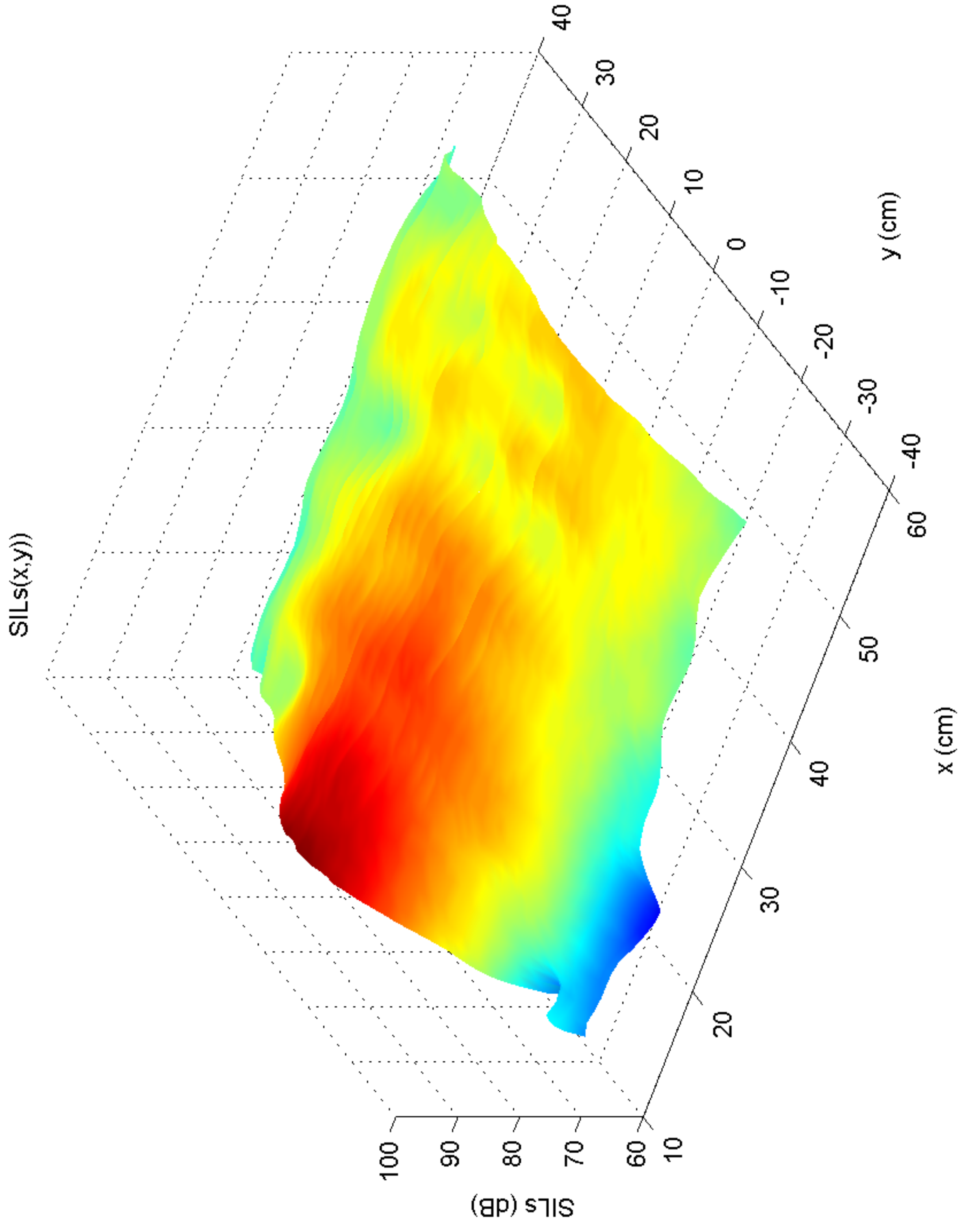


Fig 2 c) i. Real Pressure measurement for 1 speaker at 5Khz

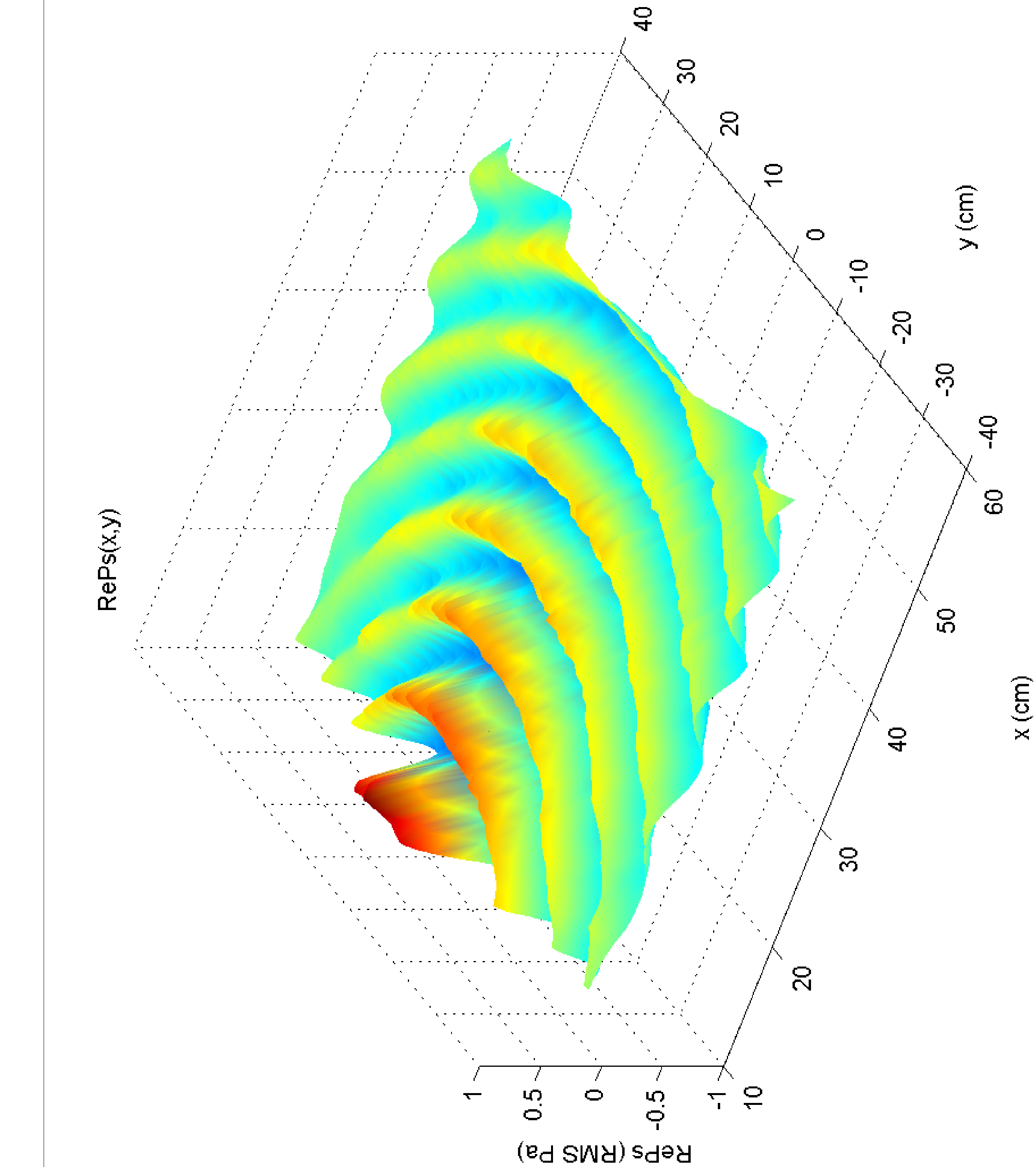


Fig 2 c) ii. Real Velocity measurement for 1 speaker at 5Khz

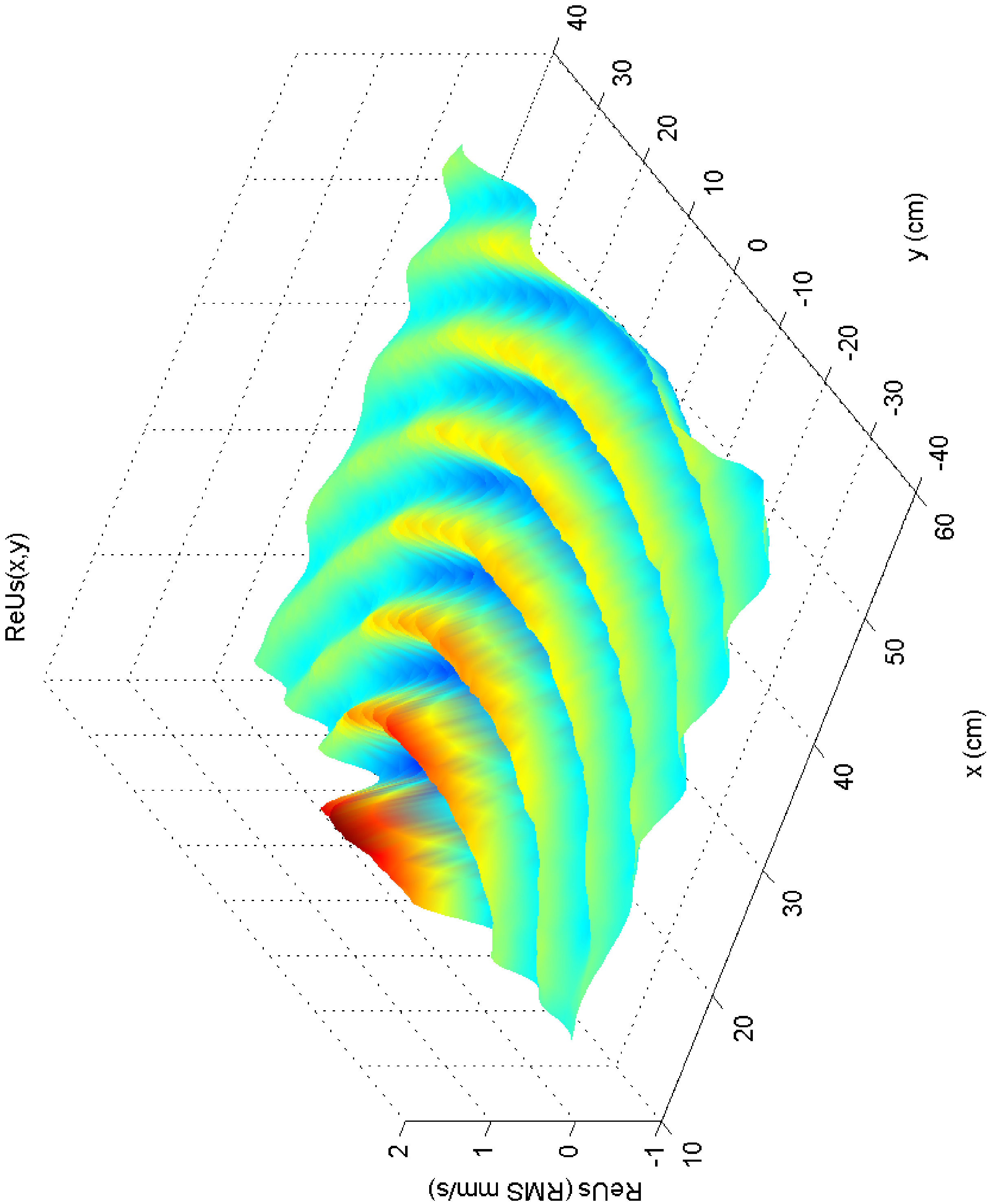


Fig 2 c) iii. Calculated Sound Intensity Level for 1 speaker at 5Khz

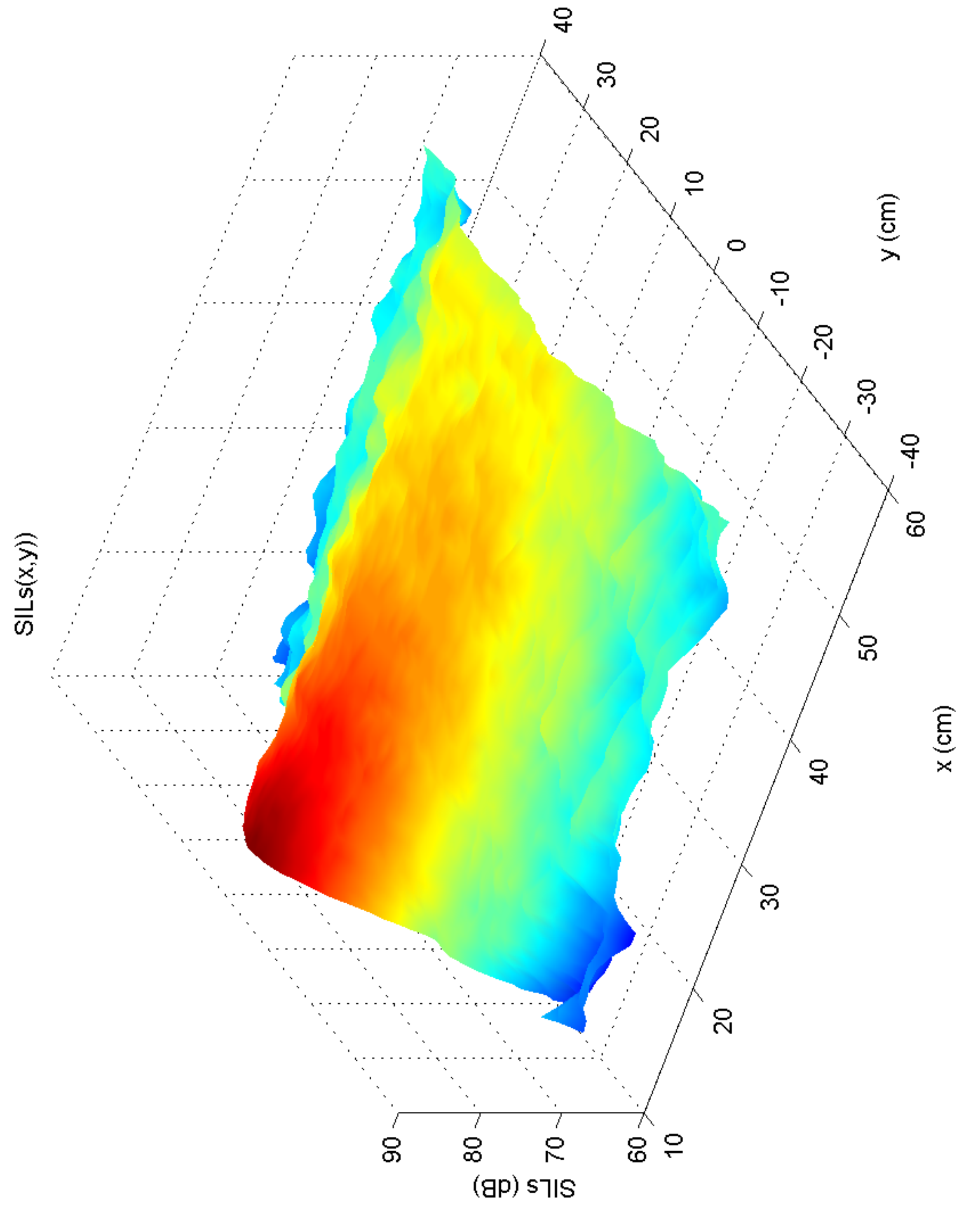


Fig 2 d) i. Real Pressure measurement for 1 speaker at 10Khz

