UCF Virtual Environment Immersion Center

Projective Sound Experiments

Final Report

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Executive Summary

This project reports on the results of investigations into "artifical ventriloquism" – that is, of novel means of projecting sounds into augmented reality environments. The report describes our experience with a specific audio technology from American Technology Inc., referred to as *Hypersonic Sound* *tm* that uses ultrasonic sound energy to project a "virtual sound image".

Outline

I. Brief Description of the Technology

The Hypersonic Sound System (HSS) is a portable electronic device housed in a black aluminum enclosure approximately 4 x 12 x 12 inches in size and weighing about 8 pounds. It requires 110v power and receives a monaural audio signal via an 1/8" jack. The device includes a volume control that varies the gain of its input amplifier, and a two-color LED indicator. Green indicates normal operation and red indicates that the incoming signal's level, together with the volume control's settings, are collectively too high and are producing clipping.

HSS is sold by its makers (at a loss) for $1000 per unit, in order to encourage experimental use.

II. Summary of Outcomes

When the HSS beam is directed against an object (e. g. a wall) and the hearer responds as though the sound source were located on the object, we refer to this experience as a "virtual sound source". When the HSS beam is directed at the hearer, we refer to this experience as a "direct sound source". In summary, our observations are as follows:

- The HSS can indeed produce highly directional perceived sound, in both the direct and virtual modes. However, the beam is not narrow enough to reliably deliver "private audio" via direct mode to individual hearers while excluding nearby listeners, in the absence of deliberately managed background interference sounds.

- Experimentation indoors is very challenging, since the hypersonic beam reflects off walls - often in unintended ways - and produces confusing and contradictory measurements. This result has substantial implications for possible indoor deployment of HSS systems.

- Outdoor experimentation is more controllable than indoor experimentation, since back reflections can be minimized. However, care must be taken to manage background noise.

- Direct sound sources are very compelling, and produce accurate localization across ranges of up to 200 feet.

- Virtual sound sources are also compelling, but are more difficult to apply in practice. When the hearer is behind the plane of the face of the HSS unit, the hearer almost always correctly localizes the virtual sound source to within ten degrees of its actual azimuth. However, if the hearer is in front of the HSS unit, there is substantial potential for confusion between the direct and virtual sources.
- Several anomalous virtual sound images were produced, in circumstances that do not admit of any easy explanation. Field testing of any proposed HSS applications is mandatory, as theory will not yield reliable auditory experiences.

- There is some evidence for differences in the angular dispersion of virtual sound sources, depending on the material against which the beam is directed. This is to be expected, based on the physics of the system.

III. Experimental Description

1. Background
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1. Background.

The Hypersonic Sound System (HSS) is produced by American Technology Corporation of San Diego, CA. HSS uses a beam of ultrasonic energy containing multiple frequencies (48 kHz and up) to produce audible sound by heterodyne ("beat frequency") within the air column occupied by the beam of ultrasonic energy.

The speed of sound is about 300 meters per second, or 30,000 cm/sec.

(wavelength)*(frequency)=speed;

e. g (cm/wave) * (waves/sec) = cm/sec.

thus, wavelength=speed/frequency, or 30,000/48,000 = .63 cm.

The emitter's frontal area is 28 cm x 28 cm, or approximately 44 wavelengths square. This fact is the basic source of the device's tight directionality.

When an emitter's size approximates the wavelength of the emitted signal, a spherical wave-front is produced, which expands with a surface area proportional to the square of the distance from the emitter; thus producing inverse-square dispersal of energy across the expanding surface.

A frequency of 1000 hz, for instance, yields a wavelength of 30 cm or about one foot. Thus a signal in this frequency range, produced by a normal speaker whose diameter might be approximately one foot, will produce a spherical wavefront.

However when the wavelength is a small fraction of the size of the emitter, an essentially flat wavefront is produced. If it were truly flat and constrained to a channel, such a signal would lose strength only due to interactions with the channel, and could travel very long distances. Since our hypersonic beam is not in a channel, it will lose some energy to adjacent air. The manufacturer claims that the audible sound pressure level drop-off at the center of the beam is as follows:

Range meters	Level, dB
2	95
4	88
6	85
8	82
10	81
12	80
14	79.5
16	79

Decibels are used as a measure of relative sound energy intensities; dB = 10 $\log_{10}$ E2/E1 for two energy intensities E1 and E2. Audible sound is referenced against a standard sound energy density of 10^{-12} watts per square meter, which is referred to as 0 dB. This value represents an approximation to the softest sound a healthy 21 year old can detect in midrange frequencies (in the vicinity of middle A, 440 hZ). Thus, a sound ten times louder (10^{-11} watts/m^2) is a 10dB sound; 100 times louder is a 20 dB sound; etc.

2. Objectives of the HSS Experiment

We are interested in the use of HSS as a component of multisensory augmented reality (AR) systems for training, education and entertainment. We will explore the potential to deploy HSS in both indoor and outdoor AR systems, and to use more than one HSS system in the same space. Two specific applications are envisioned:

1) Direct Private Sound: providing audio information to an individual participant, in a way that other participants cannot hear it.

2) Indirect Public Sound: providing audio information that can be perceived by all participants, and that seems to be emitted from a location where no physical sound production equipment exists. This location is referred to as a "virtual sound source".

To investigate these issues, we need quantitiative information about the following properties of the HSS system:

1) Correspondence between perceived audio levels and measurable audio levels. It should not be assumed that a novel technique for sound production yields experiences whose perceived magnitudes correspond to measured sound pressures.

2) Properties of the direct beam: falloff of intensity with angle (distance away from center of beam) and range from emitter.

3) Properties of virtual sound sources: for each of several different target materials,

- amplitude of produced sound at a standard distance
- falloff of amplitude with distance from the virtual source
- angular properties of produced sound, with respect to incident beam angle

We also seek qualitative information about interactions between two HSS systems operating in the same space. In particular,

4) Two systems broadcasting dissimilar signals into the same space: what are the perceived results for direct and virtual source situations?

