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Distributed System Speaker Spacing for the Integrator

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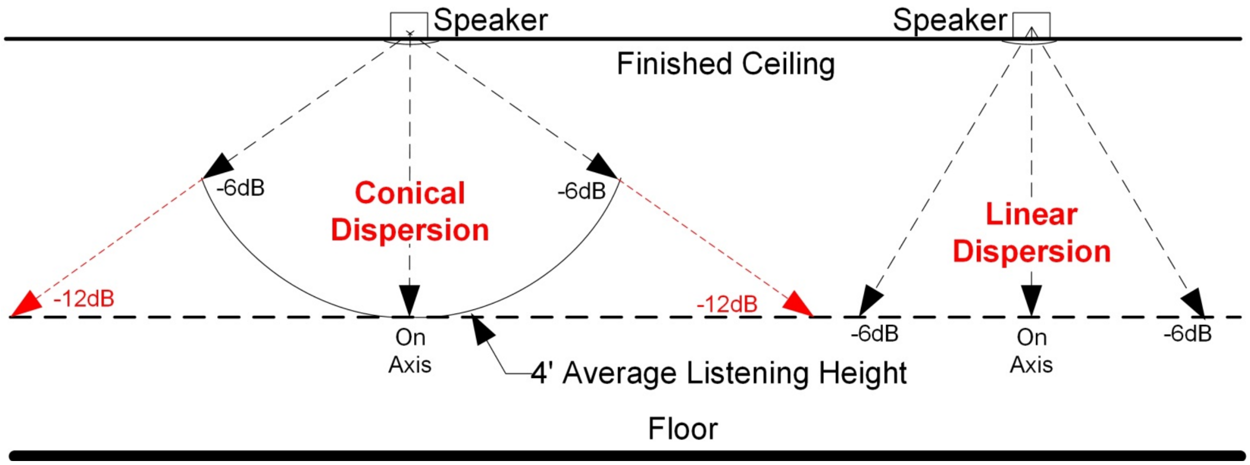
INDEX

INTRODUCTION

In this paper, we will discuss how to use simple rule-of-thumb formulas to properly space ceiling speakers that are shooting straight down at the floor in a distributed speaker system. Before we begin that discussion, it is important to have a clear understanding of a specification that we call “Speaker Dispersion.”

SPEAKER DISPERSION

<u>Conical Dispersion</u>: By definition, "Conical Dispersion" is the coverage angle of a speaker measured at an equal distance from the speaker where the sound pressure level (SPL) at the 2kHz octave band (important for speech articulation) is no more than 6dB lower than the SPL on-axis (straight out in front of the speaker). Conical Dispersion is shown on the left in the drawing below with the black arrows showing the conical -6dB down points.



It is common industry practice for audio manufacturers to give a Conical Dispersion specification for loudspeakers. It's easy to see on the drawing on the left above, that for a wide dispersion speaker, the conical -6dB measurement points will be up in the air, far above the average listening height. Because it is the industry standard, Conical Dispersion is given on Lowell Manufacturing spec sheets so that our speaker specifications can be compared to those of our competition, but it's obvious from the drawing above that we can't calculate speaker spacing based on measurement points that are up in the air. On the Conical Dispersion drawing shown on the left above, the red arrows show that at the average listening height, the actual SPL is more like -12dB. What is really important for speaker spacing is the -6dB points at the average listening height where the sound is actually heard by the listeners. At Lowell Manufacturing, we call the angle of dispersion with the -6dB points calculated at the average listening height the "Linear Dispersion" as shown on the right in the drawing above. Lowell offers both the Conical Dispersion and the Linear Dispersion on specification sheets.

For the remainder of this article, when speaker dispersion "D" is called for in a rule-of-thumb formula, we will always be referring to the Linear Dispersion angle that is listed on the Lowell specification sheets, not the Conical Dispersion angle.

Linear Dispersion: The "Linear Dispersion" angle is **usually narrower** than the "Conical Dispersion" angle. To understand why, we need to look at an acoustic law of Physics called the Inverse-Square Law.