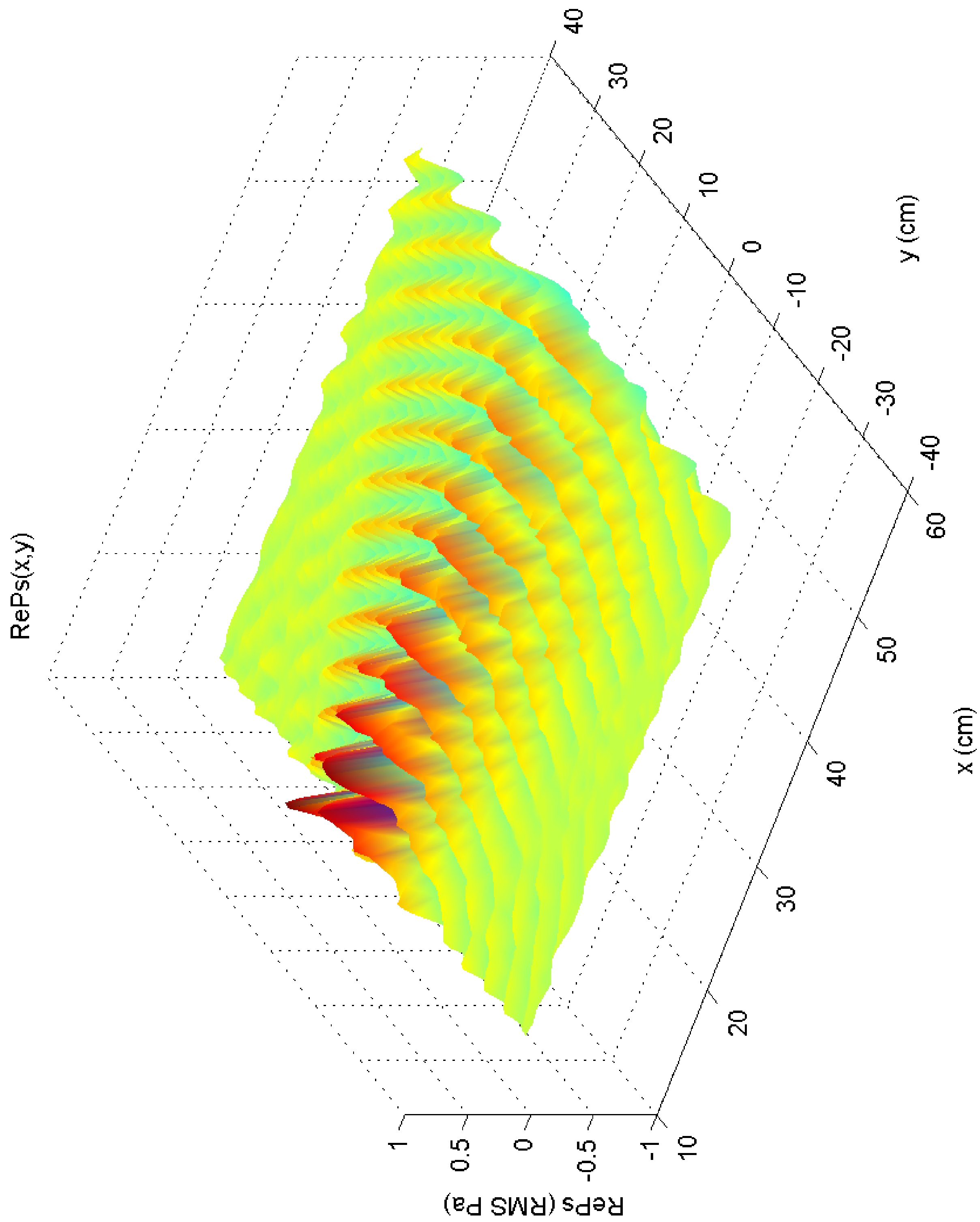


Fig 2 d) ii. Real Velocity measurement for 1 speaker at 10Khz

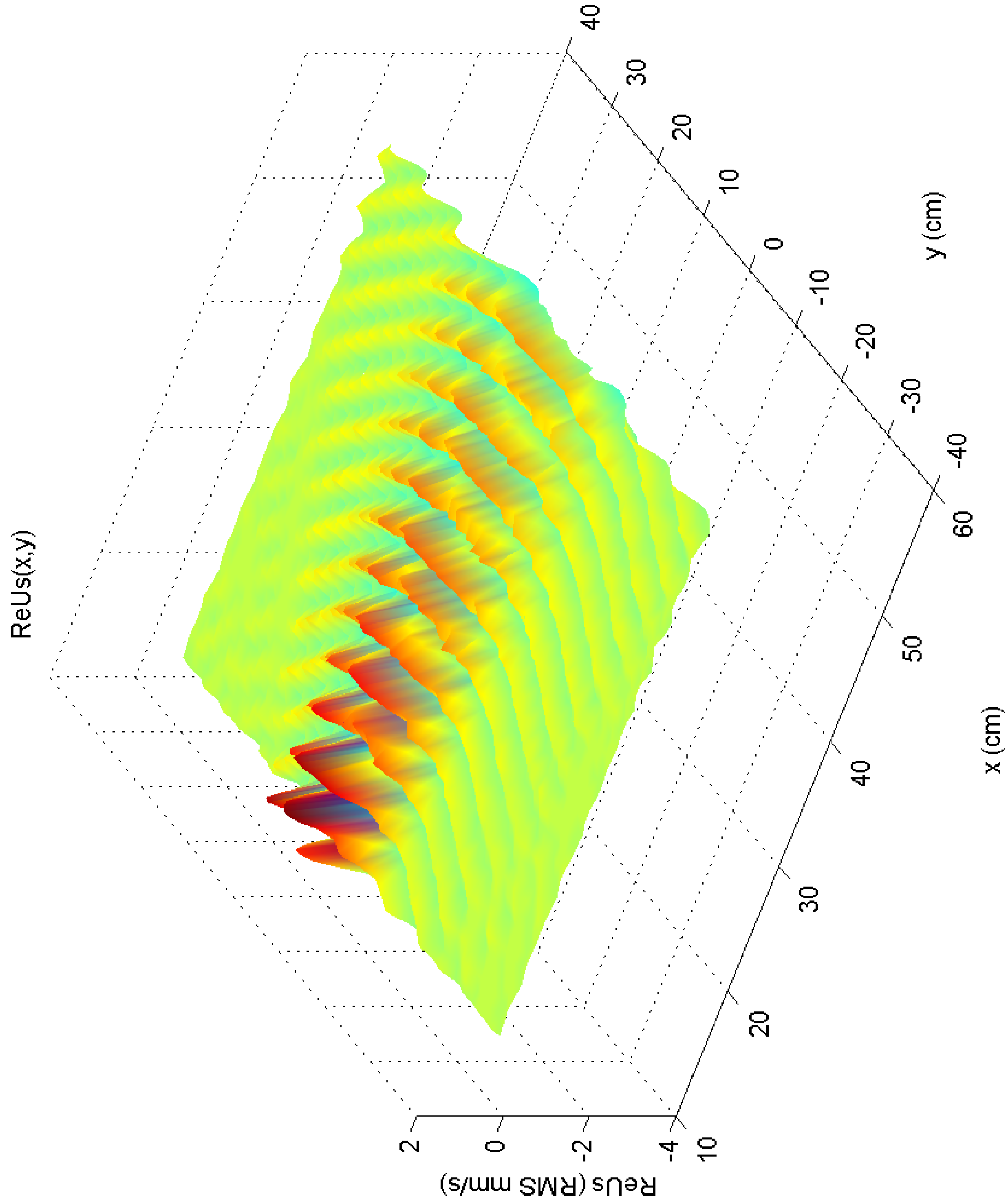


Fig 2 d) iii. Calculated Sound Intensity Level for 1 speaker at 10Khz

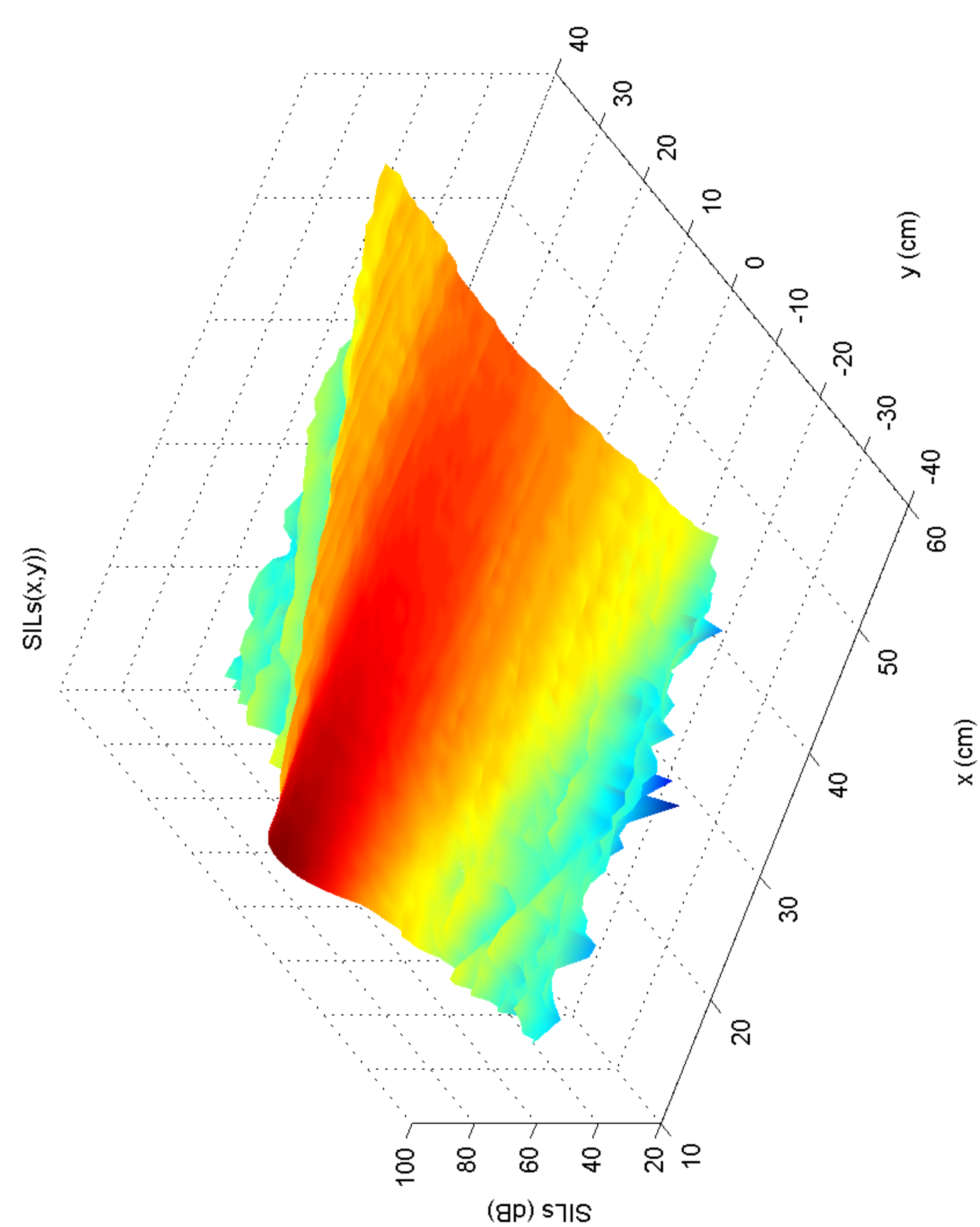


Fig 3 a) i. Real Pressure measurement for 4 linear speakers at 1Khz

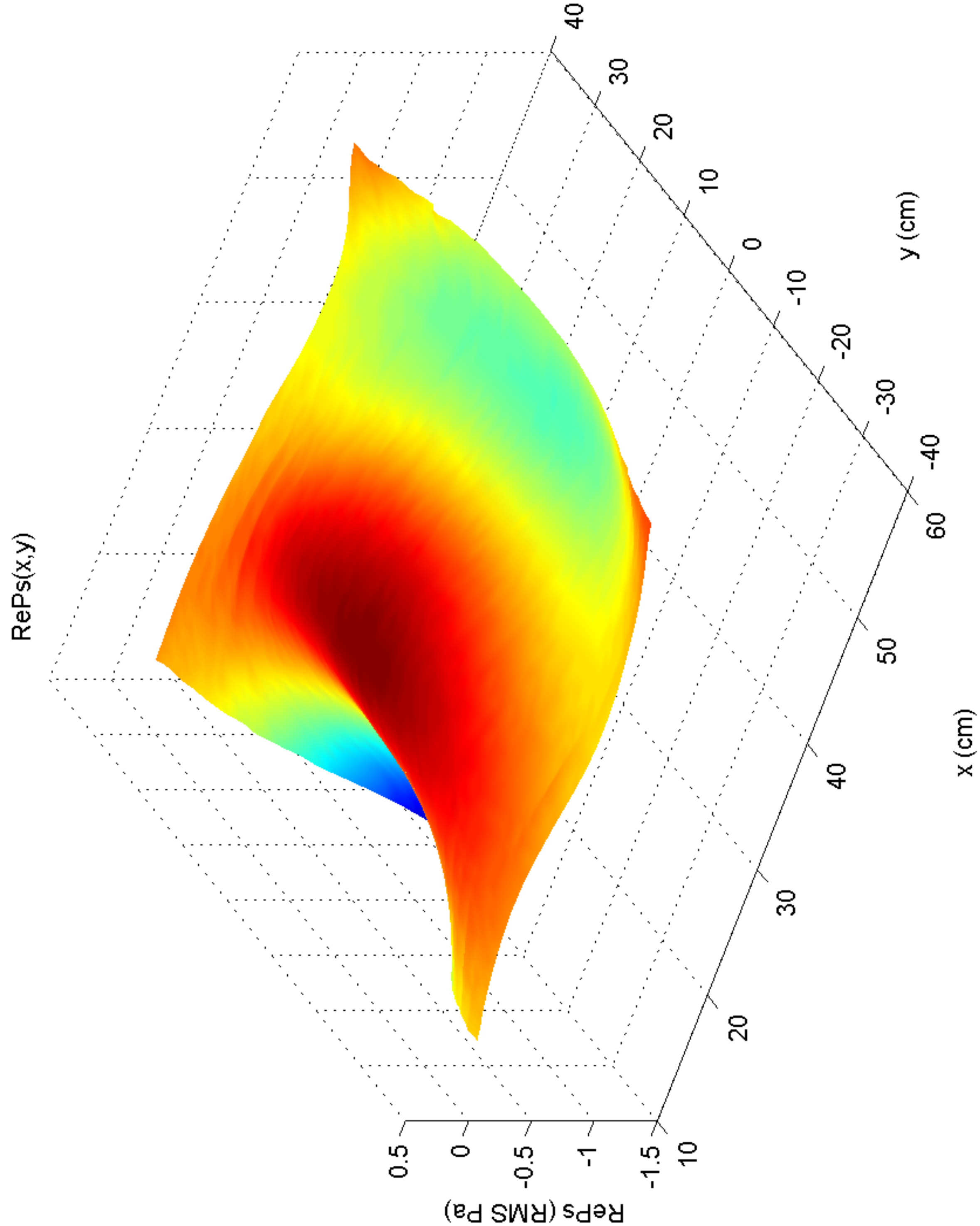