5) Two systems broadcasting the identical signal into the same space: what are the perceived results for direct and virtual source situations?

Equipment and Locations. For these simple experiments, we will use two HSS Model R220A directed audio sound systems. Each is equipped with a Radio Shack 42-6012 battery powered CD player. Each HSS and each CD player is set for its maximum volume of sound display, unless distortion is noted. The most common form of distortion is clipping. An LED on top of the HSS system reports clipping, which is also perceptible to the listener as a kind of a 'chirping' effect. If any signal produces distortion, the input level from the CD is reduced until perceptible distortion is eliminated. The level that is determined to produce no distortion will be used for all sounds.

Each device is mounted on a tripod and its center is approximately five feet from the floor. The devices are aimed parallel to the floor.

We will use the demo CD provided with the HSS units as one of our sound sources. It contains various natural sounds such as birds and running water, as well as several minutes of male and female human voices in dialog. We also generated a CD containing separate tracks with 30 second sine wave ("flute") tones of 440, 880, 1760, 3520 and 7040 hZ, these being middle 'A' and four octives up. The "Standard suite" of sounds will consist of birds, running water, speech, and the five tones listed above.

A simple signal switcher/splitter was built to direct signals via mini-phone jack cables from a CD player to either of two destinations, up to 50 feet apart.

For comparison to the HSS system, we used a small ten watt PA amplifier with a six inch speaker.

3. Instrumentation and Measurement

We initially conducted experiments with a pair of dB meters- a Radio Shack 83-2055 Sound Level Meter, and a commercial dB meter provided by Jose' Maunez-Cuadra. We were concerned to determine if the subjective levels of loudness as perceived by humans, corresponded to the measured (dB) sound pressure levels when listening to HSS.

Indoor Experiment 1: Black Lab at IST. Working at IST in the high bay area ("Black Lab") we set up the PA amplifier and the HSS system and experimented with 440 hz and 880 hz sine wave signals. The switchbox was set up so that the listener could quickly switch the signal back and forth between the PA amplifier and the HSS system. An experimenter stood by to adjust the sound level on the HSS system as requested via hand signals from the listener.

We established a measured level with the PA amplifier (e. g. 75 db at 10 feet), and then asked the listener to switch back and forth between PA and HSS, signaling via hand gestures to raise or lower the HSS amplitude until the subjective experience of the two devices was the same.

We found that neither audio meter was capable of consistently measuring a dB level from the HSS signal that corresponded accurately to the measured reference value from the

PA system. We therefore (erroneously) concluded that the instrumentation was being confused by the hypersonic energy in the HSS beam. (Our subsequent experience demonstrated that the problem was internal reflections within the Black Lab, as will be discussed below.)

In order to work around this apparent inability to measure dB levels of the HSS beam, we developed an indirect "titration" method for measuring perceived sound level. Using a Mackie audio mixer, we developed a calibration between measured dB levels from the PA system, and settings on the Mackie mixer's master level control. We then attempted to have the experimental listeners, observe a HSS signal, switching back and forth to the PA system (which was positioned at a fixed distance from the listener) and adjusting its level to match the perceived level of the HSS.

After several hours of experimentation, we could see that there was no consistent pattern emerging in the data gathered in this fashion. We observed that the ambient background noise in the Black Lab varied between 60 and 65 db, which required that we set the working signal levels at 70 to 75 db. This level was unpleasant for the experimenters, and when some configurations yielded levels approaching 80 db, we concluded that we needed a quieter environment.

Indoor Experiment 2: Radio-TV Lab, On Campus. We moved the entire experiment to the Radio-TV Sound Stage in the Communications Building. This space has especially designed low velocity air conditioning and was not being used by other experimenters (as was the Black Lab) and so we hoped that the measurement process would proceed more efficiently.

However, after several hours it became clear that the indirect "titration" method was simply too cumbersome, and was not producing any reliable or consistent results. We concluded that the TV studio, while much quieter than IST's Black Lab, was still producing as many internal reflections as the Black Lab. It was time to try outdoor measurements, so we went in quest of a quiet outdoor location.

The UCF campus, it turns out, is a noisy place. The IST parking lots, various locations around dormitories, and the UCF Arboretum were all investigated and found to have average background noise from traffic, air conditioning fans and passing pedestrians of 62 to 65 dB.

We adjourned to Moshell's home in Oviedo, which is located in ten acres of pine forest. It is 0.8 miles east of Alafaya Trail, on Chapman Road. We chose days of moderate temperature, so that Moshell's air conditioning system could be turned off.

Outdoor Experiment 3: Oviedo. Using the Radio Shack hand held dB meter, we observed background ambient noise ranged from 54 to 63 dB. Aircraft taking off from Orlando International Airport passed overhead when wind conditions compelled takeoff patterns to the North. Experimentation ceased whenever we could hear an airplane (which would normall yield 61 to 63 db of background noise.)

Any wind that produces a rustling noise in the pine trees that is loud enough to be heard by the human ear, brought the ambient noise to 59 to 60 db. Traffic on Alfafaya Trail or in the adjacent Alafaya Woods subdivision would produce intermittant levels of 57 to 60 dB, and was worse between 7 and 9 AM. We avoided these times for experimentation.

We aimed the HSS system down the driveway and into the woods. The house was to the left, and the HSS was set up thirty feet away from the house and beaming parallel to its east wall. The driveway enters the sparse loblolly pine forest 200 feet from the house, and so HSS energy would not strike a "wall of forest" even at that range; it would be dispersed in the tunnel-like driveway's passage into the trees.

We set up the PA system directly next to the HSS. We quickly determined that in these circumstances with no hard surfaces beyond the listener to produce confusing return signals from the HSS, that the Radio Shack dB meter produced identical measurements from HSS and PA, when listeners judged the signals to be of the same amplitude.