The Inverse-Square Law is based on the fact that a sound wave emitted by a loudspeaker travels as a sphere away from the loudspeaker. The formula for the area of a sphere is $4\pi r^2$. That means that as the distance from the speaker (the radius "r") doubles, the area of the sphere that the sound from the speaker has to cover is 4 times as large because the radius term in the formula is "squared".

In the formula for sound pressure level, the sound energy from the speaker is divided by the area of the sphere to find the SPL at a certain point. Note that if X = Y/Z, that is the same mathematically as X = 1/Z times Y. In math terms, 1/Z is called the inverse. In the sound pressure level formula, the sphere area $4\pi r^2$ is in the denominator of the formula, so that is mathematically the same as an inverse. In other words, the squared radius term is an inverse in the SPL formula and that's where the Inverse-Square Law gets its name.

Inverse-Square Law: $SPL_2 = SPL_1 - 20 \log (D_2/D_1)$

- SPL_1 is the sound pressure level at the first location.
- SPL_2 is the sound pressure level at the second location.
- D_1 is the distance from the speaker at the first location.
- D_2 is the distance from the speaker at the second location.

The Inverse-Square Law says that every time you double the distance from the speaker, the sound pressure level decreases by 6.02dB (most sound guys just round that off to 6dB).

Loudspeakers typically have their highest SPL directly "on-axis" (straight out from the face of the speaker). "Off-axis" (off to the side), the speaker typically isn't as loud and the SPL typically decreases the farther off-axis the listener moves. In a Conical Dispersion measurement, the distance from the measuring test microphone to the speaker is always the same so the SPL decreases only as the off-axis SPL from the speaker decreases.

In a Linear Dispersion measurement, the microphone is closest to the speaker when it is on-axis (directly out from the speaker). As the microphone moves at the listening height to the side (off-axis) the distance from the microphone to the speaker increases. In a Linear Dispersion measurement, there will still be the SPL decreases because the off-axis SPL from the speaker decreases compared to the on-axis SPL, but at the same time, as soon as the measurement mic moves away from being directly on-axis, D_2 is greater because the distance from the speaker to the average listening height is farther than D_1 (the on-axis distance), so there will also be inverse-square distance losses and they will increase dramatically the farther the Linear Dispersion measurement is taken off-axis.

One might think if you are using a speaker like the Lowell JR410 with a Conical Dispersion of 170 degrees, that one speaker should be able to cover the whole room, but that kind of thinking does not take into consideration the inverse-square losses due to distance. At 85 degrees off axis, the JR410 is shooting sound almost sideways, but as we all know, sound doesn't travel forever. By the time that sound at 85 degrees off axis travels far enough to reach the average listening height, the sound pressure level (SPL) has been reduced to the point that it can't even be heard. Only by using the Linear Dispersion specification in the formulas to determine speaker spacing will you get an accurate representation of the SPL at the average listening height (where the listener's ears are).

A few examples can illustrate the importance of the Linear Dispersion specification:

Example 1: Consider the Lowell 12P150 driver (12" compression driver coaxial speaker). The Conical Dispersion is a *very narrow* 70 degrees. The Linear Dispersion, however, is only 60 degrees so that is the dispersion specification that should be used in any rule-of-thumb formulas for distributed speaker spacing.

Example 2: Consider the Lowell JR410 driver (4" single cone). The Conical Dispersion is a *very wide* 170 degrees. The Linear Dispersion, however, is only 100 degrees so that is the dispersion specification that should be used in any rule-of-thumb formulas for distributed speaker spacing.

Many contractors plug the Conical Dispersion angle (given by most manufacturers) into their speaker spacing formulas. It's obvious from the examples given above that using the Conical Dispersion in spacing formulas does not give an accurate result, especially for very wide dispersion speakers. Using the Conical Dispersion angle in rule-of-thumb spacing design formulas can result in a speaker system with huge dead spot holes in the speaker coverage.