Fig 3 a) ii. Real Velocity measurement for 4 linear speakers at 1Khz

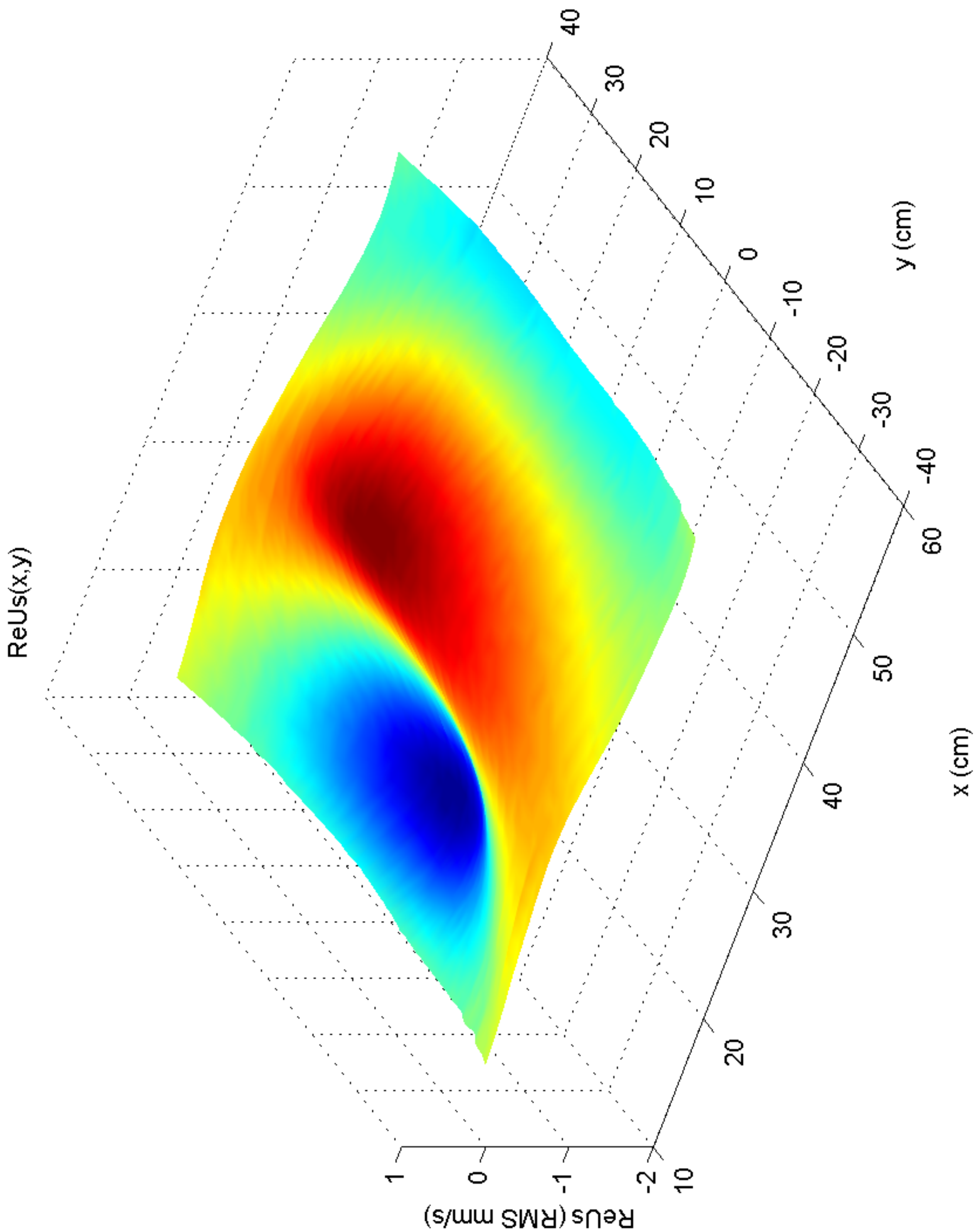


Fig 3 a) iii. Calculated Sound Intensity Level for 4 linear speakers at 1Khz

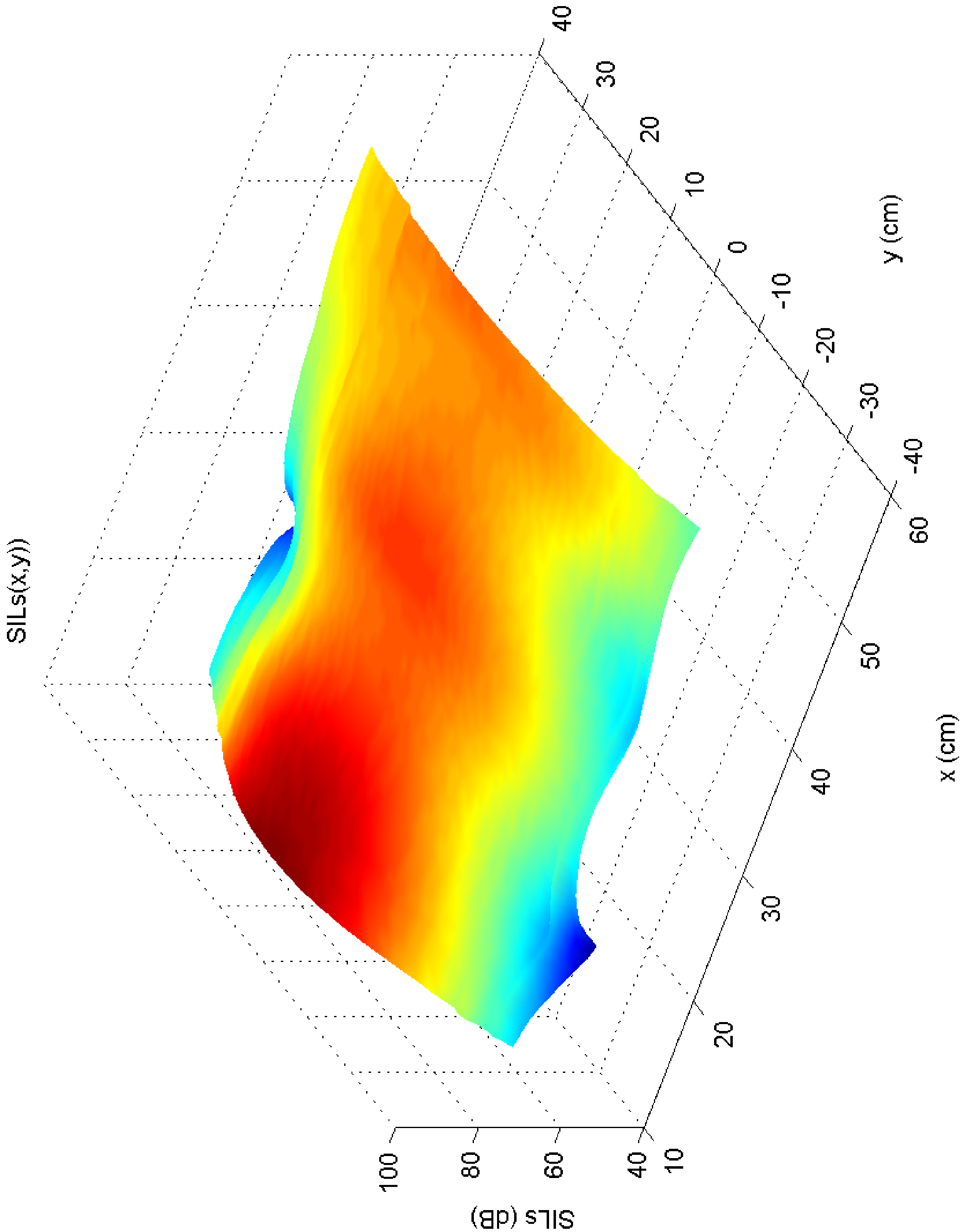


Fig 3 b) i. Real Pressure measurement for 4 linear speakers at 2Khz

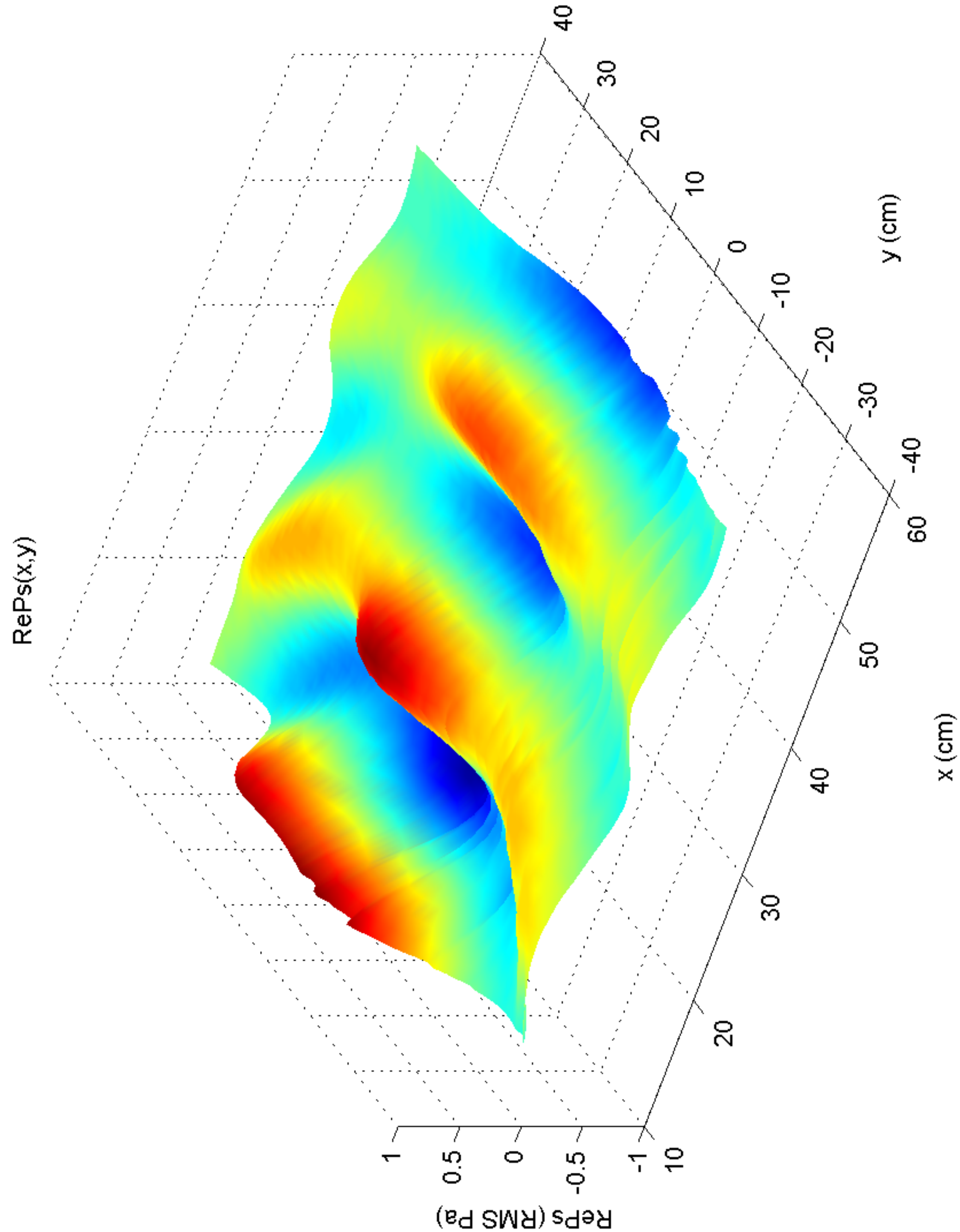


Fig 3 b) ii. Real Velocity measurement for 4 linear speakers at 2Khz

