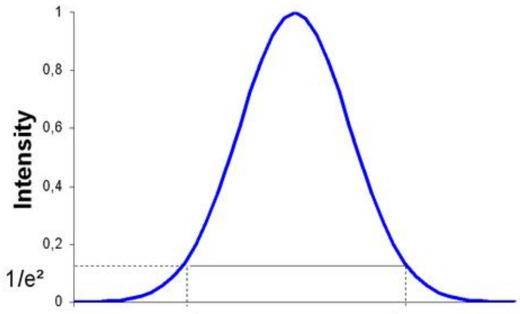
Properties of Structured Light

Gaussian Beams

Structured light sources using lasers as the illumination source are governed by theories of Gaussian beams. Unlike incoherent sources, coherent laser sources behave in a manner that even under ordinary circumstances is relatively easy to describe.



The nature of the laser cavity design, in common laser diodes, dictates the beam properties. The beam being emitted from the diode begins as a plane wave with a Gaussian intensity profile. This profile is clipped to a finite diameter either by the laser cavity or other mechanical aperture. The most common way to define the properties of a Gaussian beam is by establishing the diameter of the beam and then applying this definition of the diameter with diffraction theory to describe the beam as it propagates in space. In our study, we will use the definition of $1/e^2$ as the diameter of the beam. $1/e^2$ is the point at which the intensity of the profile drops to 13.5% of the normalized peak intensity. The beam size or waist is described by Equation 1 below where w_0 is the waist radius at the focus position and z is the position from this waist position.

$$w_z = w_0\left[1+\left(\frac{\lambda z}{\pi {w_0}^2}\right)^2\right]^{0.5}$$

Equation 1

Technologies to Generate Laser Lines

Clip Gaussian vs. Cylinder vs. Diffractive vs. ALG

	Gaussian	Diffractive	Multi-cylindrical lens array	ALG
Variables affecting line uniformity	Input beam position	Wavelength	Projection distance	Input beam position
	Input beam size	Projection distance	Detector size	Input beam size
		Detector size		
Side lobes along length of line	Diffraction caused by aperture	Higher diffraction orders	None	None
Applications	Bio-instrumentation	Visual	Visual	ALL
	Alignment	Scattering	3D	

Clipped Gaussian

Clipped Gaussian laser lines are simple to produce and can be effective in certain instances where the effects from the clipping are not important to the measurement. In addition to clipping effects, this method reduces the available power in some cases by up to 75%. Figure (1) below charts the relationship between clip point on Gaussian beams to uniformity levels and contained power, while Figure 2 charts the relationship between Uniformity and relative intensity.