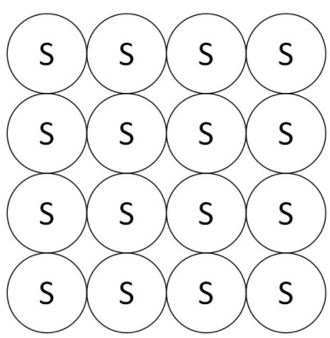
CALCULATING DISTRIBUTED SPEAKER SPACING

When sound system designers lay out the speaker spacing for a distributed paging or music system, they should always consider the speaker coverage at the “listening height” which is defined as the average height of the listener’s ears. For office sound systems it is usually assumed that the office workers will be seated at their desks, so the average listening height is generally considered to be 4’ above the finished floor. In an application where the listeners will usually be standing (like in a museum or a ballroom) the average standing listening height is generally considered to be 5’ above the finished floor.

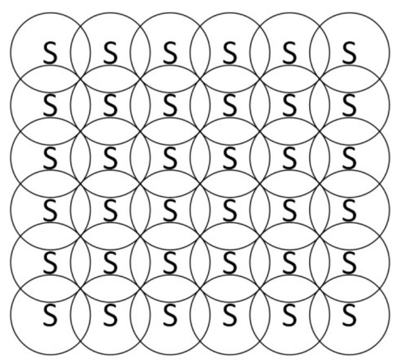
Most system designers consider the minimum coverage pattern that is acceptable for a blanket covered distributed speaker system to be “Edge-to-Edge Coverage” where the edges of the speaker’s coverage circles (at the listening height) just touch each other.

Take for example a recessed ceiling speaker that has a linear dispersion of 90 degrees at the 2kHz octave (the octave most important for speech articulation). For this example, we will assume the office ceiling height is a standard 9’ from the finished floor. The ceiling height is 9’, minus the average listening height at 4’, so that means the speaker has a throw of 5’. With a 90 degree linear dispersion, we can use some basic trigonometry and know that at a throw of 5’ we can draw a dispersion circle with a diameter of 10’ (at the listening height).

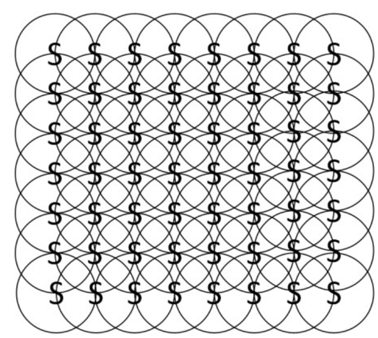
The diagram below shows that with Edge-to-Edge Coverage the coverage circles of the speakers just barely touch. Notice that there are large dead spots between 4 speakers whose coverage circles touch. For most paging and background music applications, Edge-to-Edge Coverage is acceptable.



Edge-to-Edge Coverage



Minimum-Overlap Coverage

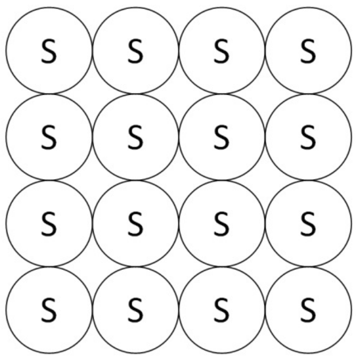

Edge-to-Center Coverage

Once we start talking about higher quality foreground music, we want to close those dead spots so it is wise to consider “Minimum-Overlap Coverage” as shown above. Note that it takes a lot more speakers to produce Minimum-Overlap Coverage where there are no dead spots between speakers.

For extremely high quality pro sound systems, some designers will use “Edge-to-Center Coverage” where the dispersion circle from one speaker extends to the center of the adjacent speaker as shown above. The sound pressure level will be very uniform at the listening height, but notice that Edge-to-Center Coverage requires roughly 4 times the number of speakers that are required for Edge-to-Edge Coverage. It becomes clear why, for cost reasons, Edge-to-Edge Coverage is what is used most often by integrators for paging and background music systems.