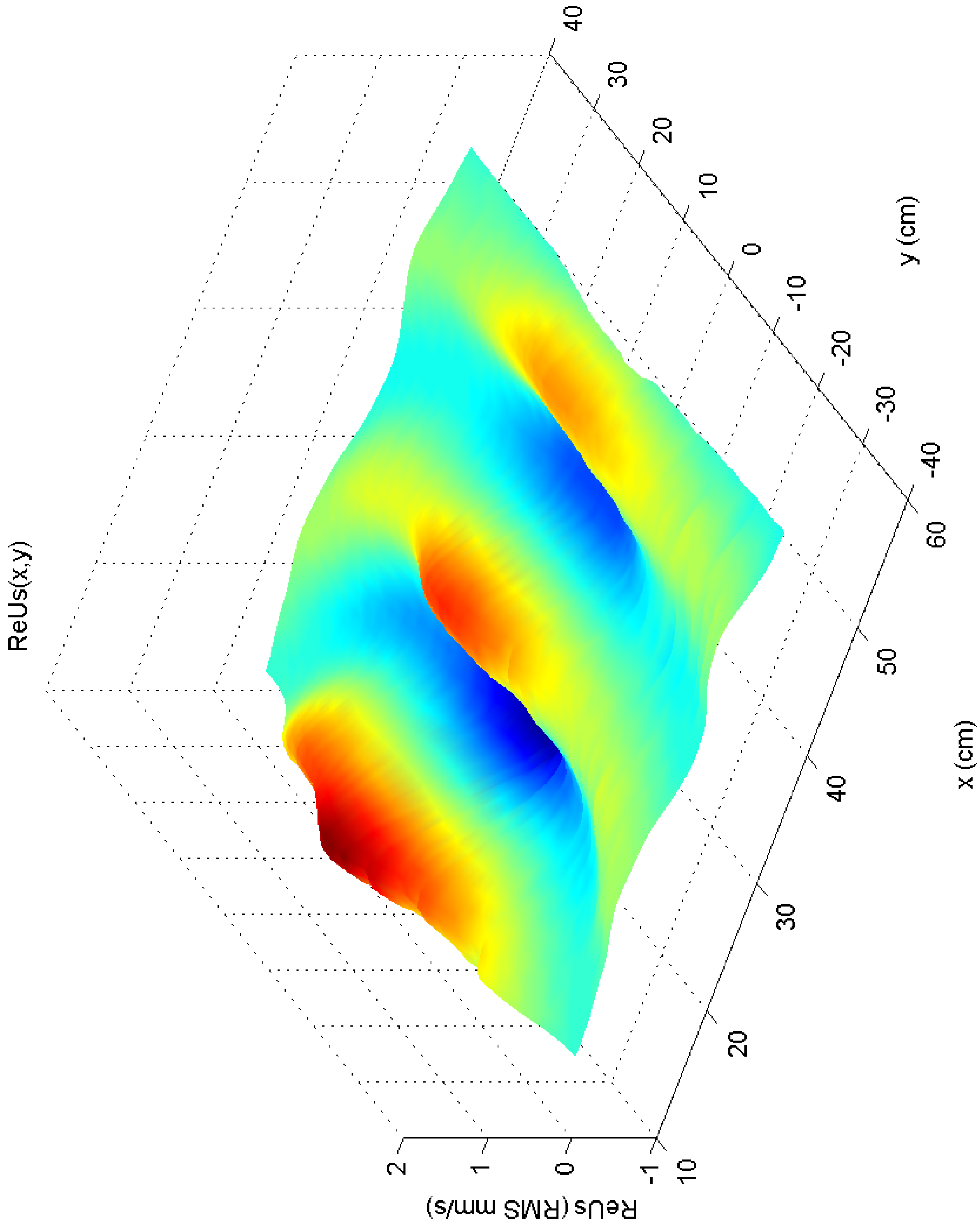


Fig 3 b) iii. Calculated Sound Intensity Level for 4 linear speakers at 2Khz

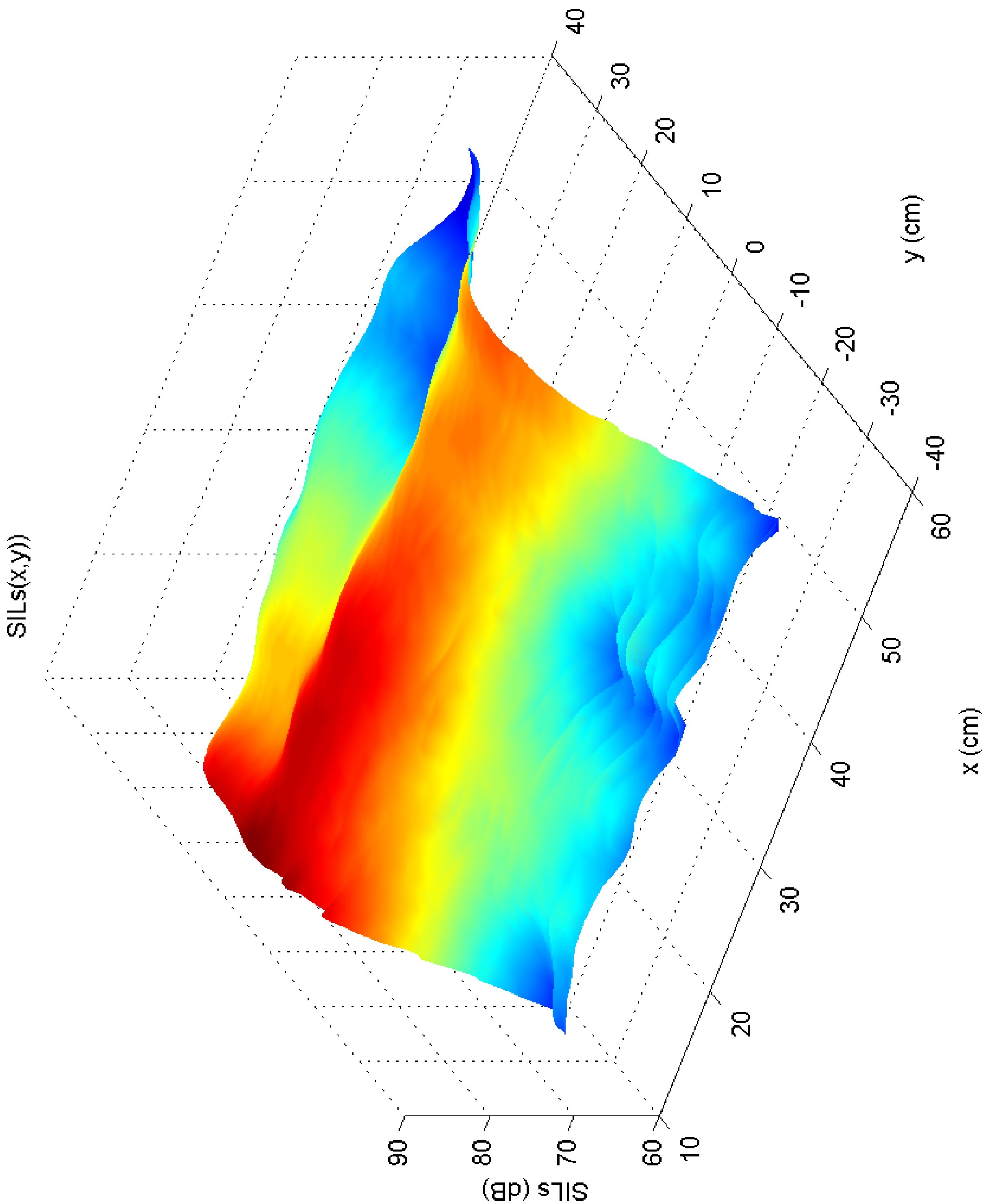
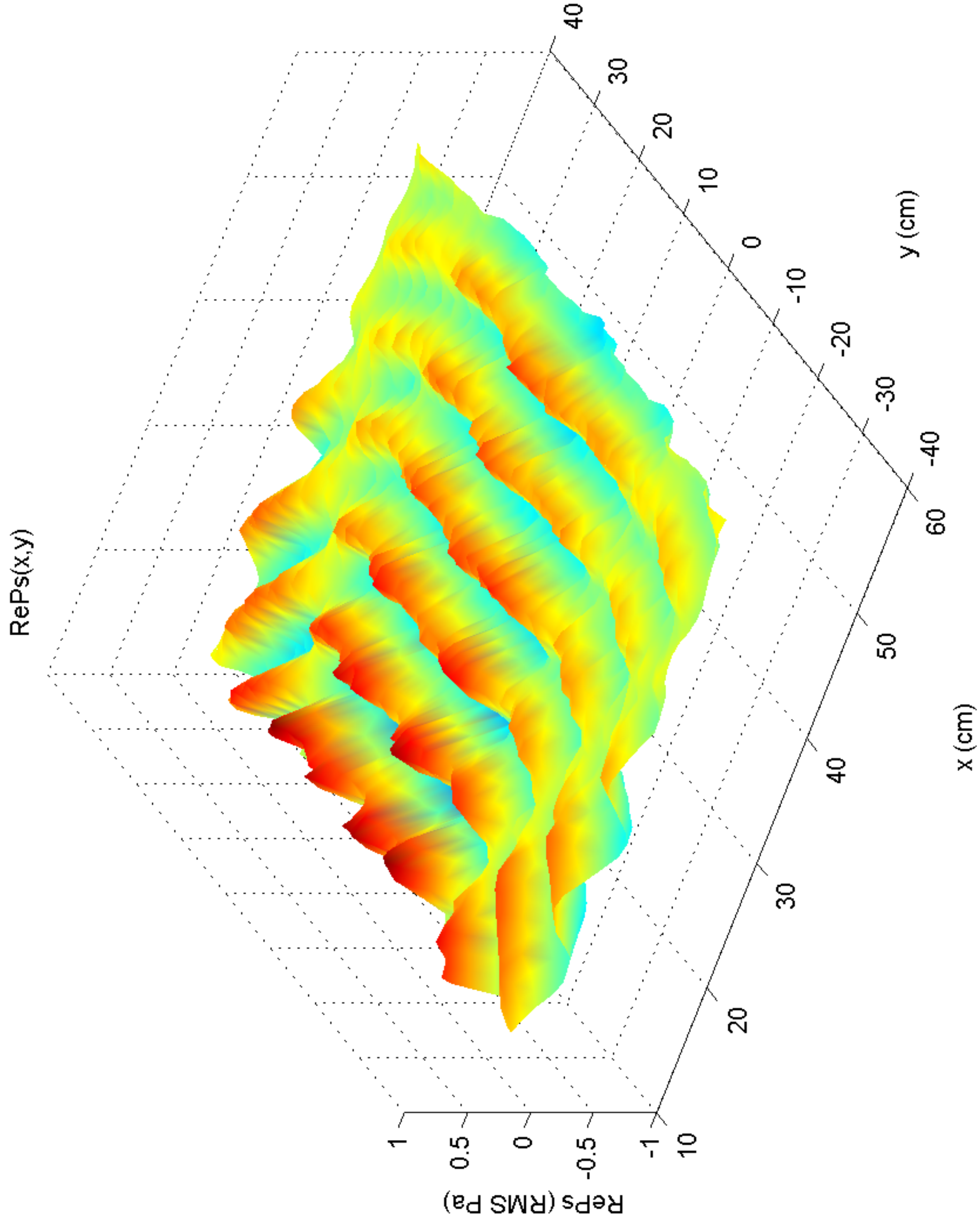


Fig 3 c) i. Real Pressure measurement for 4 linear speakers at 5Khz



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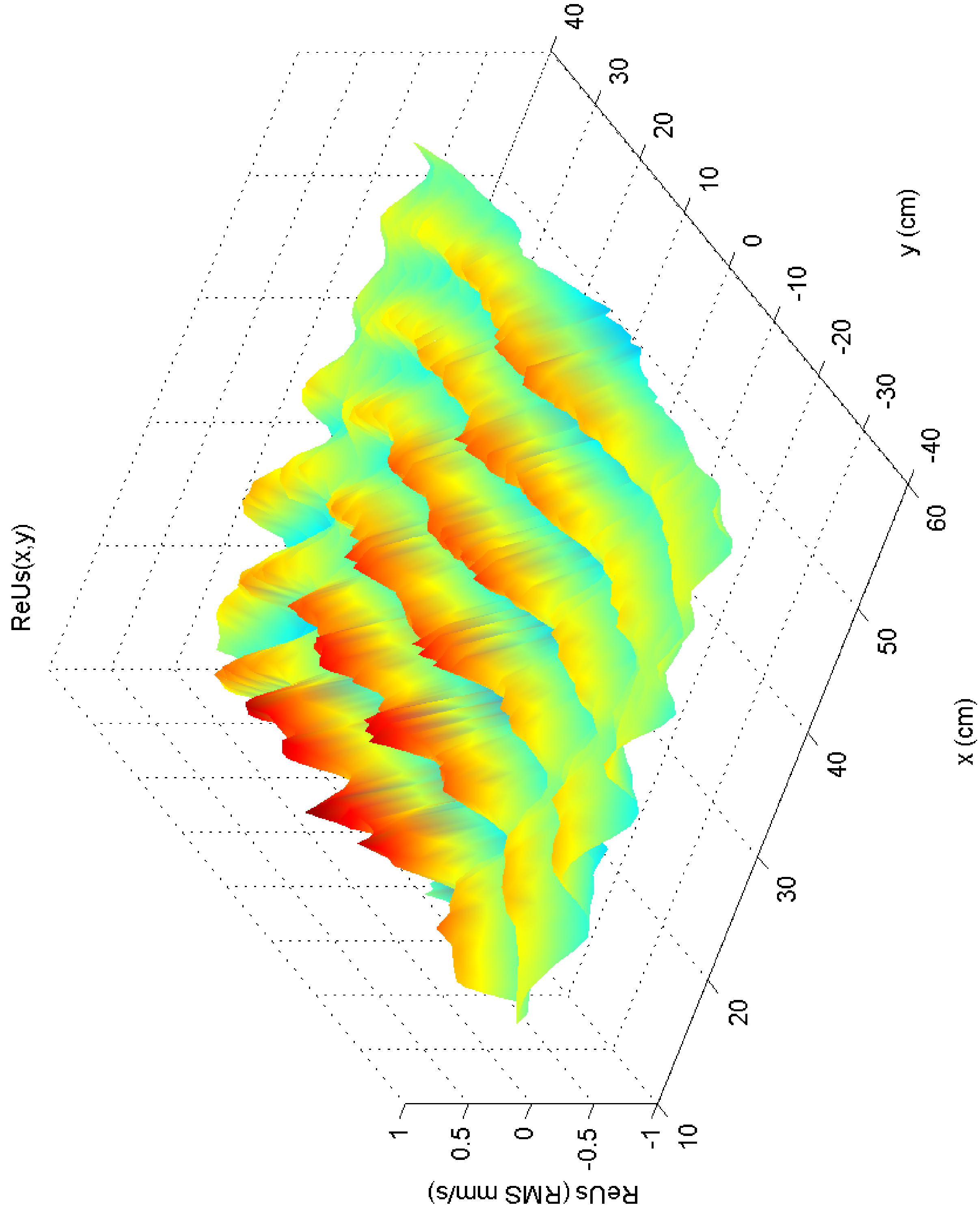
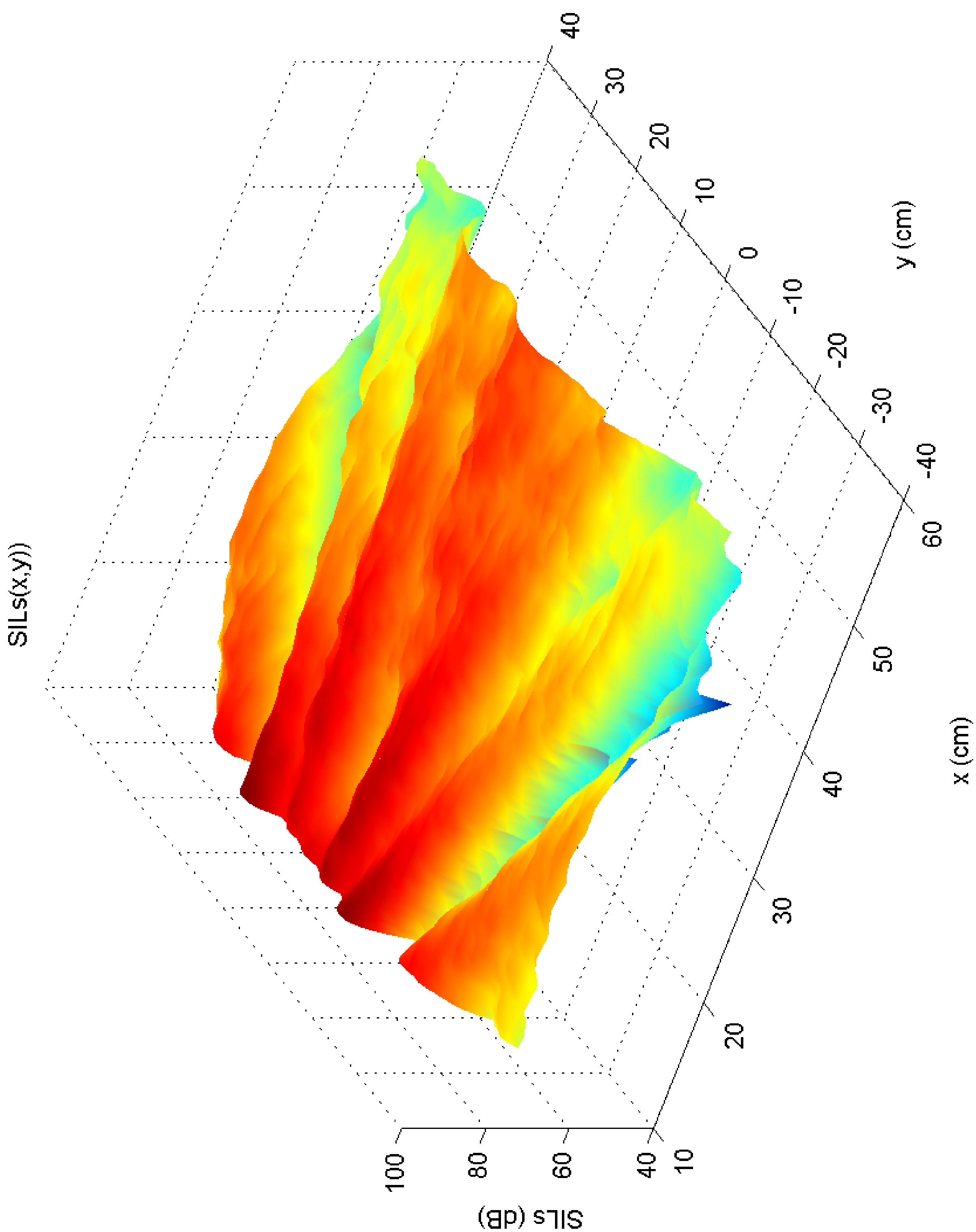