C: Clip Level
U: Uniformity
Cp: Contain Power
Ri: Relative Intensity

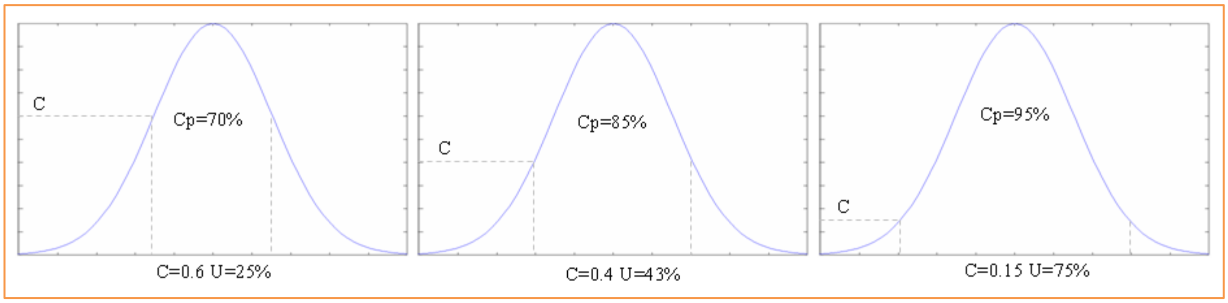


Figure 1

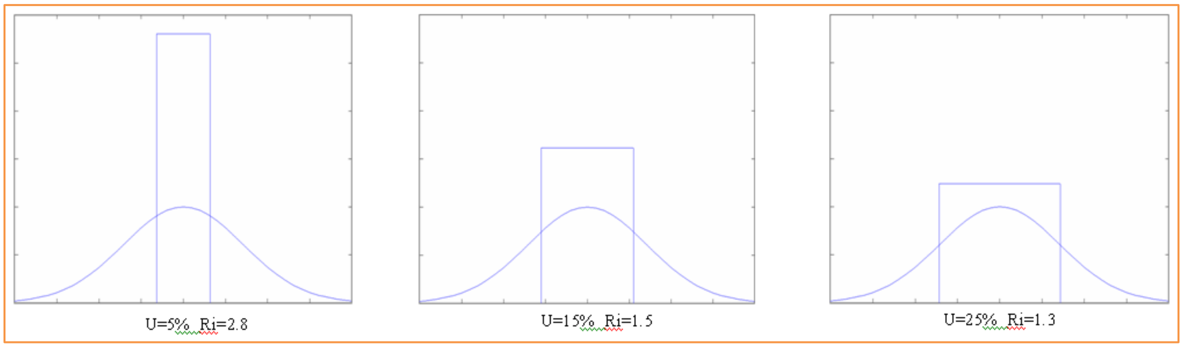


Figure 2

Cylinder Arrays

Cylinder arrays are a cost effective way to create lines independent of wavelength and input beam size. The method is to generate multiple small sections of lines that when projected visually look like a continuous line. This type of line generator is susceptible to working distance and detector size.

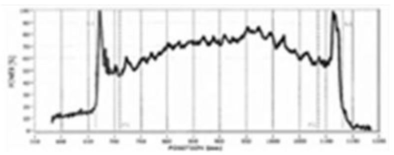


Figure 3

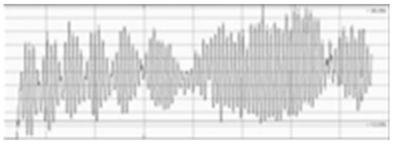


Figure 4

Looking at the profile in the near field (Figure 3), this method produces an acceptable line profile for some applications. As the projected distance increases, however, we see that the profile takes on the periodic nature of the line segments (Figure 4).

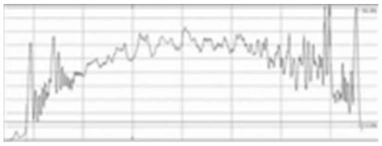


Figure 5

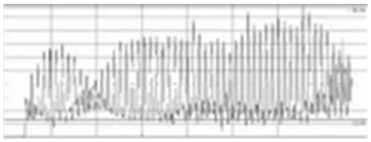


Figure 6

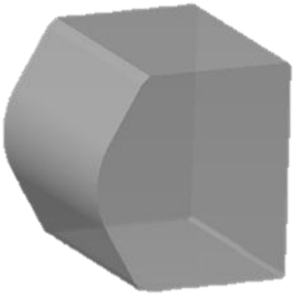
In a similar fashion, this method, regardless of projection distance, is dependent on the pixel size being used to image the line. Figure 5 shows the profile of the line using a pixel size of 7 mm, while Figure 6 is the profile using a 3 um Pixel size. In one condition, this is a usable profile to generate measurements, while in the other is not usable at all.

Diffractive

Diffractive technologies typically generate a line by repeating a series of small closely spaced dots. Depending on the technology used, these lines suffer from various effects or limitations. These patterns are wavelength dependent. With the typical Machine Vision laser system being passive cooled, the wavelength drifts with the temperature of the diode. This drift will change the efficiency of the diffractive and the separation angle between features, causing the pattern to shift in uniformity, efficiency and size.

Closely spaced or overlaping coherent beams can interfere with each other causing patterns or fringes which result in ripple in the line profile. This can be interperted by the imaging system as scatter or noise, lowering the accuracy of the measurements.

ALG (Aspheric Line Generator)



Refractive aspheric line generators are a technology that generates a uniform top hat profile by combining the function of a roof prism and an aspheric cylinder. The prism acts on the incoming beam to refract the light at a specific angle (Fan Angle). The Aspheric cylinder re-distributes the energy from the edges into a constant distribution between the two points, making a line of uniform intensity.

Since this is a refractive element, there is no dependence on wavelength or temperature. The distribution of energy does not have any other structure from interference or feature separation. It is, however, important to closely match the incoming beam size to the polish size of the optic (see Figure 6 below). The mismatch in this attribute will affect the distribution of the power into the line.