RULE-OF-THUMB FORMULAS for DISTRIBUTED SPEAKER SPACING

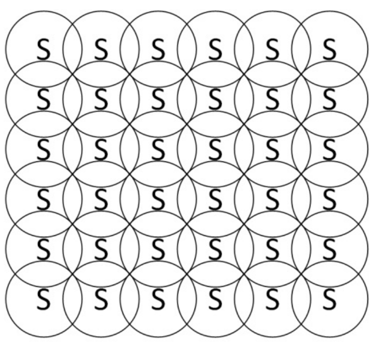
- H = Height of the speaker face above the floor
- L = Average listening height (Typically 4' for seated listeners and 5' for standing listeners)
- D = Linear dispersion angle of the speaker (The -6db point dispersion angle at listening level)
- TAN = The trigonometric tangent function on your calculator



Edge-to-Edge Coverage

For Square "Edge-to-Edge" Coverage

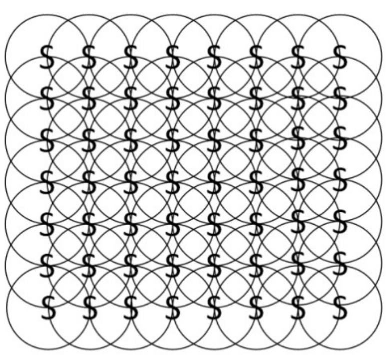
Center to Center Speaker Spacing = 2 (H - L) TAN (½ D)



Minimum-Overlap Coverage

For Square "Minimum-Overlap" Coverage

Center to Center Speaker Spacing = 1.5 (H - L) TAN (½ D)



Edge-to-Center Coverage

For Square "Edge-to-Center" Coverage

Center to Center Speaker Spacing = (H - L) TAN (½ D)

*Note: The rule-of-thumb formulas given above are for **square** speaker spacing. Hexagonal speaker spacing formulas are also available, but they are difficult for the contractor to lay out on drawings and it is even harder for the typical installer to space speakers out in a hexagonal pattern in the field, so we are not recommending their use.*

SPEAKER SPACING EXAMPLES

Example 1: System will be for paging and background music in an office setting. Finished lay-in tile ceiling is 9' from the finished floor. I will design for square Edge-to-Edge spacing.

- Speaker chosen: Lowell ES-4T
- Conical Dispersion: 175 degrees, Linear Dispersion: 95 degrees
- Edge-to-Edge speaker spacing = 2 (H–L) TAN (1/2 D)
- H = 9'. L = 4' (seated listening height) D = 95 degrees
- Edge-to-Edge speaker spacing = 2 (9'–4') TAN (47.5 degrees) = 10.9'

For the speakers to fit in the ceiling tiles, I need to either space my speakers on 10' centers or 12' centers. The application isn't super critical but I don't want to offer less than Edge-to-Edge coverage so I decide to go with 10' centers. To lay out my speakers, I come in 5' from the side wall and 5' from the rear wall (or as close as possible depending on the layout of the ceiling tile. I put a row with one speaker every 10'. Then I move over 10' and put a second row with one speaker every 10'. If that pattern doesn't fit in the room where I have 5' to the other side wall, I would typically scoot the pattern over so there is a little extra space near the outside walls where typically nobody would be sitting.

Another option would be that I feel that since the application isn't super critical I decide that it will be acceptable to offer slightly less that Edge-to-Edge coverage so I go with 12' centers. To lay out my speakers I come in 6' from the side wall and 6' from the rear wall (or as close as possible depending on the layout of the ceiling tile). I put a row with one speaker every 12'. Then I move over 12' and put a second row with one speaker every 12'. If that pattern doesn't fit in the room so I have 6' to the other side wall, I would typically scoot the pattern over so there is a little extra space near the outside walls where typically nobody would be sitting.