Fig 3 c) iii. Calculated Sound Intensity Level for 4 linear speakers at 5Khz



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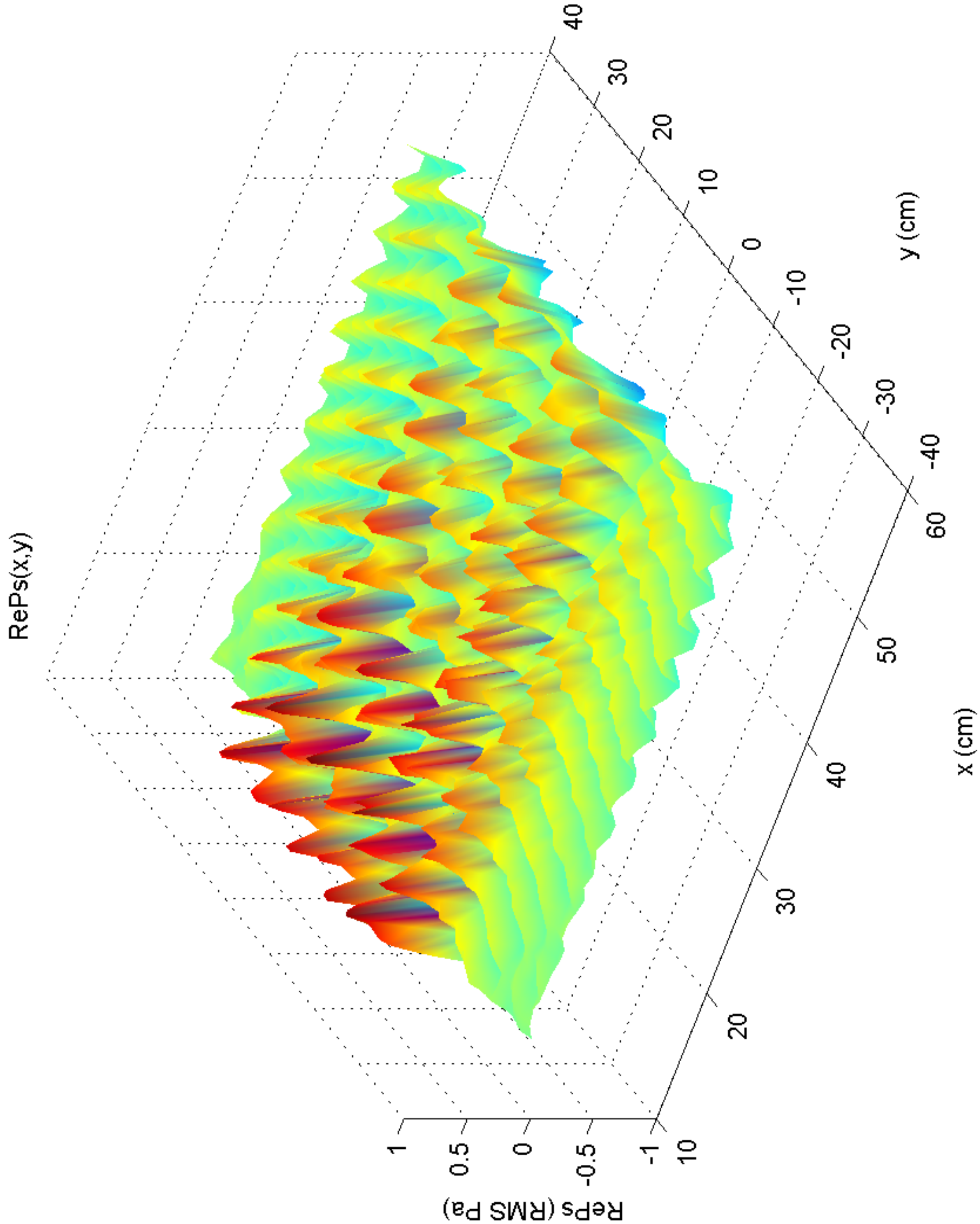