Line Uniformity

Variations in the components and processes that go into making a uniform line can generate mismatches, as well as introduce structure to the wave front of the intensity profile. These variations can cause large intensity edges, non-flat top profiles, periodic structure, and scatter from poorly matched/produced systems.

Measurement

Line uniformity is a measure of the variation of the normalized intensity profile from the average intensity over a give region (see Figure 7). Traditionally, this is taken over the central 80% of the projected line, thus eliminating any mismatch at the edge of the line. This measurement uses a slit detector to integrate the power as it scans the length of the projected line. The result is the reported uniformity or deviation from the average intensity in the measurement region. Uniformity is expressed as the maximum intensity (I_{Max}) minus the minimum intensity (I_{Mi}) divided by the sum of (I_{Max}) and (I_{Min}).

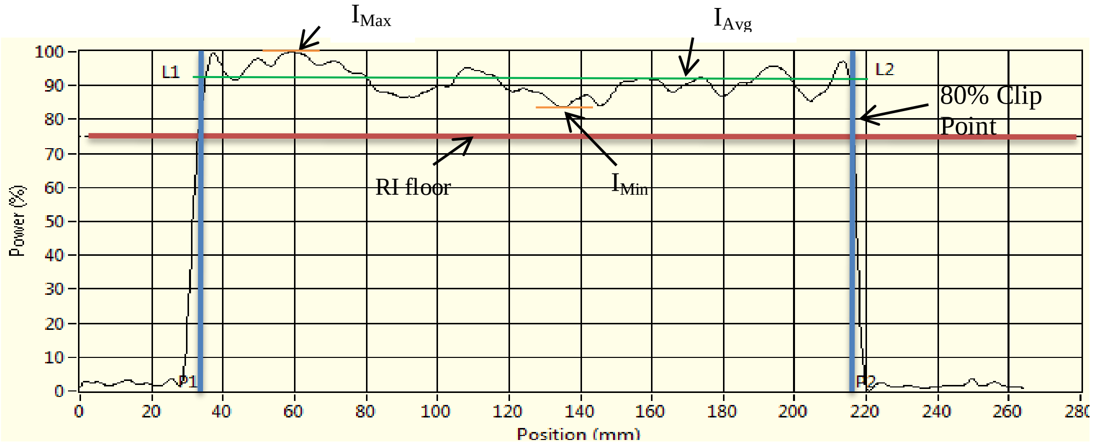


Figure 7

Beam Size and Uniformity

Beam uniformity is dependent on multiple factors: beam size, surface roughness, aspheric profile, etc. The major contributing factor, however, is the match of the beam size to the polish diameter. Figure 8 below shows a progression of profiles created by a roof prism varying a semi-matched, to matched, to mismatched condition. The repeatability of beam matching from laser to laser is dependent on the variation in the divergence in the diode as well as the variation in the polishing accuracy of the optic.