Bidding Short-Cut: Often in a bidding situation, the number of speakers for a given area needs to be determined quickly and there is no time to do a complete speaker layout. Using the example above, for square edge-to-edge spacing, if we have determined that we are going to space the speakers on 10' center-to-center spacing, that means that every speaker is going to cover a square area that is 10' X 10' (including the dead spots between speakers). That means that every speaker will cover 100 square feet. If we are given that the office space is a total of 30,000 sq. ft., then by dividing 30,000 sq. ft. by 100 sq. ft. = approximately 300 speakers are required.

<u>Example 2:</u> System will be for foreground music in a restaurant setting. Finished lay-in tile ceiling is 12’ from the finished floor. This is a high-end restaurant so I want to have super even coverage with no dead spots. I will design for square Minimum-Overlap spacing.

- Speaker chosen: Lowell ES-62T
- Conical Dispersion: 120 degrees, Linear Dispersion: 90 degrees
- Minimum-Overlap speaker spacing = 1.5 (H - L) TAN (1/2 D)
- H = 12’. L = 4’ (seated listening height) D = 90 degrees
- Minimum-Overlap speaker spacing = 1.5 (12’–4’) TAN (45 degrees) = 12’

To lay out my speakers I come in 6’ from the side wall and 6’ from the rear wall (or as close as possible depending on the layout of the ceiling tile). I put a row with one speaker every 12’. Then I move over 12’ and put a second row with one speaker every 12’. If that pattern doesn’t fit in the room so I have 6’ to the other side wall, I would typically scoot the pattern over so there is a little extra space near the outside walls where typically nobody would be sitting.

<u>Example 3</u>: System will be for direct radiating sound masking in an office setting. Direct radiating sound masking is the only choice because this is a drywall ceiling. Finished drywall ceiling is 11.25' from the finished floor. I know that overlapping coverage for sound masking is critical so I choose to design for square Edge-to-Center Coverage.

- Speaker chosen: Lowell ES-4T
- Conical Dispersion: 175 degrees, Linear Dispersion: 95 degrees
- Edge-to-Center speaker spacing = (H–L) TAN (1/2 D)
- H = 11.25' L = 4' (seated listening height) D = 95 degrees
- Edge-to-Center speaker spacing = (11.25'–4') TAN (47.5 degrees) = 7.9'
- I know I have plenty of overlapping coverage so to make things easier on the installers, I'll round that up to 8' centers.

To lay out my speakers I come in 4' from the side wall and 4' from the rear wall (or as close as possible depending on the layout of the ceiling tile). I put a row with one speaker every 8'. Then I move over 8' and put a second row with one speaker every 8'. If that pattern doesn't fit in the room so I have 4' to the other side wall, I would typically scoot the pattern over so there is a little extra space near the outside walls where typically nobody would be sitting.

Example 4: Let's assume in example 3 that when I propose the price to the customer it is way over budget. I explain to the customer that overlapping coverage on direct sound masking is critical, but I value-engineer the design to try to meet the customer's budget. This time I design with square Minimum-Overlap Coverage. Finished drywall ceiling is 11.25' from the finished floor.

- Speaker chosen: Lowell ES-4T
- Conical Dispersion: 175 degrees, Linear Dispersion: 95 degrees
- Minimum-Overlap speaker spacing = 1.5 (H - L) TAN (1/2 D)
- H = 11.25' L = 4' (seated listening height) D = 95 degrees
- Minimum-Overlap speaker spacing = 1.5 (11.25' - 4') TAN (47.5 degrees) = 11.87'
- I know the customer's budget is tight so to make things easier on the installers, I'll round that up to 12' centers.

To lay out my speakers I come in 6' from the side wall and 6' from the rear wall (or as close as possible depending on the layout of the ceiling tile). I put a row with one speaker every 12'. Then I move over 12' and put a second row with one speaker every 12'. If that pattern doesn't fit in the room so I have 6' to the other side wall, I would typically scoot the pattern over so there is a little extra space near the outside walls where typically nobody would be sitting.