Fig 3 d) ii. Real Velocity measurement for 4 linear speakers at 10Khz

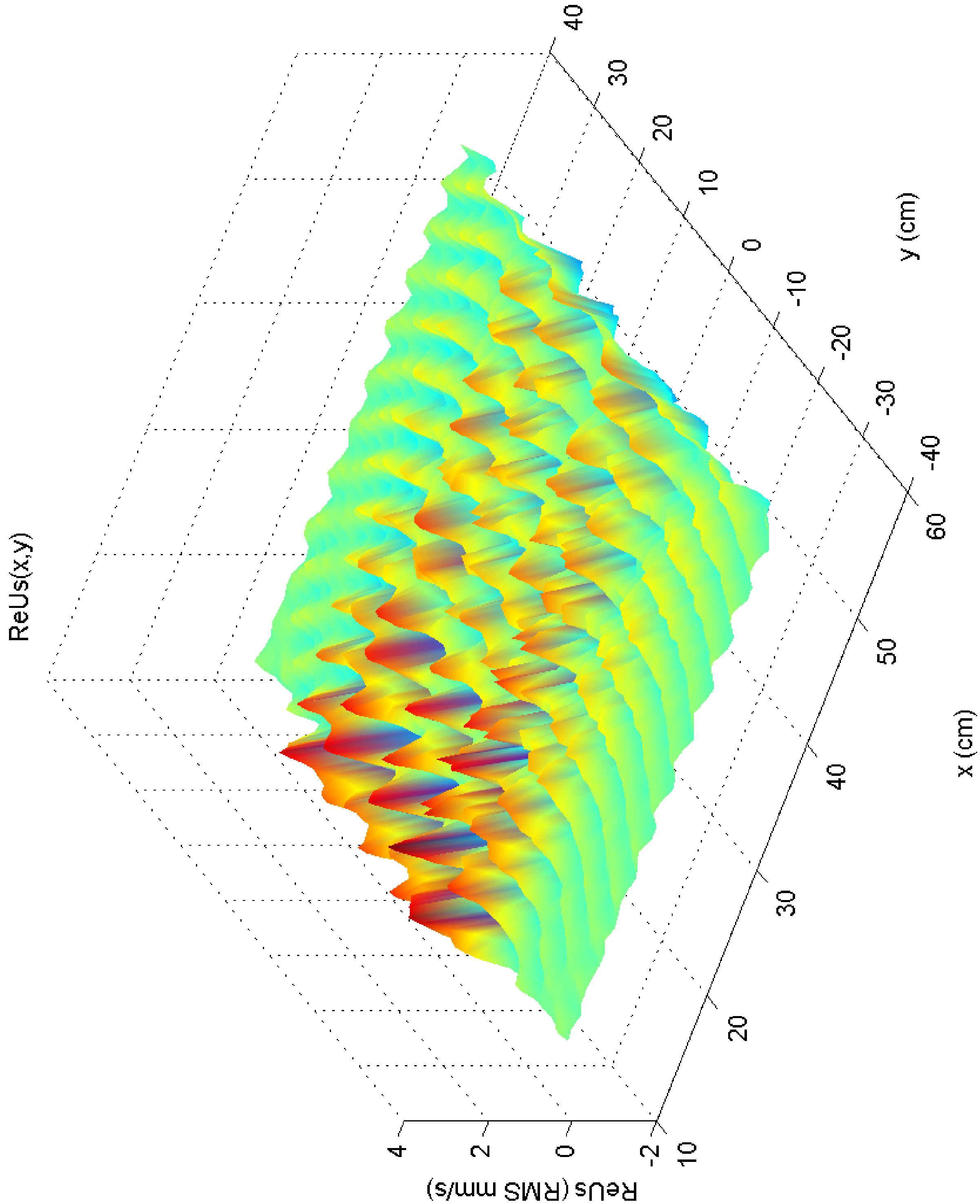


Fig 3 d) iii. Calculated Sound Intensity Level for 4 linear speakers at 10Khz

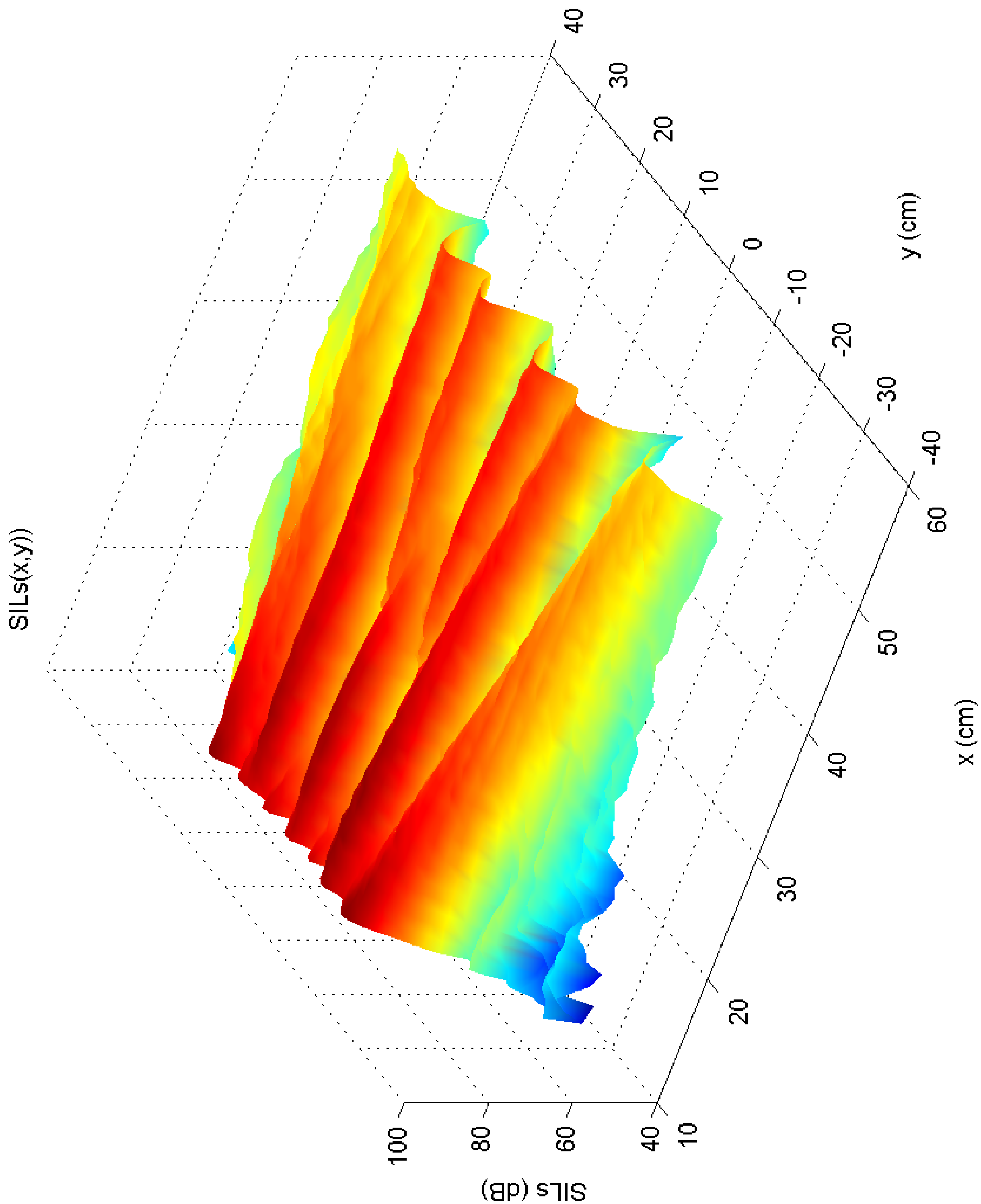


Fig 4 a) i. Real Pressure measurement for 4X4 Array at 1Khz

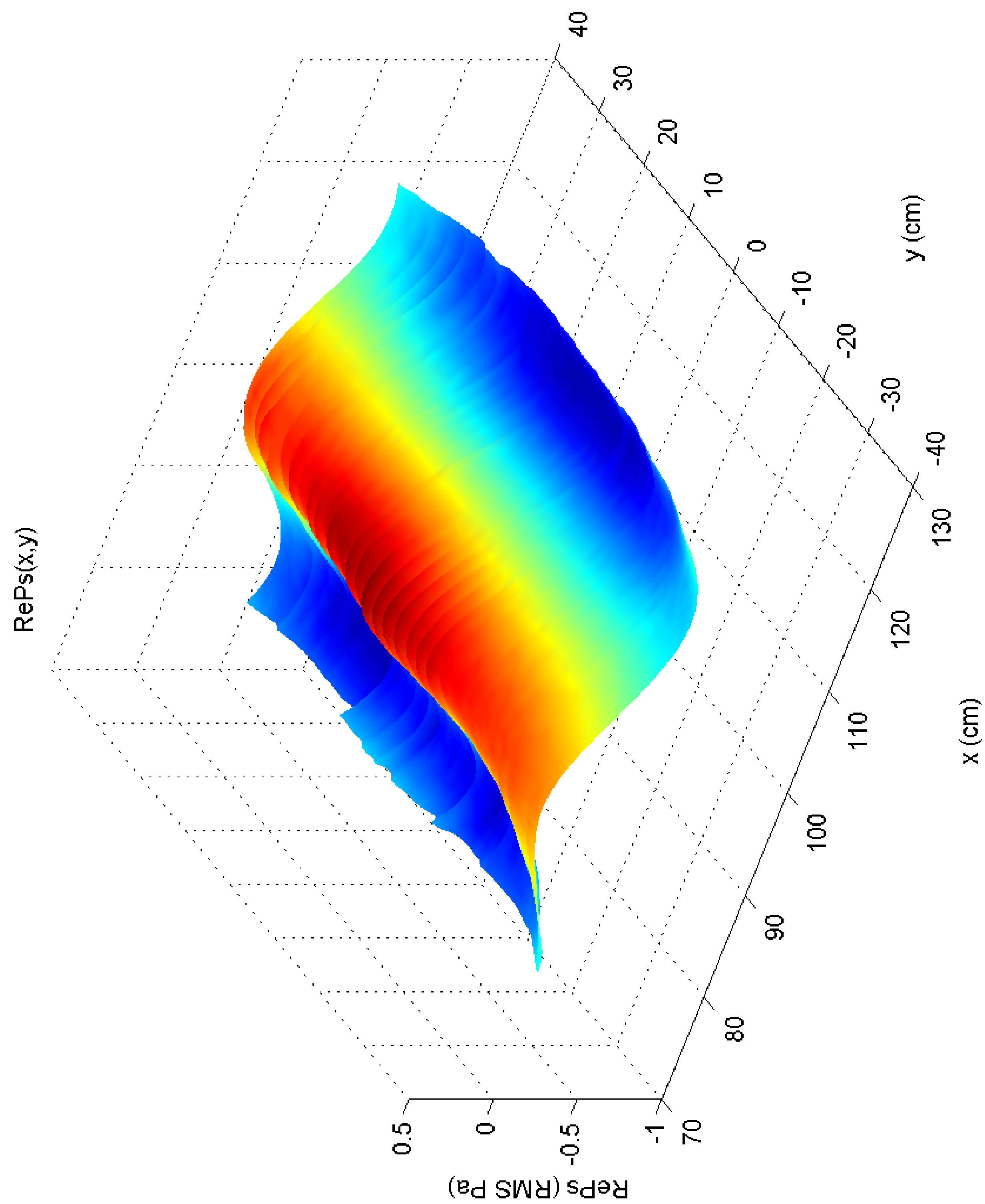


Fig 4 a) ii. Real Velocity measurement for 4X4 Array at 1Khz

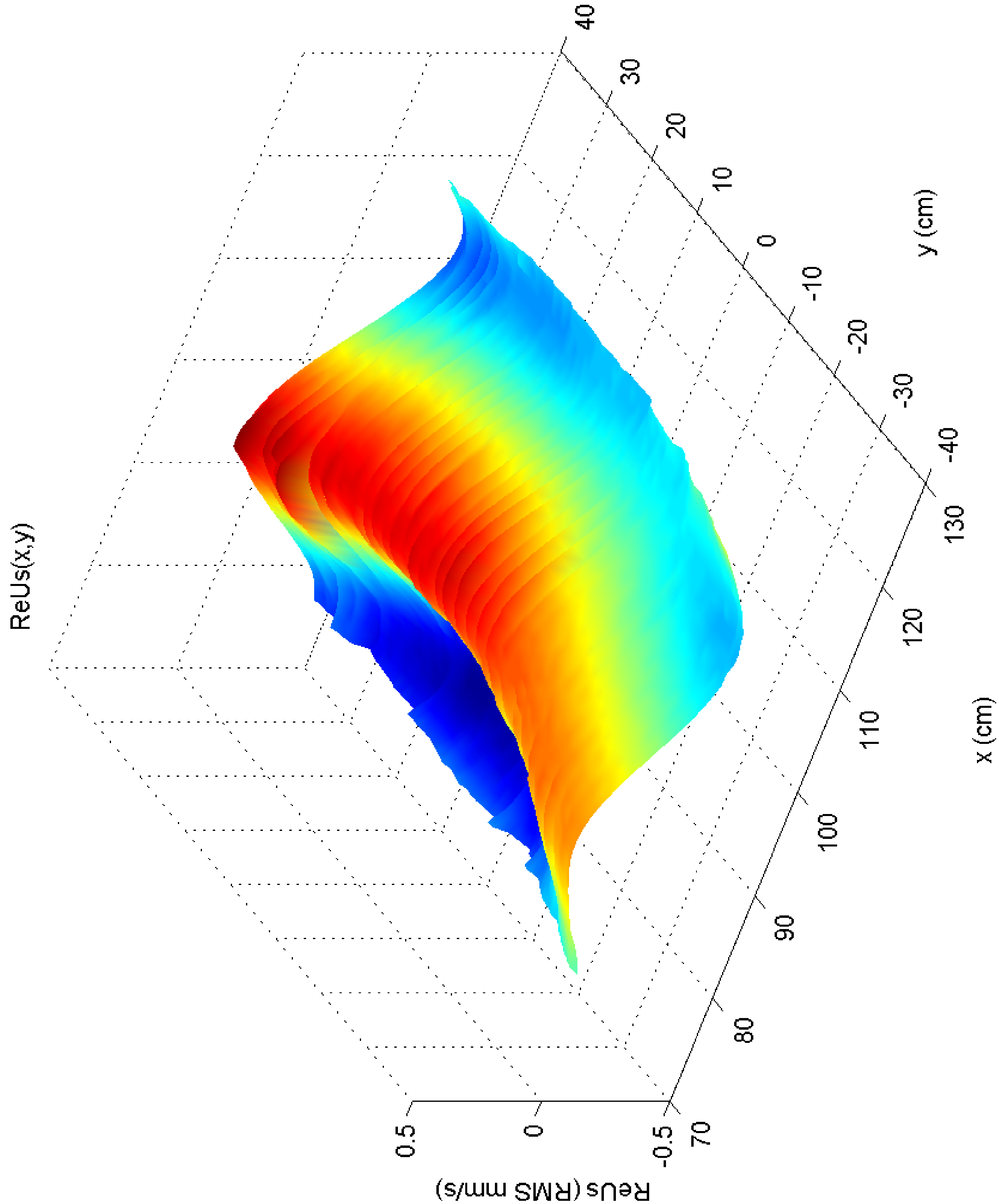


Fig 4 a) iii. Calculated Sound Intensity Level for 4X4 Array at 1Khz

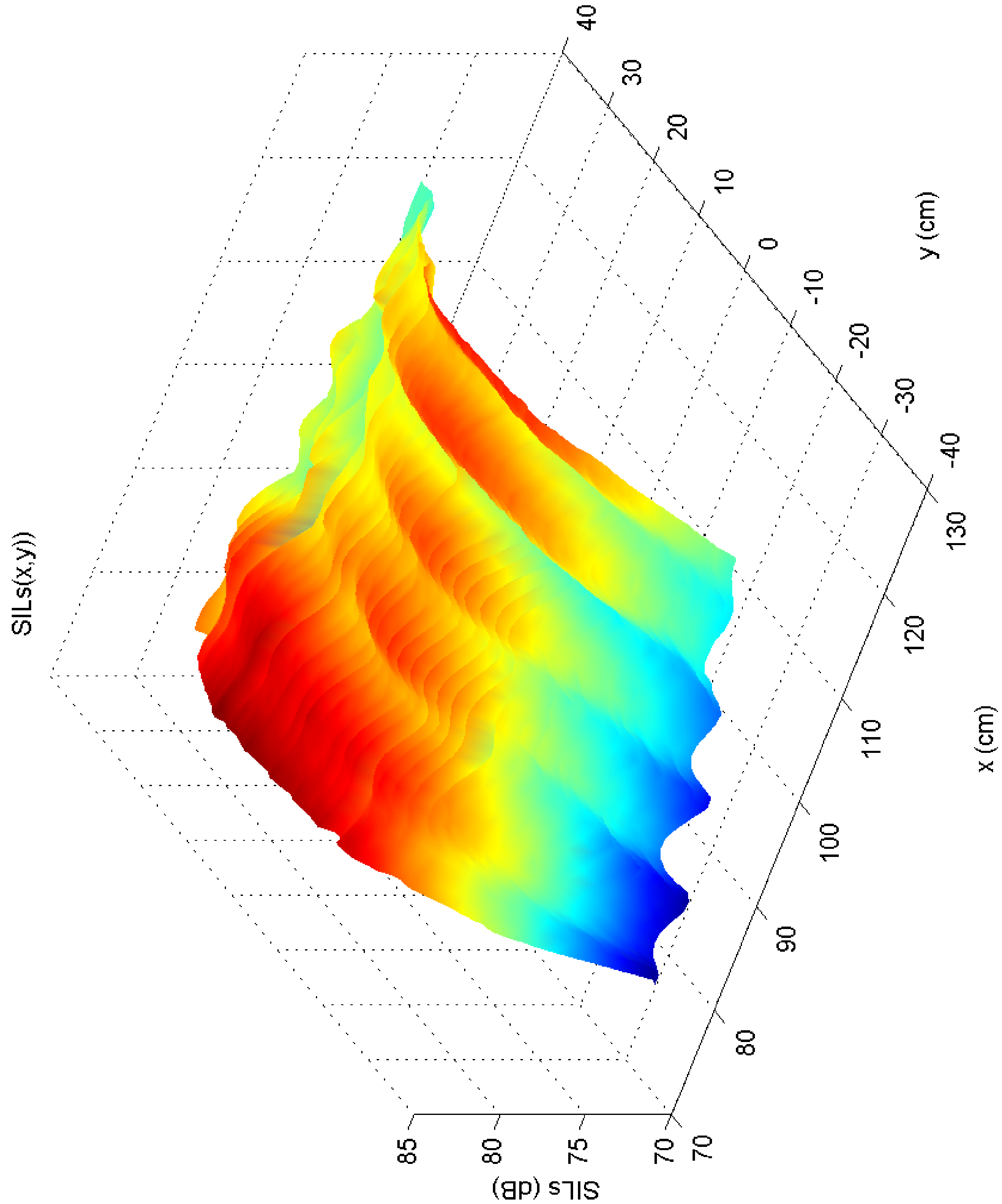
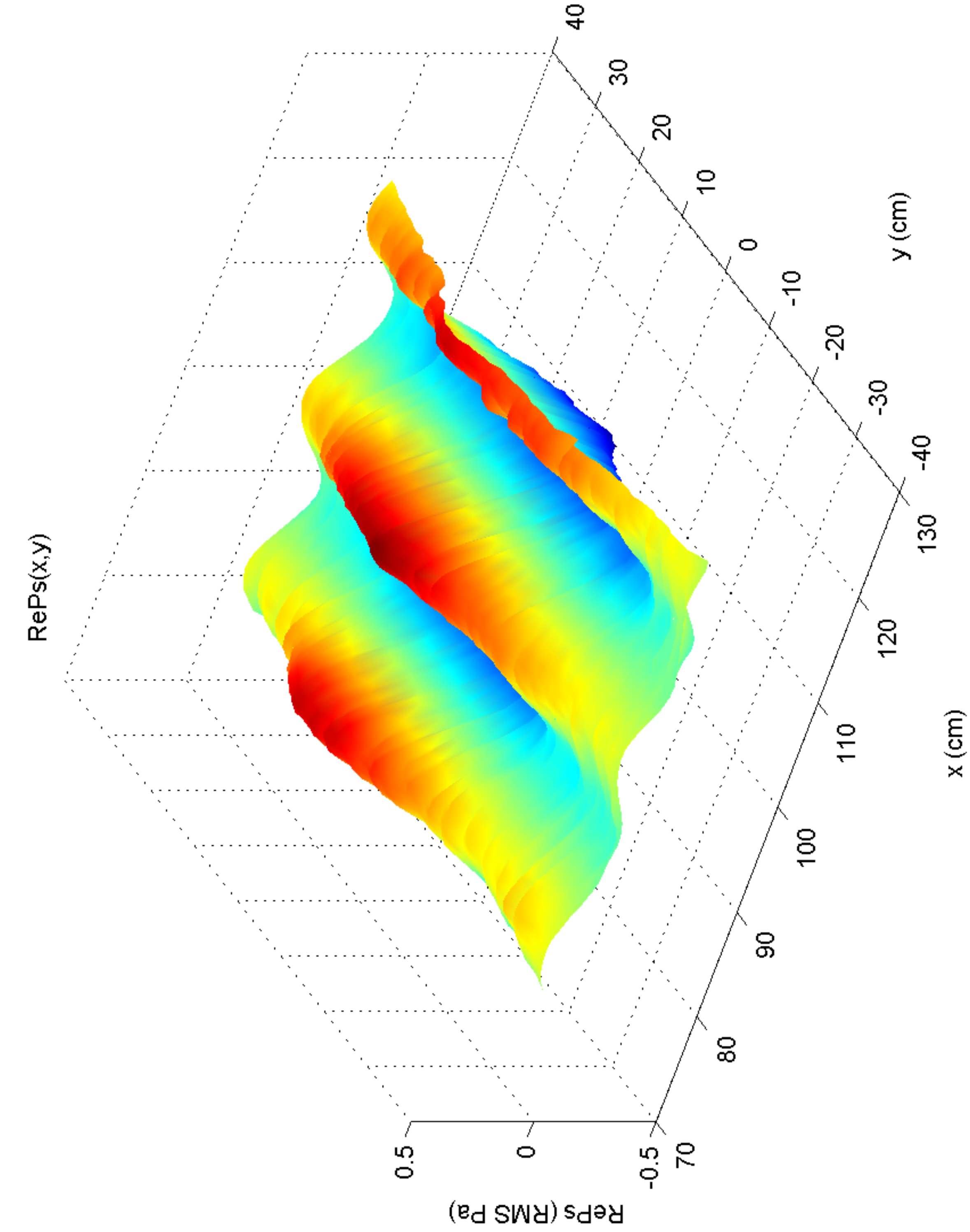


Fig 4 b) i. Real Pressure measurement for 4X4 Array at 2Khz



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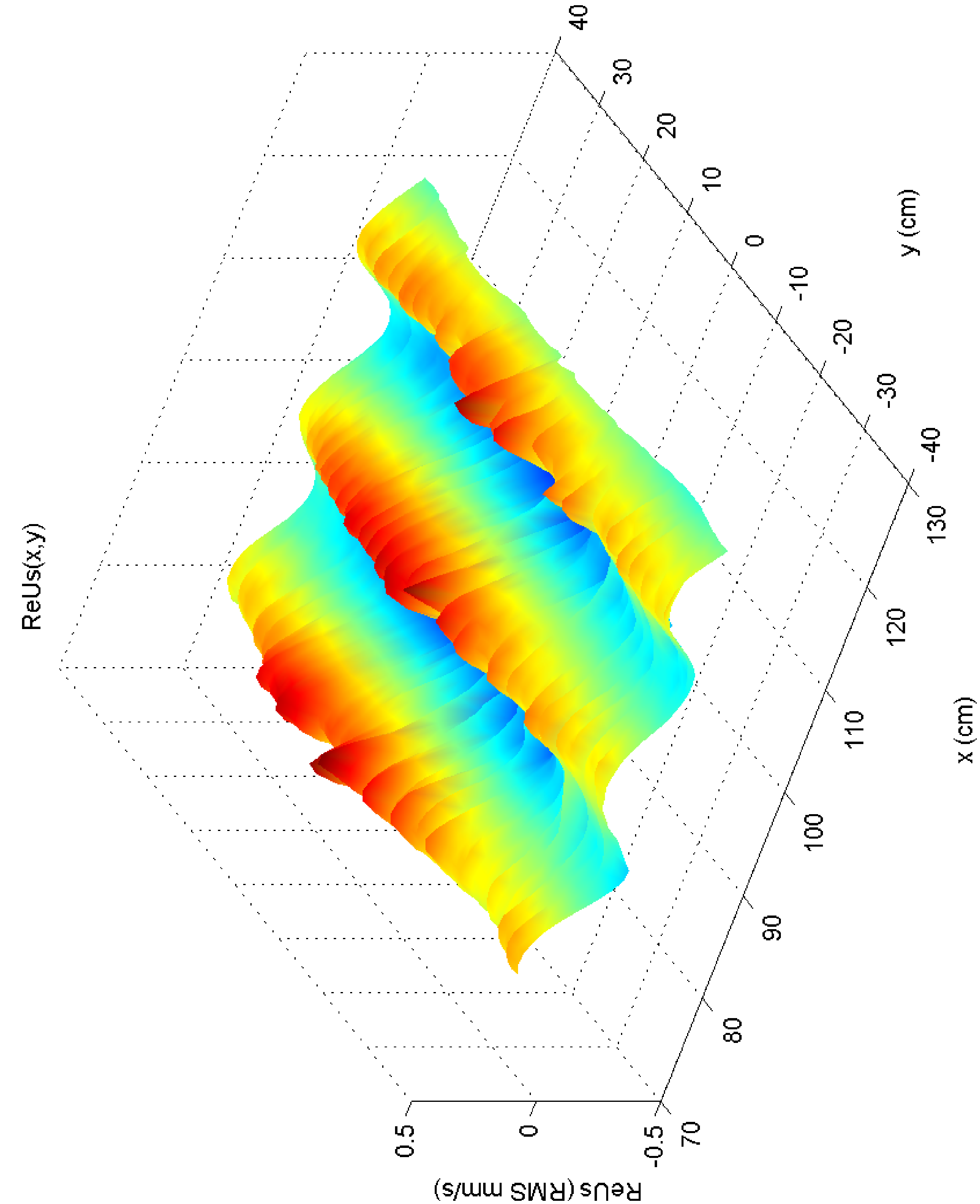