This greatly simplified the experiment, since we could directly measure sound levels and would not have to use the titration method.

4. The Main Experiments

Direct Sound Sources. We set up the HSS and PA system pointing down the driveway (so that no background objects would reflect signals and confuse the measurements.) We used 440 hz and 880 hz sine waves, and measured the pattern of dispersal at a range of 15 feet. We constructed a vertical yardstick that could be driven into the ground, and moved the Radio Shack dB meter across a grid of cells.

The measuring worker always stood to the side (not directly behind the dB meter), and read off the measurements to an assistant. A variation of 2 to 3 dB was normal, due to the constant presence of ambient sounds ranging from birds chirping, to doors slamming in the subdivision, to the passage of an ice cream truck. We took the lowest reading among a varying collection of readings, since this would be the one with the minimum of ambient.

Measurement at 440 hz. Here is a color coded chart of the 440 hz results. Remember that the HSS system has a low pass filter at 440 Hz. This filter's effect is obvious when comparing this chart with the following one for 880 Hz.

440 Hz Test

PA SPEAKER				HSS ULTRASOUND				Degrees Vertical
56	57	57	57	58	58	55	55	31
56	61	57	54	60	59	56	56	22
62	63	61	65	62	58	57	57	11
62	63	61	64	63	61	55	57	0
63	61	61	63	62	59	56	55	11
56	62	63	57	61	59	56	55	22
60	58	59	58	57	58	57	55	31
65	67	59	65	59	58	57	56	40
-31	-22	-11	0	0	11	22	31	

Degrees lateral

dB

79,78
77,76
75,74
73,72
71,70
69,68
67,66
65,64
63,62
61,60
59,58,57

We display the dispersal pattern side by side, but in fact we measured the speaker and HSS bilaterally and found that both patterns were essentally symmetrical. As you can see, the speaker system is "all over the map" spatially, whereas the HSS system is closely centered around the center line (zero degrees horizontal and vertical displacement.)

We repeated the speaker measurements several times because we found the data to be so inconsistent. However the patterns were reasonably consistent. We concluded that the 440 hz sine wave was producing standing waves in the emission field from the simple 10 watt PA amplifier's speaker. We were particularly surprised by the strong band of signal right at ground level (65 and 67 dB off to the left at -31 and -22 degrees.) This was a persistent artifact after several rearrangements and remeasurements.

Note that we set the PA system's volume control to match the measured intensity at the center of the HSS beam. We knew that HSS would be producing a relatively weak signal this close to its cutoff frequency of 400 Hz.

Measurements at 880 Hz.

880 Hz Test

PA SPEAKER -31	PA SPEAKER -22	PA SPEAKER -11	PA SPEAKER 0	HSS ULTRASOUND 0	HSS ULTRASOUND 11	HSS ULTRASOUND 22	HSS ULTRASOUND 31	Degrees Vertical
68	72	77	78	69	66	61	58	31
68	66	70	75	73	69	64	58	22
75	76	77	74	77	73	67	57	11
76	77	80	78	79	75	66	60	0
71	72	67	72	74	73	66	61	11
77	79	77	79	71	70	64	60	22
71	71	73	74	68	67	65	62	31
75	76	77	77	64	63	59	58	40

HSS

Degrees lateral

dB
79,78
77,76
75,74
73,72
71,70
69,68
67,66
65,64
63,62
61,60
59,58,57

Now that we are an octive away from the 440 Hz cutoff, we can see that the HSS system is producing a much stronger signal (79 dB at beam center). We adjusted the PA system to have the same central beam intensity. Again we see the PA system as having a broad and somewhat jumbled distribution of energy. The dispersal itself is not surprising, since the sound's wavelength is about 1 foot and we were measuring at a range of 15 feet away from an 8 in speaker cone.

The contrast with the HSS is instructive. 11 degrees away from the beam in either horizontal or vertical directions, the sound intensity dropped off approximately 4 dB. By interpolation we can see that to get to a 10 dB dropoff, one as to go out to approximately 17 degrees in the horizontal and 25 degrees in the vertical direction. This is consistent with our listener directionality experiments reported below.

The manufacturer provides a graph on page 15 of the HSS Owner's manual, titled "Audio Beam Dispersal, 3 kHz." At a range of 4.5 meters this chart reports a dispersal of 25 cm. This corresponds to a beam divergence of 3.18 degrees. However there is no information given as to what sound pressure level is measured at this dispersal angle.

Granting the possibility that the beam may produce a tighter pattern at higher frequencies, we are still forced to conclude that the manufacturer's beam dispersal seems to be using some nominal dropoff value such as 2 or 3 dB as its criterion. This uncalibrated chart leads to an unrealistic expectation that a listener, standing say 50 cm off axis at a range of 5 meters, would hear a 10 dB attenuation of the signal compared to center beam. Our data indicates that (at 880 hz) the attenuation would actually be only 2 to 3 dB at this range.

Indirect Sound Sources

The perception of indirect sound sources is much harder to measure quantitatively than that of direct sound sources. We quickly discovered that when we were directing HSS against a wall of the house from 30 feet away, and standing 40 or more feet back to listen, that the measured dB levels were in the low 60s - and often within the ambient noise. In other words, you could not reliably detect a difference on the dB meter when the HSS system was turned on and off.

However, human subjects had no difficulty in identifying the content of the sound signal as well as its perceived location. We used two different signals - 880 hz sine wave, and a recording of male and female voices discussing the virtues of the HSS system (the demo CD provided by American Technology, Track 6.)

The 880 hz signal is more convenient for measuring levels, but as mentioned above, the levels were not reliably measurable in virtual sources. We therefore used the human voice recording for our qualitative directionality tests, since it is more "ecologically valid" - that is, in a military training situation we would be more likely to use sounds such as human speech, than pure test tones.