SUMMARY

Speaker layout for distributed sound systems is not terribly difficult. It does take some information about the ceiling, some knowledge about the application of the system, and an understanding about the level of quality required by the customer. The most important thing that we discussed in the paper is that all of the rule-of-thumb formulas in the world don't do any good if you plug in the wrong dispersion specification. Proper speaker spacing for adequate coverage at the listener's ear height can only be determined if the Linear Dispersion of the speaker at the average listener's height is known.

APPENDIX A

The “Linear Dispersion” for all Lowell Manufacturing speaker systems and “speaker with grille” combinations is given in the chart below. *Note: The speaker models given are those that could be used in a distributed speaker system mounted recessed in the ceiling or surface mounted to the ceiling aiming straight down, since that distributed speaker system configuration is the only one where “Linear Dispersion” specifications apply.*

Model	Linear Dispersion
12P150	60º
12P150 with FW-12 grille	60º
12P150 with FW-12Q grille	60º
12P150 with RS12-AW grille	60º
12P150 with WB-12 grille	60º
12Q250	70º
12Q250 with FW-12 grille	80º
12Q250 with FW-12Q grille	80º
12Q250 with RS12-AW grille	80º
12Q250 with WB-12 grille	80º
4A30	100º
4A30-T870	100º
4A30 with CN-4M grille	75º
4A30 with SG-4 grille	90º
4A30 with WB-4 grille	85º
4A30 with WB-4T grille	85º
6A40	85º
805A	70º
805A with A8-AW grille	75º
805A with CS-8H grille	75º
805A with DSQ-8 grille	75º
805A with IC-105A grille	75º
805A with LO8-P grille	75º
805A with RS8-AW grille	75º
805A with WB-8 grille	75º
805A with WB-8T grille	75º
805A in LT custom assembly	80º
810	75º
810-T470	75º
810-T72	75º
810-T870	75º
810 with A8-AW grille	80º
810 with CN-8M grille	70º
810 with CS-8H grille	80º
810 with DSQ-8 grille	80º
810 with FW-8 grille	75º
810 with FW-8T grille	75º
810 with IC-105A grille	80º
810 with JG-8X grille	75º
810 with LO8-P grille	80º
810 with RS8-AW grille	80º
810 with SG-8 grille	80º
810 with WB-8 grille	80º
810 with WB-8T grille	80º
8A50	70º
8A50-T870	70º
8A50-T870-S	70º
8A50-TM1670	70º
8A50-TM1670-S	70º
8A50-TS3270	70º
8A50 with A8-AW grille	70º

Model	Linear Dispersion
8A50 with CN-8M grille	65º
8A50 with CS-8H grille	70º
8A50 with DSQ-8 grille	70º
8A50 with FW-8 grille	70º
8A50 with IC-105A grille	70º
8A50 with JG-8X grille	70º
8A50 with RS8-AW grille	70º
8A50 with SG-8 grille	70º
8A50 with WB-8 grille	70º
8C10DVCA	70º
8C10DVCA-2T72	70º
8C10DVCA with A8-AW grille	80º
8C10DVCA with CN-8M grille	70º
8C10DVCA with CS-8H grille	80º
8C10DVCA with DSQ-8 grille	80º
8C10DVCA with FW-8 grille	75º
8C10DVCA with FW-8T grille	75º
8C10DVCA with IC-105A grille	80º
8C10DVCA with JG-8X grille	75º
8C10DVCA with LO8-P grille	80º
8C10DVCA with RS8-AW grille	80º
8C10DVCA with SG-8 grille	80º
8C10DVCA with WB-8 grille	80º
8C10DVCA with WB-8T grille	80º
8C10DVCA in LT custom assembly	80º
8C10MRB	70º
8C10MRB-T72	70º
8C10MRB with A8-AW grille	70º
8C10MRB with LO8-P grille	70º
8C10MRB with RS8-AW grille	70º
8P100	175º
8P100 with A8-AW grille	75º
8P100 with CN-8M grille	75º
8P100 with CS-8H grille	75º
8P100 with FW-8 grille	75º
8P100 with IC-105A grille	75º
8P100 with JG-8X grille	75º
8P100 with RS8-AW grille	75º
8P100 with SG-8 grille	75º
8P100 with WB-8 grille	75º
8P100 in LT custom assembly	75º
BC810-72	80º
C1830-870	60º
CT830A	65º
CT830A-T470	65º
CT830A-T72	65º
CT830A-T870	65º
CT830A with A8-AW grille	60º
CT830A with CN-8M grille	55º
CT830A with CS-8H grille	60º
CT830A with DSQ-8 grille	60º
CT830A with FW-8 grille	60º
CT830A with FW-8T grille	60º
CT830A with IC-105A grille	60º
CT830A with JG-8X grille	60º