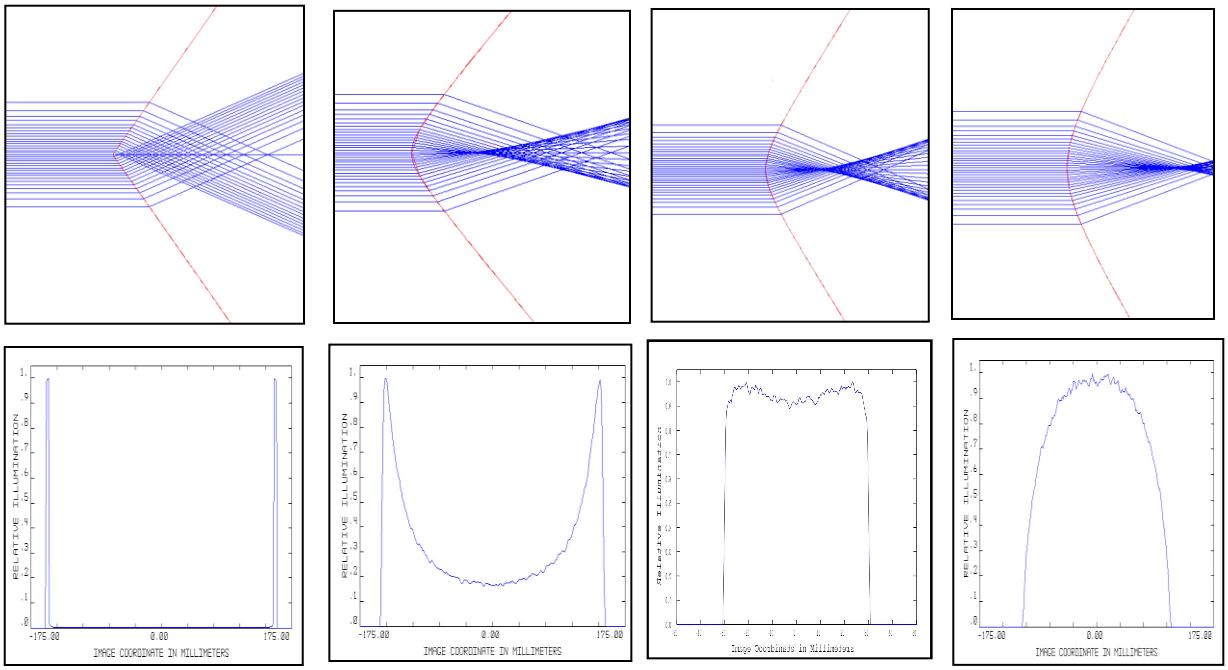


Figure 8

Laser Line Straightness

Projected laser lines are rarely straight. Tapered ends or a slightly S-shaped line can occur and are often indicators of poor line straightness (see Figure 9). Depending on the type of line profile that is projected by the laser, this can be due to misalignment or imperfections in the lens such as an uneven surface.

Measurement

Line straightness refers to the transverse displacement of the projected laser line with respect to the best fit line (see Figure 10).

Quantifying line straightness requires determining the position of the laser line at a specified focal distance, as well as the best fit line and the length of the line, L (see Figure 10). Next, determine the largest variations of the projected laser line ($\square_1$ and $\square_2$) relative to the best fit line. Calculate the total deviation: $\square = \square_1 + \square_2$. Straightness error (%) can be expressed as ($\square$/L) x 100.

Bore-sight & Fan Angle

The “curved” profile (see Figure 9) is caused by the angle between the lens and the incident beam. This curvature can be expressed as (dx/L) x 100 (see Figures 11 and 12).

A general rule of thumb is:

$$\text{Curvature (\%)} = \frac{\text{Fan Angle }(^\circ) \text{ x Boresight [mrad]}}{4375\text{[1]}}$$

The above calculation illustrates that laser line straightness is directly proportional to the fan angle and the boresight.

Fan Angle	Curvature (%)	
	3.5 mrad	7 mrad
15°	0.012%	0.024%
30°	0.024%	0.048%
60°	0.048%	0.096%

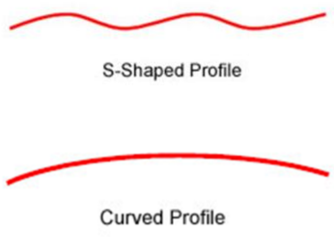


Figure 9 – Types of straightness errors. Laser line profiles can vary in shape, as seen in the two common examples above.

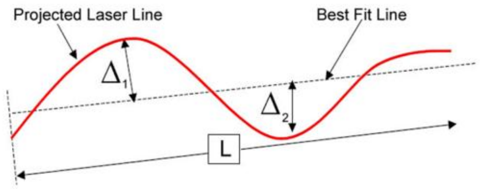


Figure 10 – An example of an S-shaped laser line profile. The figure highlights the projected line and the best fit line that can be derived from a fluctuating profile.

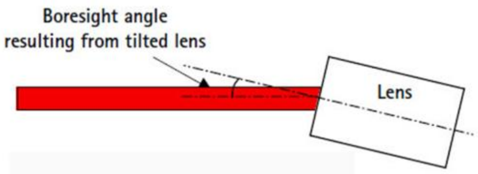


Figure 11 – Incident beam with respect to a misaligned lens.

Figure 12 – Curved laser line profile.

Line Width

Line thickness is a function of multiple parameters, but is best expressed as a function of the input beam size. In general, the larger the input beam the smaller the Gaussian focus at a given working distance. The input beam diameter can be changed by the divergence of the diode or the focal length of the collimator. Coherent has optional collimators that can be selected to produce thinner lines for more demanding applications.