Setup. Moshell's house has a porte-cochere, a guest bedroom with glass windows and a stucco wall, and a laundry room with three large glass windows. There is also a tree house located six feet up in a cluster of loblolly pines. These four targets were designated (from left to right) as

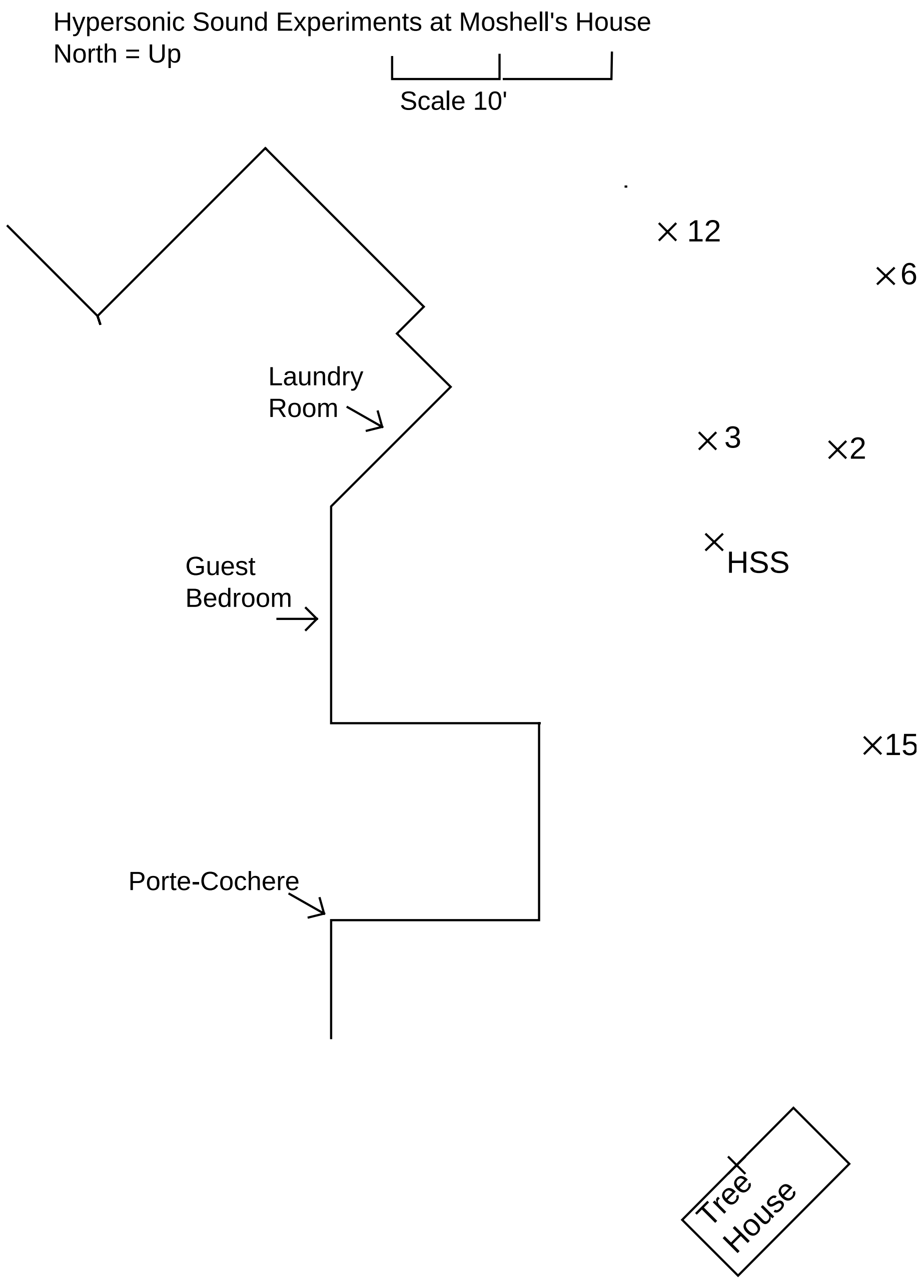
TH - Tree House
PC - Porte-Cochere
GB - Guest Bedroom
LR - Laundry Room

The targets were chosen because each has a distinctive property. The tree house has a superstructure four feet wide located at the northeast end of a platform that is 4 x 8 feet (with hand-rail), and is remote from the rest of the structures. Its background is 'soft' - a thin grove of pine trees. At the altitude of the tree house, there are few branches or needles.

The porte-cochere provided an interior ceiling corner, to the left of the house's entrance. We have found that HSS when beamed into an interior corner - particularly at the point where two walls meet the ceiling- a particularly strong virtual source effect is observed.

The guest bedroom provided a convenient stucco wall surface, which we expected to disperse the energy somewhat more broadly than a glossy surface would. (This turned out to be the case.) However there are adjacent glass windows, so this is not a "pure" stucco wall.

The laundry room windows provided a glossy surface to evaluate for specular, or mirror-like, reflection. However, there were one-foot vertical strips of stucco between the three laundry windows.



The HSS emitter was mounted on its tripod at location HSS. Wooden stakes numbered 2,3,6,12 and 15 served as reference points (the numbers were left over from a different experiment.) Their locations were measured from fixed points on the house.

A pointing measurement device was constructed, consisting of a 1 ft. square flat wooden table on a tripod. To this was affixed a compass rose and a triangular pointer of wood. A magnetic compass was used to orient this device at each reference point.

Procedure. A listener would walk around the pointing device, with eyes closed. This served to disorient the listener. An operator would randomly point HSS at one of the four locations (TH, PC, GB, LR) and turn on the voice dialog recording. The listener would then point the indicator in the direction he thought the sound was coming from. If he heard two or more sources, he was instructed to report both of them.