Model	Linear Dispersion
CT830A with LO8-P grille	60º
CT830A with RS8-AW grille	60º
CT830A with SG-8 grille	65º
CT830A with WB-8 grille	60º
CT830A with WB-8T grille	60º
D1410-72	95º
D3410-72	80º
D6410-72	100º
DSQ-805-72	75º
DSQ-810-72 (special order only)	80º
ES-4T	100º
ES-52T	95º
ES-62T	90º
ES-82T	85º
ES-82CDT	60º
ESP-52TB	95º
ESP-52TW	95º
ESP-62TB	90º
ESP-62TW	90º
ESP-82TB	85º
ESP-82TW	85º
ESP-82CDTB	60º
ESP-82CDTW	60º
IM12P-3SW	60º
IM12P-TS100-3SW	60º
IM12Q-3SW	80º
IM12Q-TS100-3SW	80º
IM8A-2SW	70º
IM8A-TS32-2SW	70º
IM8P-2SW	75º
IM8P-TS100-2SW	75º
IMC12P-2W	65º
IMC12P-TS100-2W	65º
IMC12Q-2W	85º
IMC12Q-TS100-2W	85º
IMC12Q-TS32-2W	85º
IMC8A-1W	70º
IMC8A-TS32-1W	70º
IMC8P-2W	85º
IMC8P-TS100-2W	85º
IMC8P-TS32-2W	85º
JR410	100º
JR410-T470	100º
JR410-T72	100º
JR410-T870	100º
JR410 with CN-4M grille	80º
JR410 with SG-4 grille	100º
JR410 with WB-4 grille	95º
JR410 with WB-4T grille	95º
LH-15TA	45 º

Model	Linear Dispersion
LH-30TA	40 º
LT2-810-72-BB	80º
LT2-810-72-BB-VC	80º
LT2-810-BB	80º
LT2-830-T870-Vb	65º
LT2-830-TM16-Vb	65º
LT2-8A-T870-Vb	75º
LT2-8A-TM32-Vb	75º
LT2-8A-Vb	75º
LT-410-72-BB	100º
LT-410-870-BB	100º
LT-4A-T870-Vb	95º
LT-4A-Vb	95º
LT-6A-T870-Vb	85º
LT-6A-TM16-Vb	85º
LT-6A-Vb	85º
LT-810	80º
LT-810-72	80º
LT-810-72-BB	80º
LT-810-72-BB-VC	80º
LT-810-72-VC	80º
LT-810-BB	80º
LT-830-870	65º
LT-830-870-BB	65º
LT-830-BB	65º
LT-8A-T870-Vb	75º
LT-8A-TM32-Vb	75º
LT-8A-Vb	75º
LUH-15T	60º
LUH-15TA	60º
LUH-15TX	60º
LUH-15TI	60º
OS-100TB	90º
OS-100TW	90º
OS-150TB	70º
OS-150TW	70º
OS-50TB	85º
OS-50TW	85º
R1810-72	80º
R1810-72K	80º
R1810-72S	80º
R7810-72	80º
R7810-72K	80º
RPAK-810-72	80º
RT1810-72	80º
ULD-SG8-2T572	80º
ULD-WB8-2T572	80º
ULS-SG8-CT572	80º
ULS-WB8-CT572	80º
ULT-SG4-CT572	100º
ULT-WB4-CT572	95º