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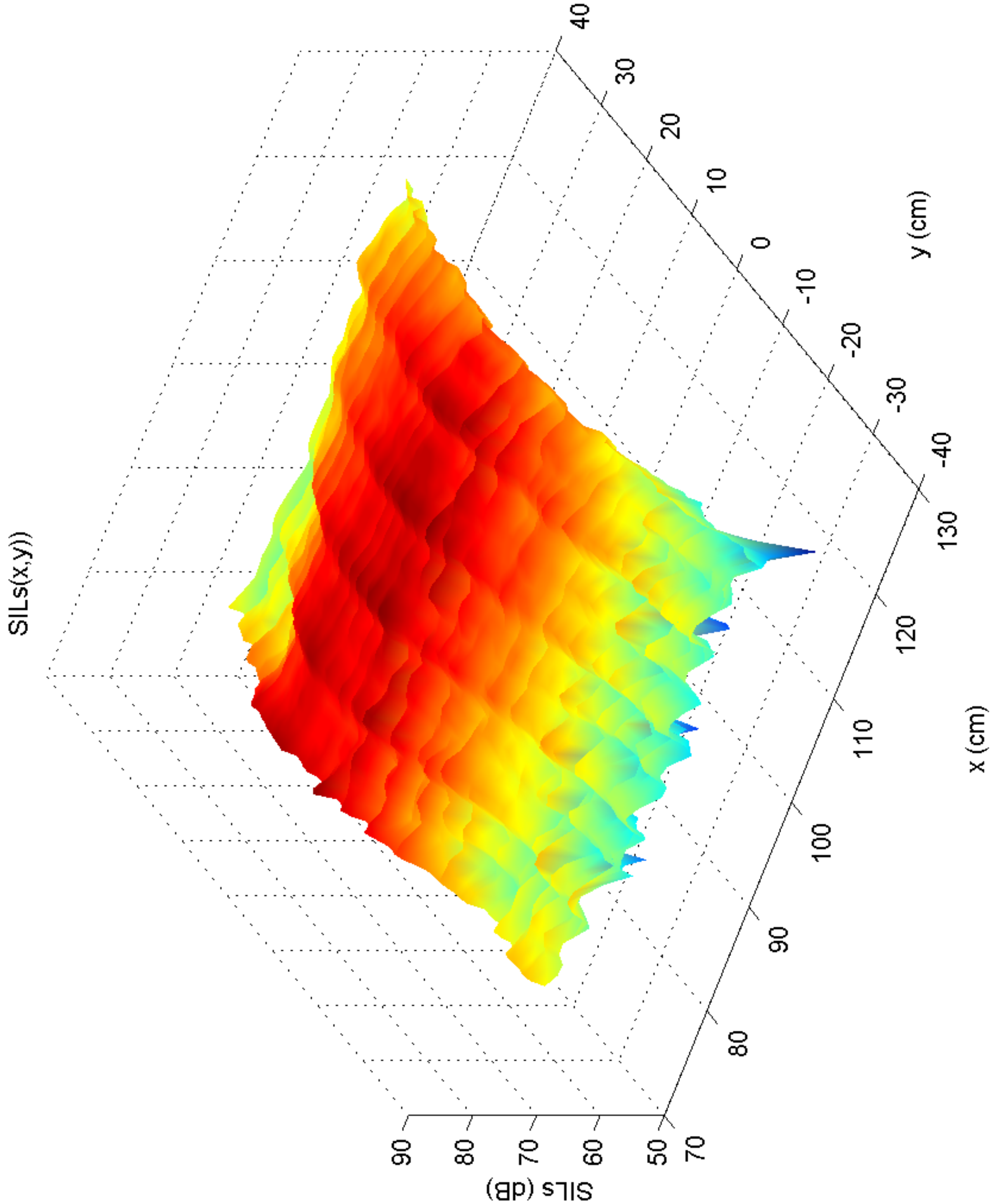


Fig 4 c) i. Real Pressure measurement for 4X4 Array at 5Khz

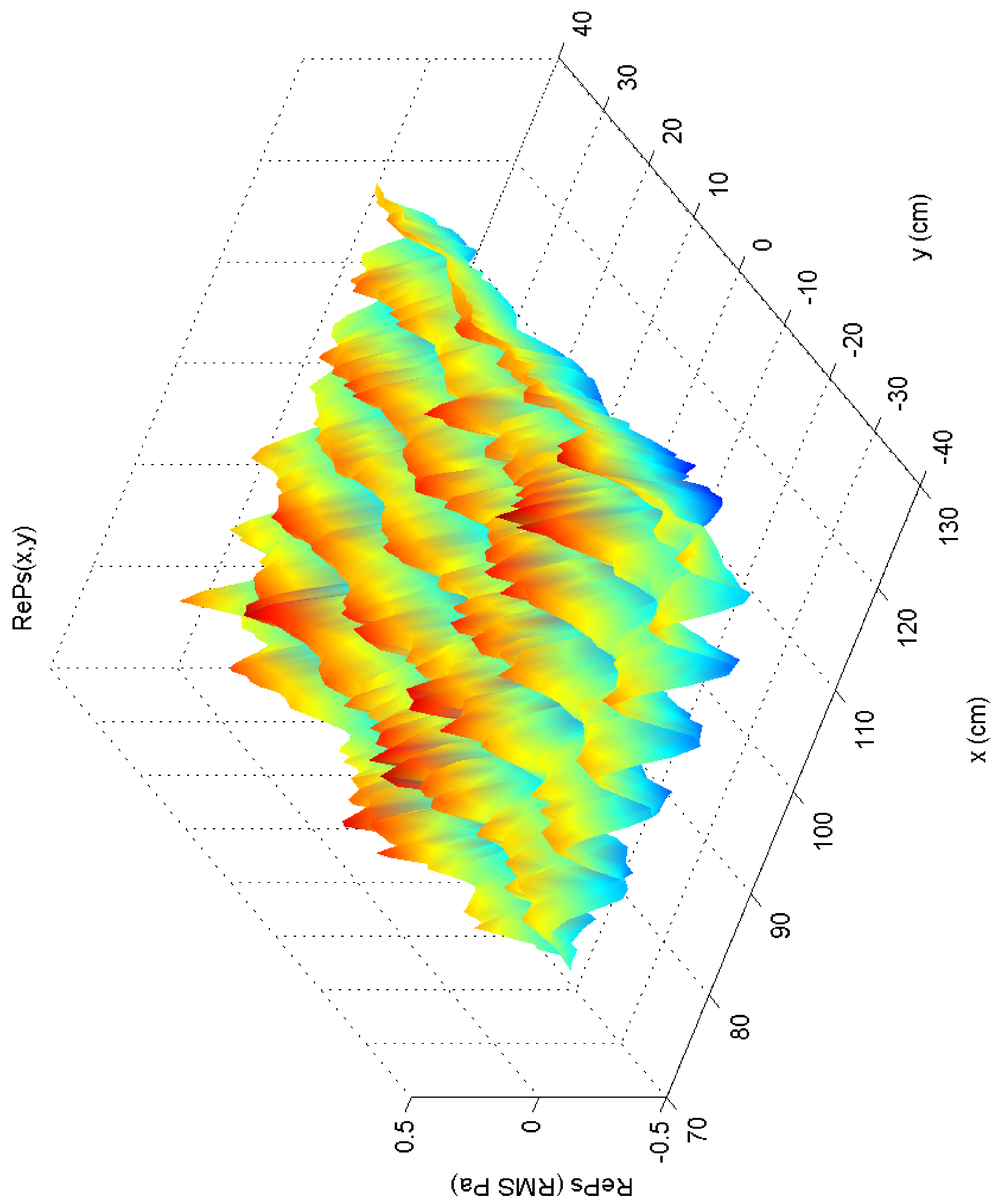
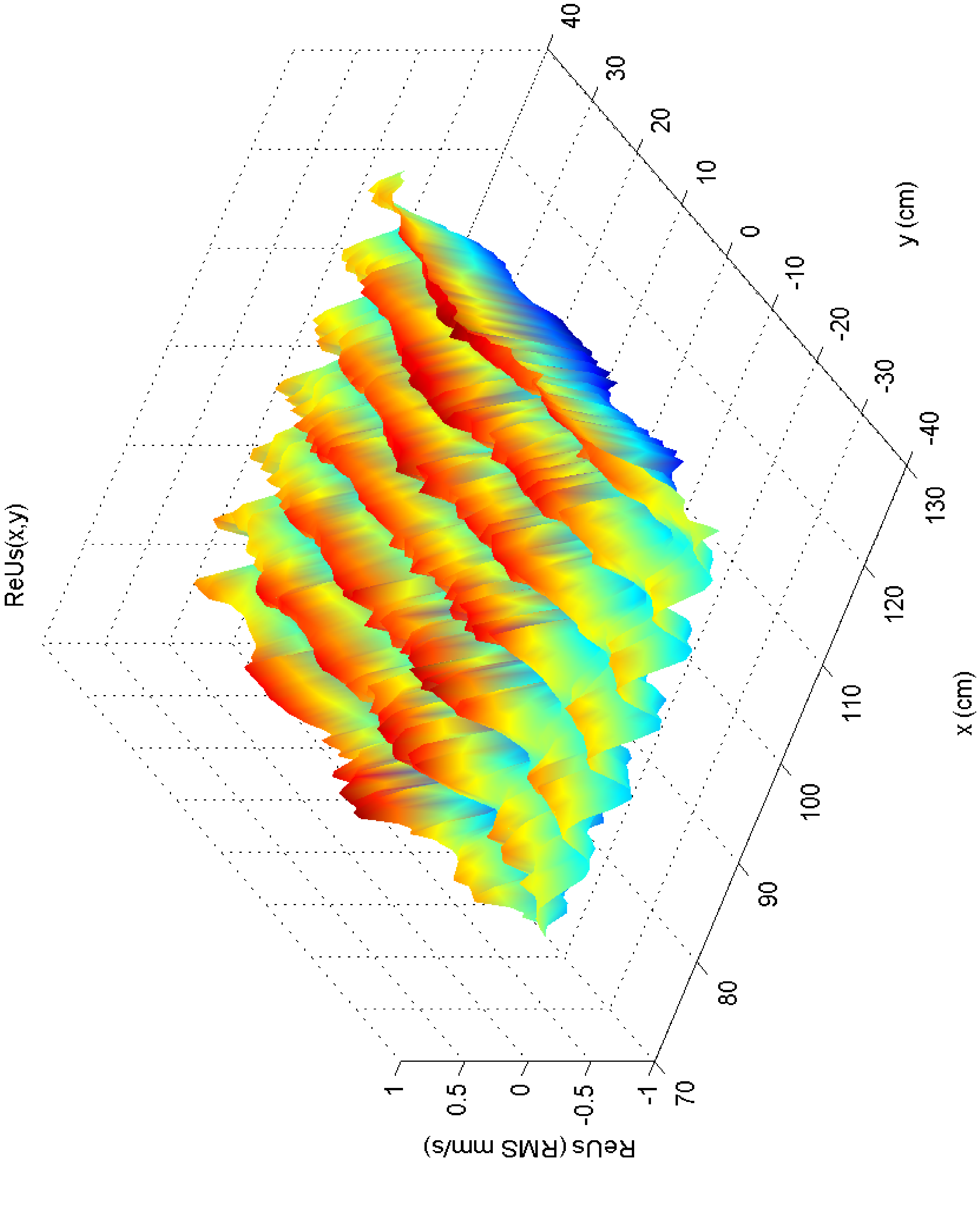


Fig 4 c) ii. Real Velocity measurement for 4X4 Array at 5Khz



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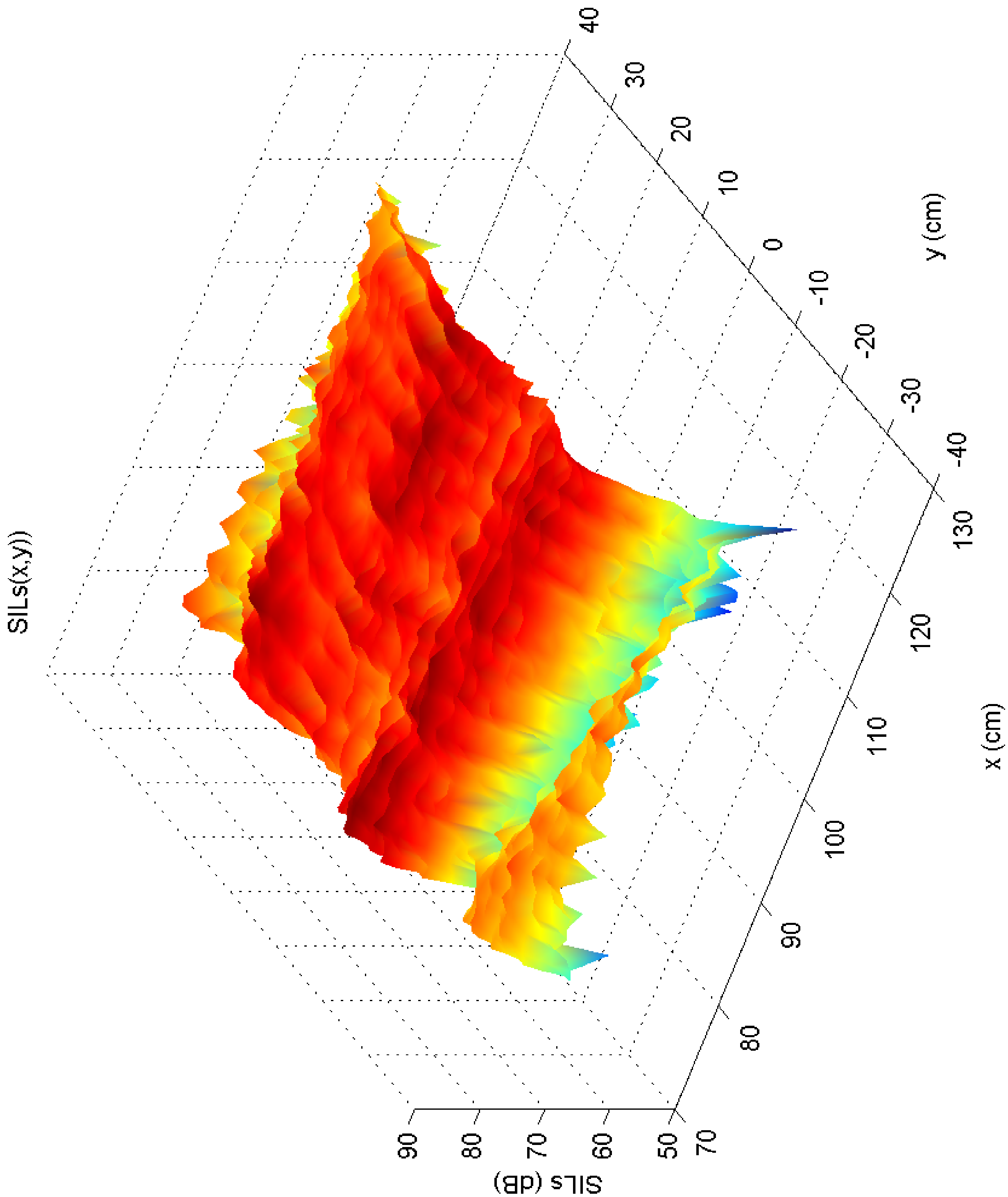