The listener would announce a confidence level between 1 (almost no confidence) and 5 (certainty as to location.) Then he would open his eyes, read the compass direction, and announce the results to the recorder.

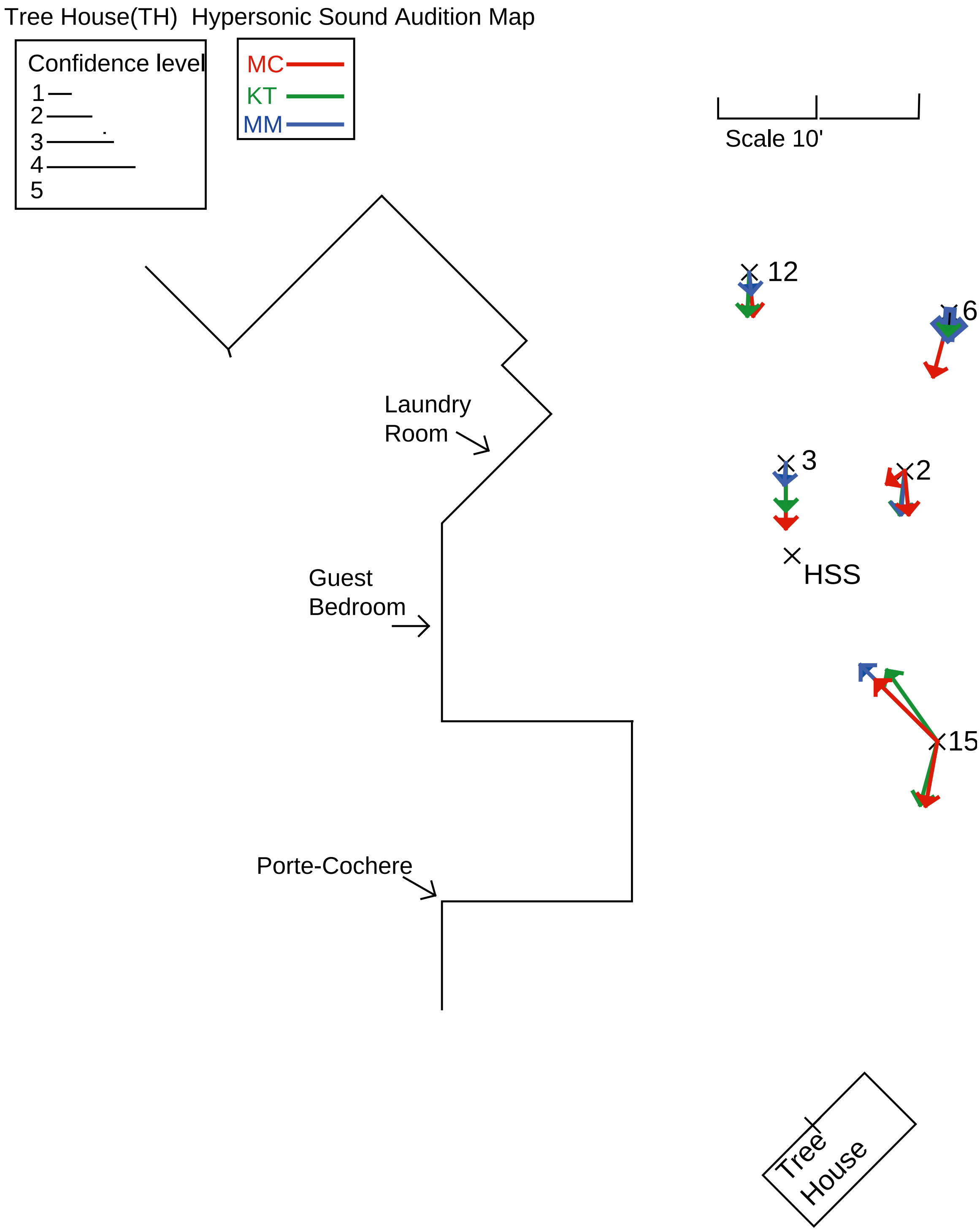
Three workers rotated in the roles of operator, listener and recorder. In the first experiments in early February, Michael Moshell, Daniel Dobler and Sean Vendryes were the workers. However, when we began to analyze the data we realized that there were problems in how the stakes' locations were measures.

Subsequently the experiments were repeated in early march by Moshell with the assistance of Marcel Cubilla and Kawai Tang (both male, 21 years old, normal hearing.) Moshell is 57 and has slightly impaired hearing, as a normal effect of aging. The results reported here are from this latter experiment.

Data Display. We have sorted the data into four collections, displayed in the following four maps. All data from signals directed at the tree house is summarized in the first map. We use three different colored arrows to indicate the responses of Moshell (blue), Tang (green), Cubilla (red).

Tree House Data. As can be seen, the listeners agreed almost unanimously as to the direction of the treehouse. Due to its distance from the HSS and the fact that its facade was at a 45 degree angle, the signal was quite faint and most listners reported confidence of only 1 or 2. There was one deviant response (by Cubilla) who perceived the target as being to the west (with confidence=1). Upon retrying, he detected it in the south like everyone else.

From location 15, all listeners reported a direct signal considerably louder than the virtual signal. This was the case even though location 15 is thirty degrees off the signal axis from HSS to the tree house.


Tree House(TH) Hypersonic Sound Audition Map
Confidence level
1
2
3
4
5
MC
KT
MM
Scale 10'
12
6
Laundry
Room
3
2
HSS
Guest
Bedroom
15
Porte-Cochere
Tree
House

Porte-Cochere Data. The porte-cochere is an interesting situation, because there are several interfering factors. There are two square columns (not shown in the other maps) that support the porte-cochere. The HSS beam was passing just to the right of the northmost column, enroute to the interior corner. We anticipated that this would produce a virtual source that would attract listeners' attention, and perhaps would cause their observed positions to deviate to the right (from stations 2, 3, 6 and 12).