	EFL (mm)		
WD (mm)	4.5	6	8
100	48 µm	36 µm	27 µm
250	119 µm	89 µm	68 µm
500	239 µm	179 µm	136 µm
750	360 µm	269 µm	203 µm

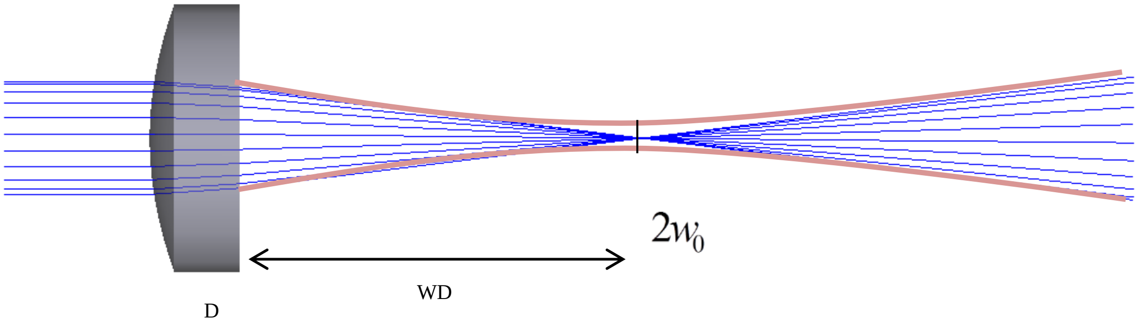
660-120, FA Focus, 17°, M^2=1.3

	Low	Nominal	High
WD (mm)	15°	17°	19°
100	54 µm	48 µm	43 µm
250	136 µm	119 µm	107 µm
500	273 µm	239 µm	214 µm
750	415 µm	360 µm	322 µm

660-120, FA Focus, 4.5 EFL, M^2=1.3

$$2w_0 = \frac{4 * WD * M^2 * \lambda}{\pi * D}$$

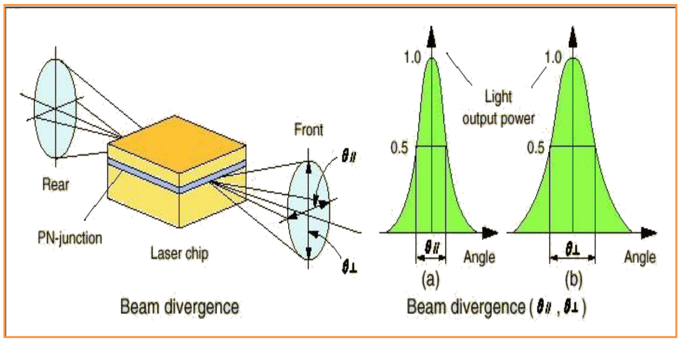
Equation 2



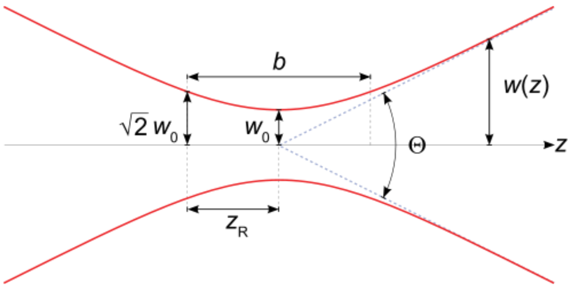
Depth of Field

The Depth of field of the focused line is typically related to the Raleigh range of the waist (w_0). The Raleigh range is defined as the distance from the focus over which the line thickness increases by √2.

There are two distinct DOF conditions for the Coherent lasers. This comes from either focusing the slow or fast axis of the laser diode. Using the fact that these two axes have different divergences, we can select which one to provide the user for focusing.



When the fast axis is selected, the divergence is greater and thus the DOF is smaller. In applications where the height of the objects being measured is large and or the location of the object has a greater uncertainty, selecting the slow axis for focus will give the largest DOF and the best results.