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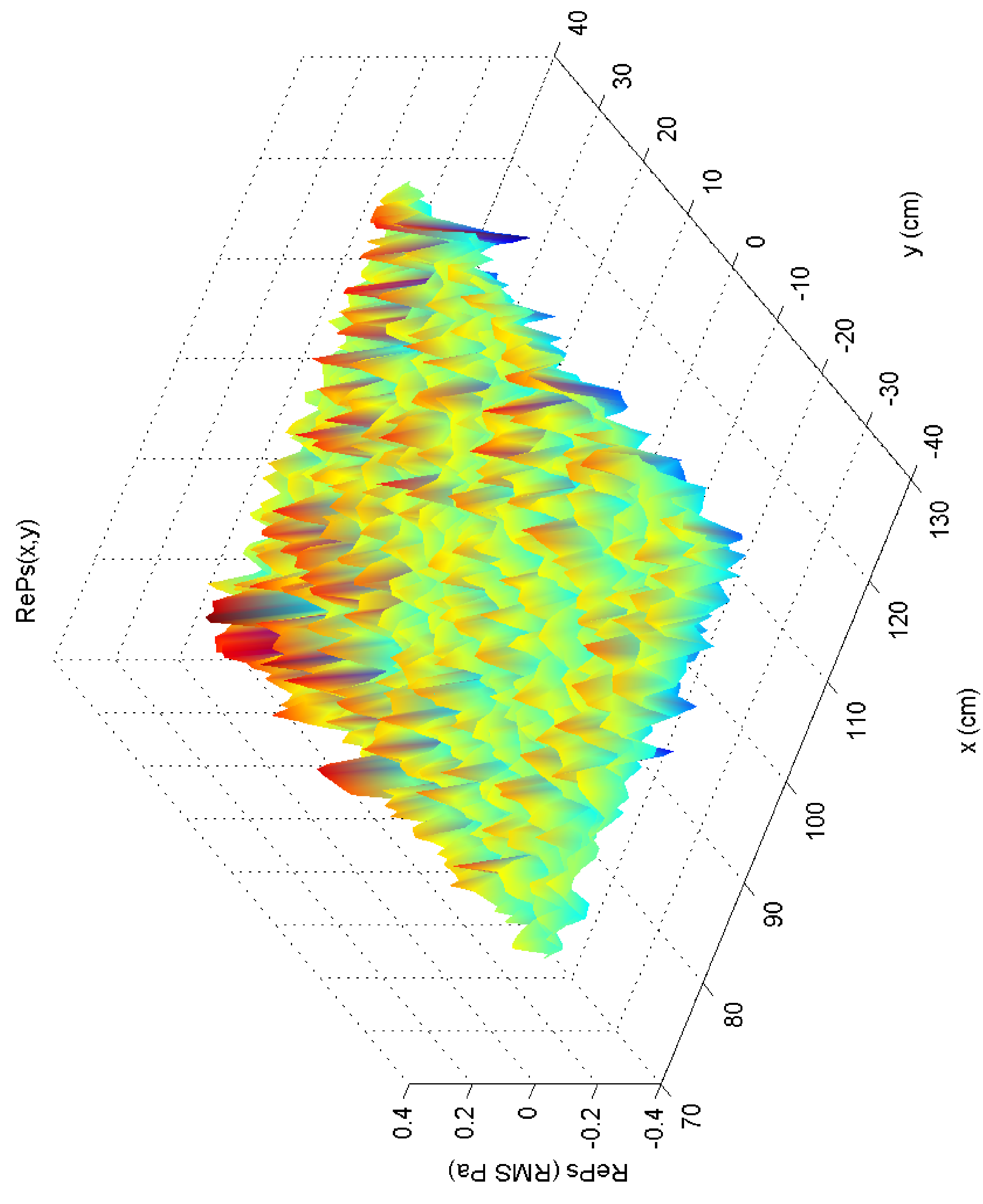

Fig 4 d) ii. Real Velocity measurement for 4X4 Array at 10Khz

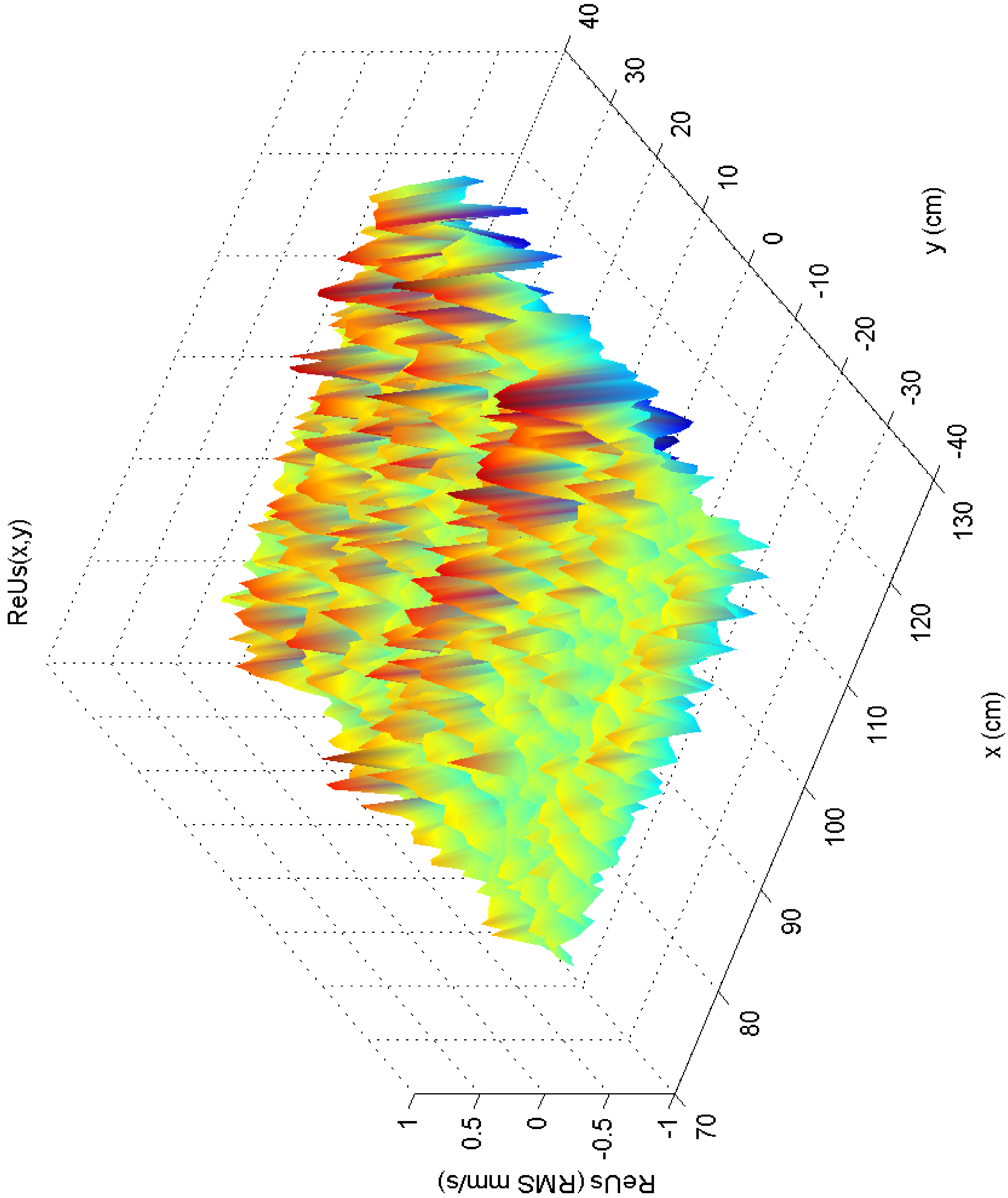

Fig 4 d) iii. Calculated Sound Intensity Level for 4X4 Array at 10Khz

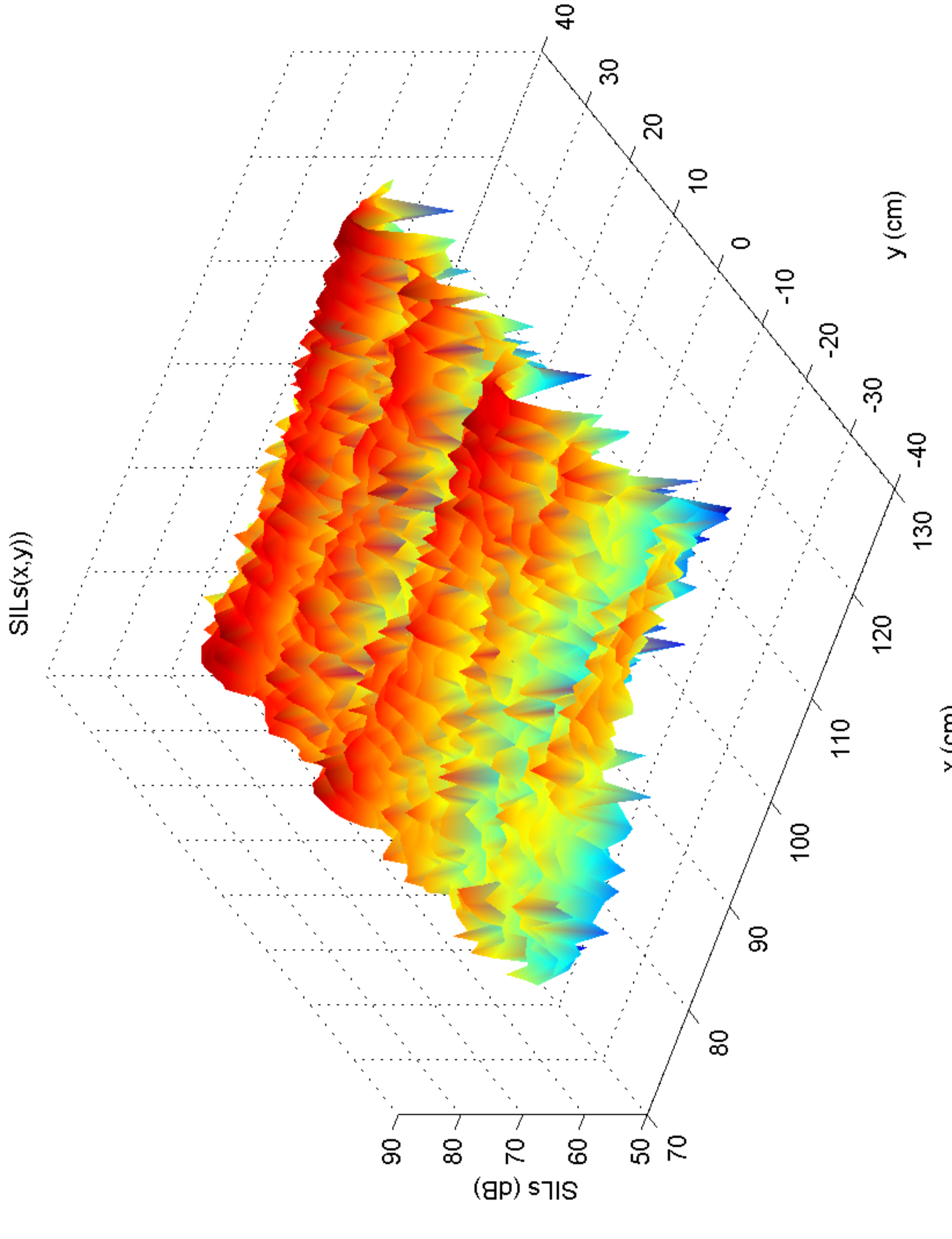

Fig 5 a) Frequency response of the cabinet from 0 to 10Khz in 10Hz steps.

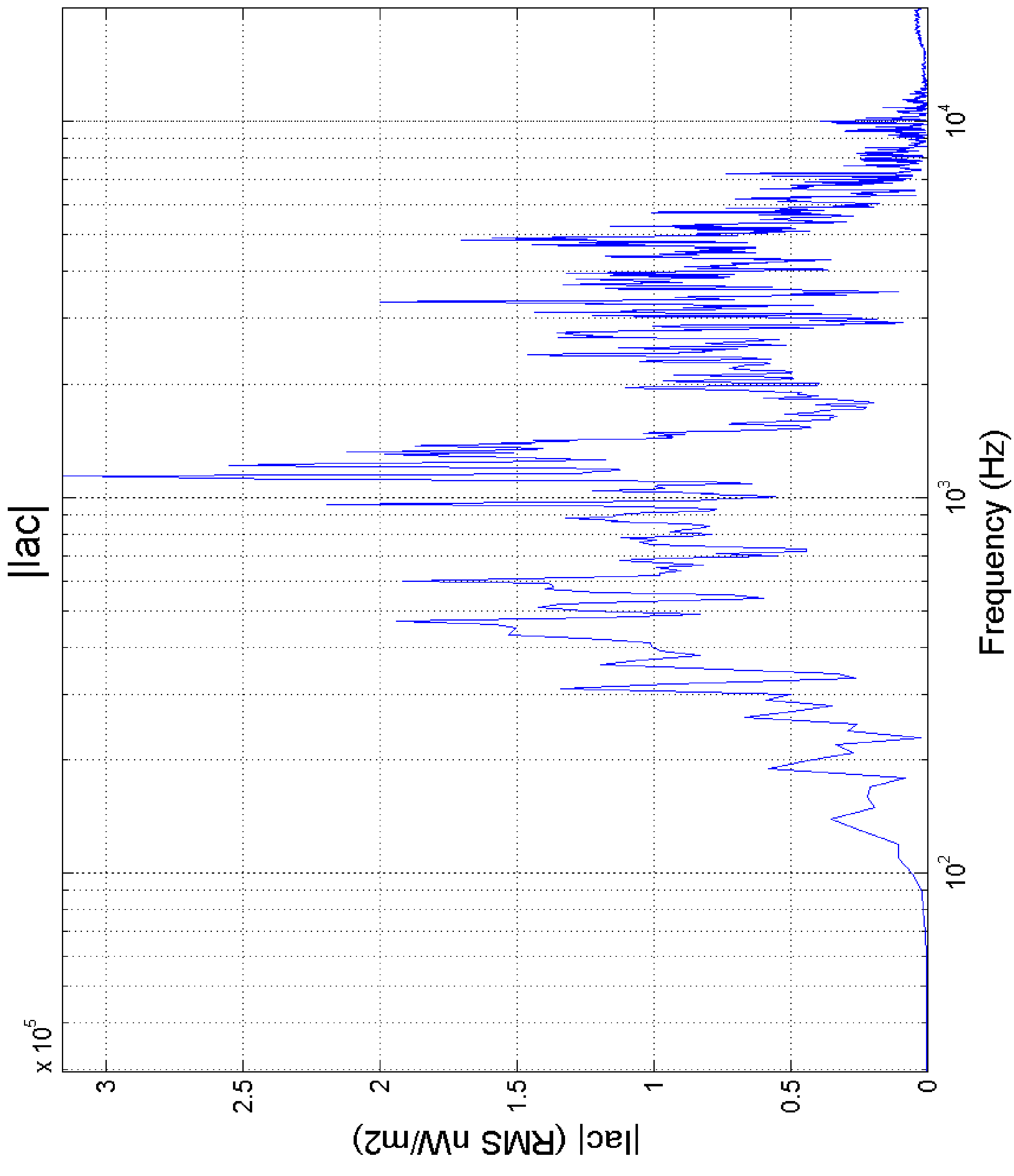

Fig 5 b) AC Current magnitude as a function of frequency, displaying characteristic minimum at 156.5 hz.