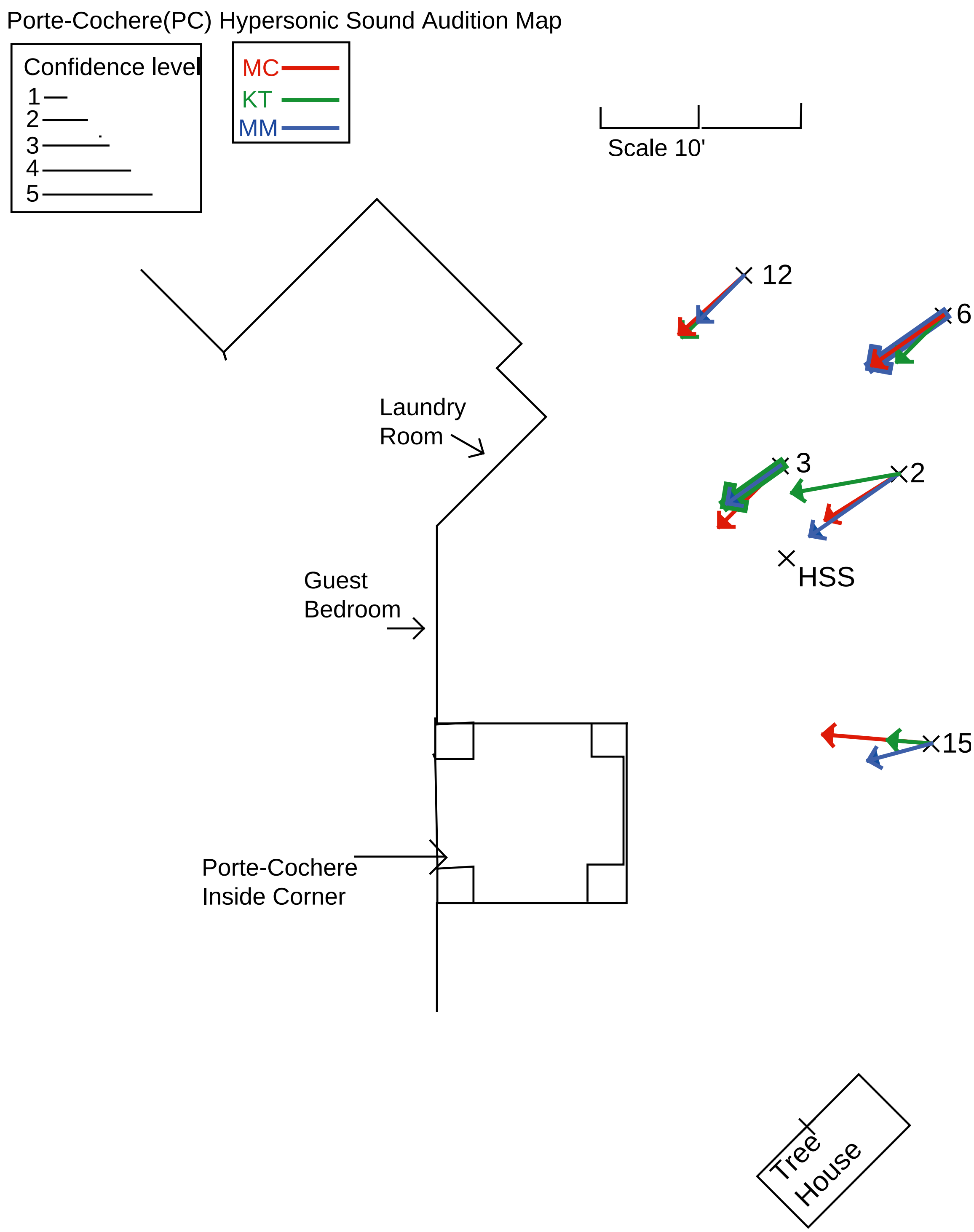
But in fact, the opposite was observed. Observations from these locations err systematically to the left of where the HSS unit was actually pointed. In fact, Tang's observation from post 2 is almost 40 degrees to the left of the actual position.

When listeners opened their eyes, they invariably reported that the sound was coming from the corner. However the eyese-closed measurements indicated a systematic error, with all 12 observations off to the right by 10 to 40 degrees. We do not know why this may have happened.

Observations from station 15 do, however, show a clear response to the virtual source coming off of the northmost column. Although the interior corner of the porte-cochere was clearly visible form station 15, no one detected a sound from that inner corner (where everyone was hearing it from the other stations.)

Two possible hypotheses can explain this observation. (1) The path length from HSS to the near column to station 15 is less than half the distance to the PC corner; thus the return would have been considerably louder. (2) When two identical (in content) virtual signals arrive, the hearer may select the louder of the two and ignore the existence of the weaker, unconsciously assigning it to the role of an artifact.