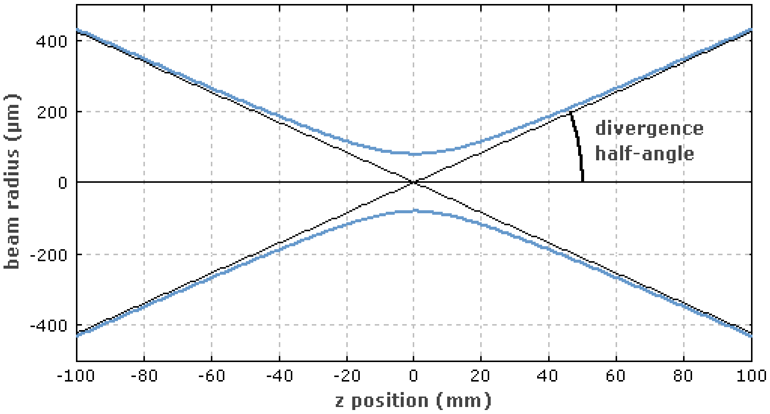


$$DOF = 2\pi * \frac{{w_o}^2}{\lambda}$$

Equation 3

Divergence

Since Gaussian beams follow the diffractive principles, we cannot achieve a perfectly collimated beam and the divergence of the beam is dependent on the waist size that is set by the optical system.



Far field divergence of a laser beam can be described as the ratio of the wavelength of the light to the beam waist at a particular focus position.

$$\vartheta = \frac{w_z}{z} = \frac{\lambda}{\pi w_0}$$

Equation 4

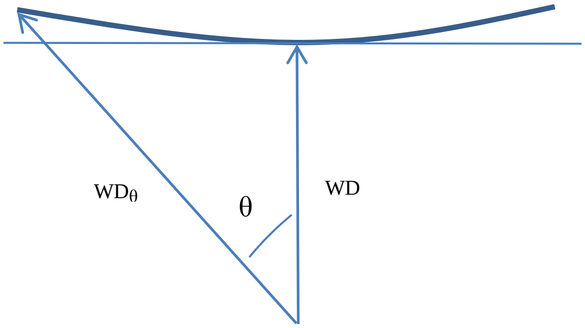
In most applications, the waist of the laser is focused on the object under inspection, the divergence changes depending on the waist position.

Divergence (mrad)		
WD (mm)	FA	SA
100	9.86	5.14
250	3.94	2.04
500	1.96	0.98

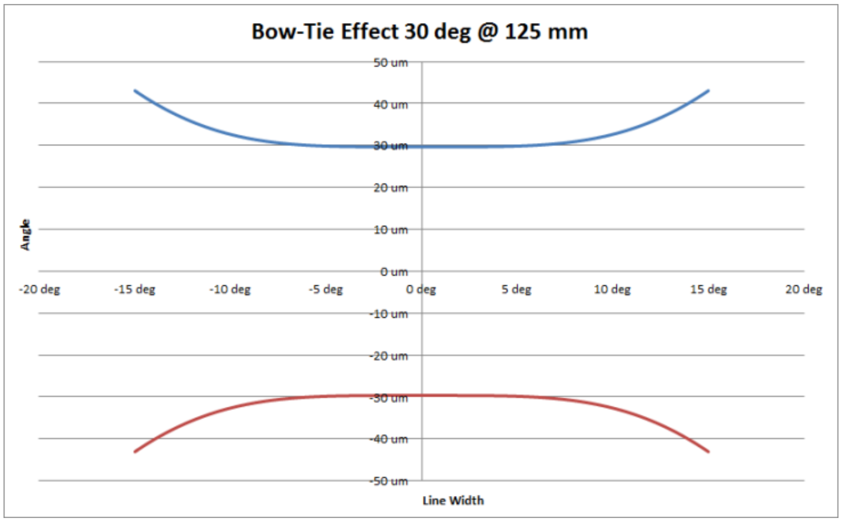
Field Dependent Focus

By nature, the lines being generated are diverging from the apparent point source, commonly the front of the laser. As the propagation is of a divergent spherical wave front, when the line is imaged or mapped to a flat object or surface, the wave front of the line will approach this plane with the center section first then symmetrically progressing until the entire wave front is incident on the surface.

This effectively generates a change in working distance from the center of the line to the edge of the line. In most cases, the focus is set for the center of the image or line.



This field dependent focus will generate a line that has a “best” focus at the center and gradually defocuses as you progress toward the edge. This is commonly called the “Bow-tie” effect. The line, as it is projected onto a flat surface, is larger as the edge narrows in the center then grows again to the other edge. A simple mathematical representation of the width of the line at a given angle is described below.



$$w_\theta = w_0 * \left[1 + \left(\frac{\lambda * WD * \left(\frac{1}{\cos\theta} - 1\right)}{\pi * {w_0}^2}\right)^2\right]^{0.5}$$

Equation 5