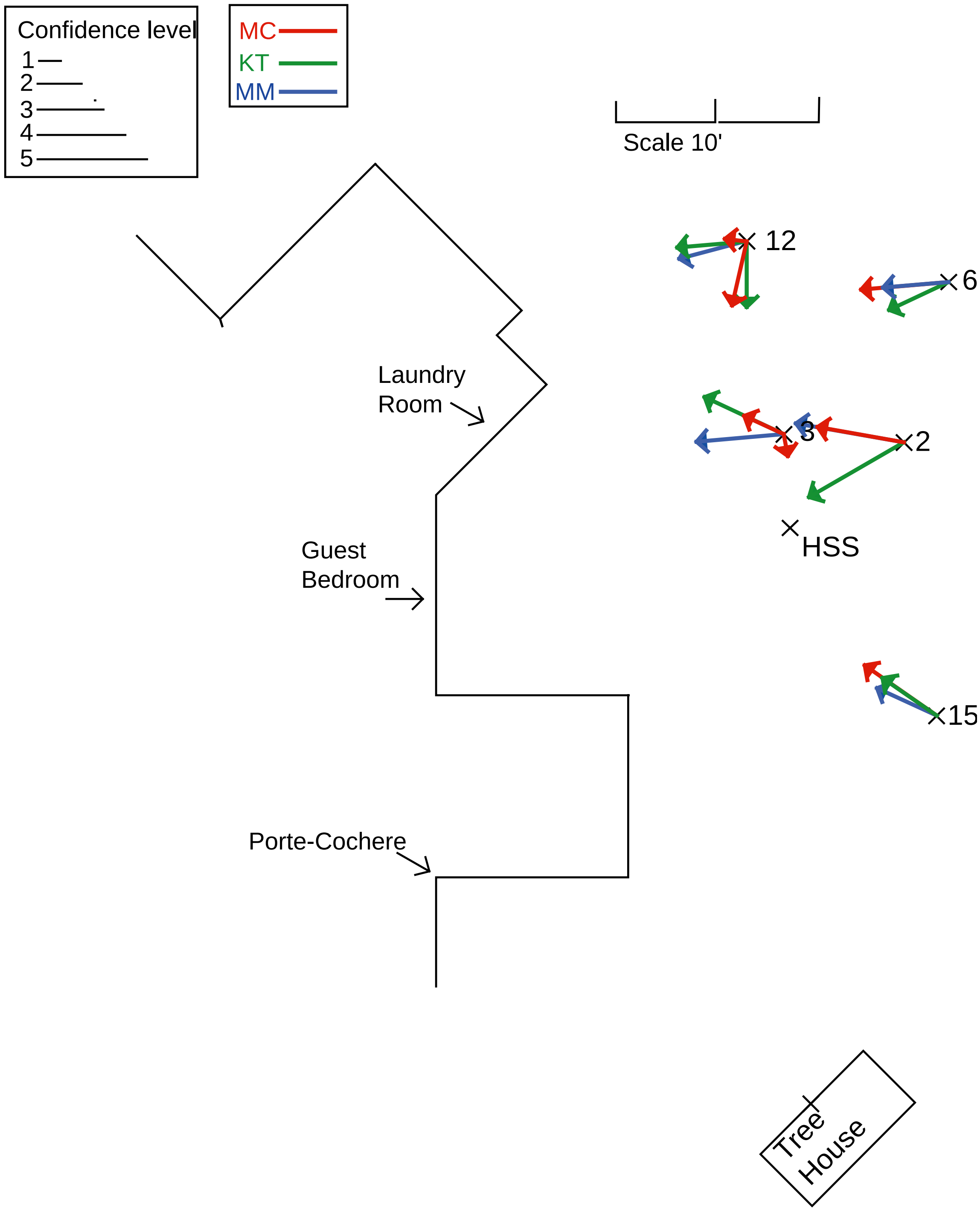
However, in experiments (upcoming) where the listener was in front of the plane of the HSS and thus was hearing a direct signal in competition with a virtual signal, two distinct sources were identified.



Guest Bedroom Data. This experiment produced perhaps the most clearcut of the four sites. The diagram below shows an arrow indicating the location of the stucco wall, where HSS was aimed. All the data arrows except one by Tang from station 2 (probably erroneous data recording) point almost directly at the stucco wall where the virtual sound source was located. This is the expected case since the setup is almost ideal - nearly perpendicular signal incidance, with all listening stations behind the plane of the HSS system.

Laundry Room Data. The situation here is interesting. Station 15 produced the expected results, which is not surprising since it was located almost perpendicular to the LR wall.

Laundry Room(LR) Hypersonic Sound Audition Map



The measurements from stations 2, 3 and 6 exhibit wide variability. These stations were observing the LR wall at an angle of 45 degrees or more. Remember that LR consists largely of glass, and thus was sending relatively more of its energy straight back and less at diffuse angles. We were somewhat surprised at the confidence levels shown by the listeners in their generally inaccurate descriptions of where the LR virtual source was.

Station 12, which was essentially at a 90 degree angle to the wall, produced the most anomalous results. The two younger listeners (Tang and Cubilla) reported clear direct signals (hence the double arrows), whereas all three listeners reported the virtual source well to the right of its actual position.

Our hypothesis is that they may have been hearing a virtual source emitted from the small "step" in the wall to the right of the LR wall itself. Even though this wall was not close to the beam direction of the HSS (about 15 degrees off axis), the presence of an interior corner consisting of friendly (stucco) surfaces, generated a compelling audio image compared to the steep-angle images coming off of the glass front surface of LR.

This could also explain the diversity of responses from stations 2, 3 and 6. Six of the nine arrows from these sites, in fact, point to the step in the wall, rather than toward the actual (intended) virtual image on the LR glass wall.

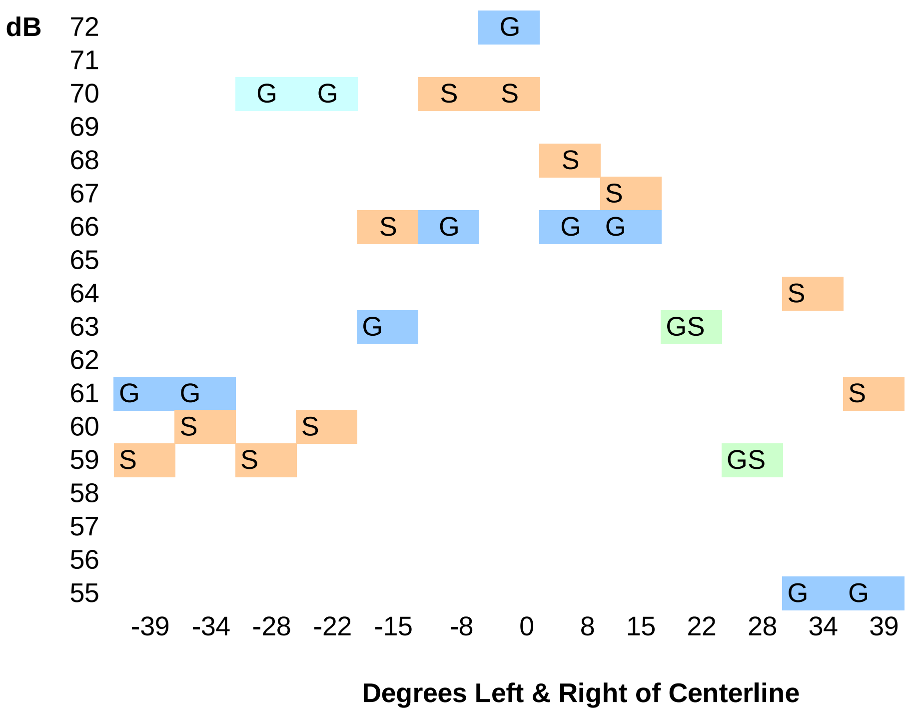
The clear lessons from this experiment are that (a) considerable attention must be paid to the geometry and composition of the targets at which HSS is pointed, in order to predict where virtual images will occur, and (b) field prototyping and pilot testing of any potential training application is mandatory. Assumptions about where virtual sources will appear, may well be wrong.

Virtual Source Dispersal Measured.

The measurement of dB levels returned from various surfaces is difficult, as aforementioned, due to the low level of the signals. We moved the HSS unit closer to the Guest Bedroom wall in order to improve our signal to noise ratio. Directly behind the HSS unit are saw palmettos and scattered pines, leading to the neighboring houses about 125 feet away. So we had some confidence that background echoes would not confound the measurements, as they clearly were doing in our indoor trials.

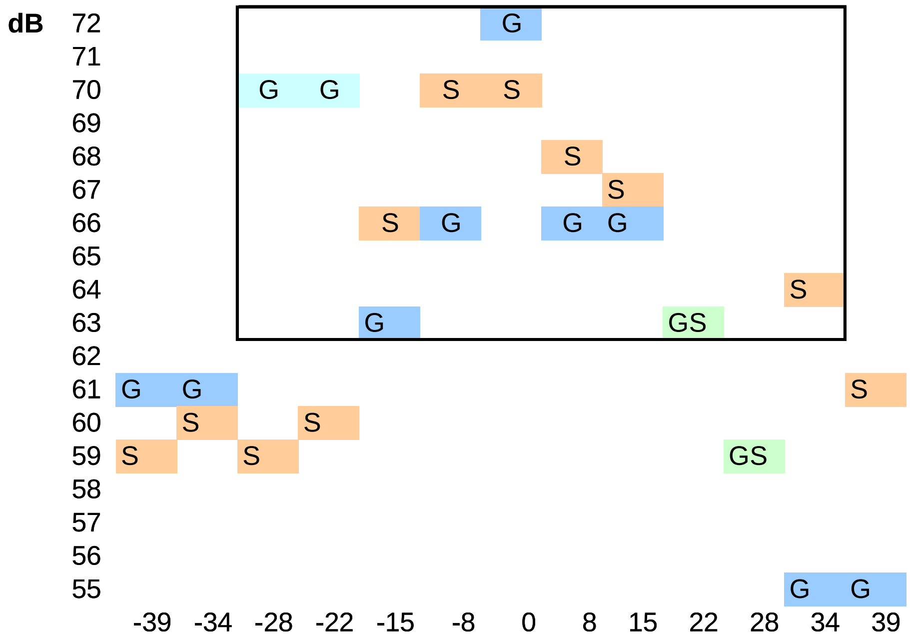
We measured reflected sound levels across the face of the three large glass windows of the Guest Bedroom. We then moved the HSS to the right so that it was centered on the stucco wall between the Guest Bedroom and the Laundry Room, and repeated the measurement.

The data is represented in the following chart. Several data points are suspicious, but they were sustained upon repeated re-measurement. We don't know why they are there, but we report what we measured.



In this chart, G denotes glass and S denotes stucco. The two 'suspicious' glass measurements at -22 and -28 degrees (70 db) are shown in lighter blue. The stucco measurements are shown in brown. Where glass and stucco had identical values, we show them in green.

This data is sufficiently noisy that it can, at most, be treated as suggestive rather than as conclusive. It does appear that the glass curve has a sharper peak than the stucco curve. If we focus on that data above 62 db (in the box, next figure) and ignore the strange G-data, we can see a bit more clearly.



Here we can see that the glass signal drops from 72 to 66 db by the time it's 8 degrees off the axis. The stucco drops to this level at 15 degrees off axis (left) and approximately 18 degrees off axis (right, by interpolation.) To get below 63 dB we would go out 15 to 22 degrees for either substance.

The Anomalies. It happens that, just on the axis from the point of impact of the HSS beam on the glass, back through those anomalous 70 dB readings, a line would point to the northernmost porte cochere column. Perhaps some kind of reflection was producing a virtual source off the post. However it makes no obvious sense to us as to why this would happen, since the HSS beam was incident at 90 degrees on the glass.

The stucco shows a much smaller (repeatable) anomaly on the opposite side, rising back up to 64 db at 34 degrees off axis, after having dropped to 59 dB at 28 degrees. However, this anomaly was not nearly so striking as the 70 db images off the glass. The glass images were clearly perceptible by all the listeners, just walking into that location.

We have no idea why these off-axis images were produced. They add weight to the caveat expressed above, about the necessity to field test any assumptions about how HSS might work in real applications.

5. Conclusions

Hypersonic Sound offers some possibilities for outdoor simulation for training, though the necessity to locate the sound projector ahead of the subjects restricts the possibliites for layout of scenarios. In its current state, the system is more appropriate for demonstrations than for deployment in realistic training development. Further experimentation is needed.