Opti-Grid
System Requirements Document

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1 Executive Summary

This document is intended to capture the engineering system requirements for proper performance of the Opti-grid sectioning microscope product. The results of these engineering and performance issues may eventually be captured on detailed component specifications and drawings as well as the assembly and test procedures (ATP) for the product. The philosophy of this document is to record the engineering issues together with any necessary theory that supports performance-driving attributes of the system and subsystems. Having this information readily available in this format allows future engineers the proper tools to determine how certain design changes might affect or improve the system performance.

The document is divided into three main sections. The first section is the Opti-Grid performance specifications (customer or product specifications) and should closely resemble data sheets and marketing documentation provided to the customers. It is critical that the engineering and marketing specifications agree.

The second section consists of error budgets that in general break down the top-level specifications into the various contributors of each critical performance attribute. For instance if the machine has a desired throughput then the throughput budget will divide the time allotted for a measurement into the various components such as data acquisition time, data analysis time, stage indexing etc. These budgets allow the engineers to deliver subsystems that when properly assembled will produce a product that meets the desired performance specified in the first section described above. Also, it will be obvious which features to improve to increase a particular performance attribute.

Finally the last section of the document is devoted to the significant subsystems of the product. In general the requirements for each subsystem can be dictated directly by the customer or through judicious parsing out of errors and performance sensitivities through one or more of the error budgets. This section will provide guidance to component specifications and engineering drawings.

2   Performance and Error Budgets

2.1   Residual Lines Budget

This is an error budget that will show the requirements necessary to meet the residual lines magnitude specification. The scaling between the factors that cause the residual lines are specified numerically so if any further improvement in performance is needed, it is a straightforward exercise to determine how to go about achieving that goal.

Contributor	Budgeted error	Units	Budgeted lines error	Comments
			PV %	PV% is same as Merit Function
Camera non-linearity	0.25%	%	0.53%	This is near the noise floor of a good camera. Ratio is 2.1
Sine mask nonlinearity	0.50%	%	1.05%	Two of 3 Sine patterns masks are <0.5% second harmonic content
calibration error	0.25	degrees	0.55%	Assumes two phases off by budgeted error in worst direction. We see 0.5% Merit function values after calibration
			2.12%	Total

Since both the camera and mask nonlinearities show up the same way, we add these errors. The calibration error, which shows up as a second harmonic disturbance in the residual lines is also added to yield the PV disturbance.

2.1.1   Residual Lines caused by Camera or Mask Nonlinearities

Since a mask nonlinearity and a camera nonlinearity are indistinguishable, they can both be modeled and thought of in the same manner. This section will describe the residual lines problem that arises from a nonlinearity in the measured intensity pattern. This nonlinearity represents a departure from the ideal measured sinusoidally varying intensity pattern.

2.1.1.1   Effects of a Second Harmonic Nonlinearity

The theoretical plot below shows the processed Opti-Grid data in the presence of a quadratic nonlinearity. This nonlinearity could be in the camera response or the intensity distribution of the mask itself. These effects are indistinguishable as measured with the Opti-Grid itself. A secondary metrology would be required to discern camera from mask nonlinearities. **The important take away here is that a quadratic nonlinearity results in a third harmonic distortion of the Opti-Grid. The magnitude of the residual**

Confocal Image and Intensity Images vs Pixel Position
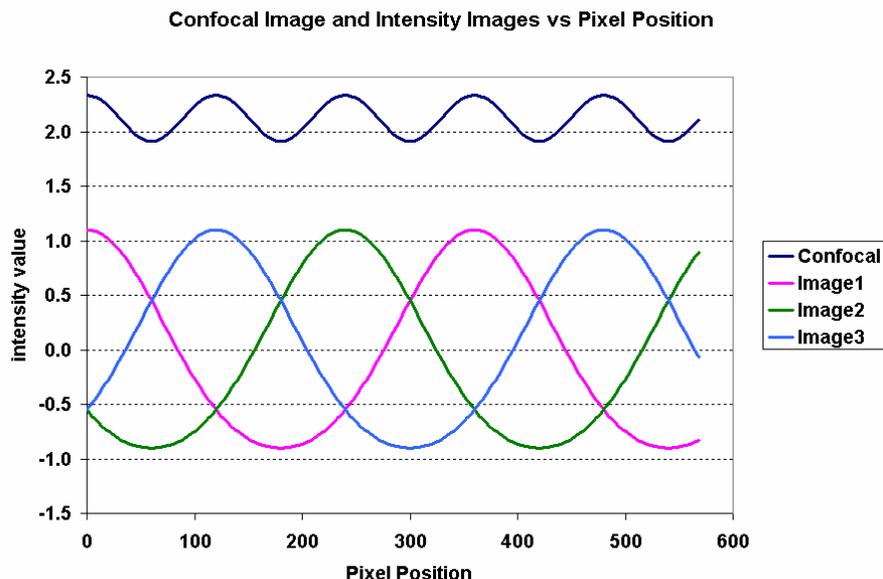
lines is 2% normalized PV per 1% second harmonic nonlinearity. The plot below is for the case of a 10% second harmonic nonlinearity.

2.1.1.2   Effects of Fourth Harmonic Nonlinearity

Since a three-bin algorithm is under study here, the effects of a third harmonic nonlinearity are identically zero. The next higher harmonic nonlinearity is the fourth harmonic that produces a third harmonic residual lines problem as in the case of the second harmonic nonlinearity discussed in the previous section. Once again, the magnitude of the residual lines is a 2% normalized PV per 1% harmonic distortion.

Confocal Image and Intensity Images vs Pixel Position
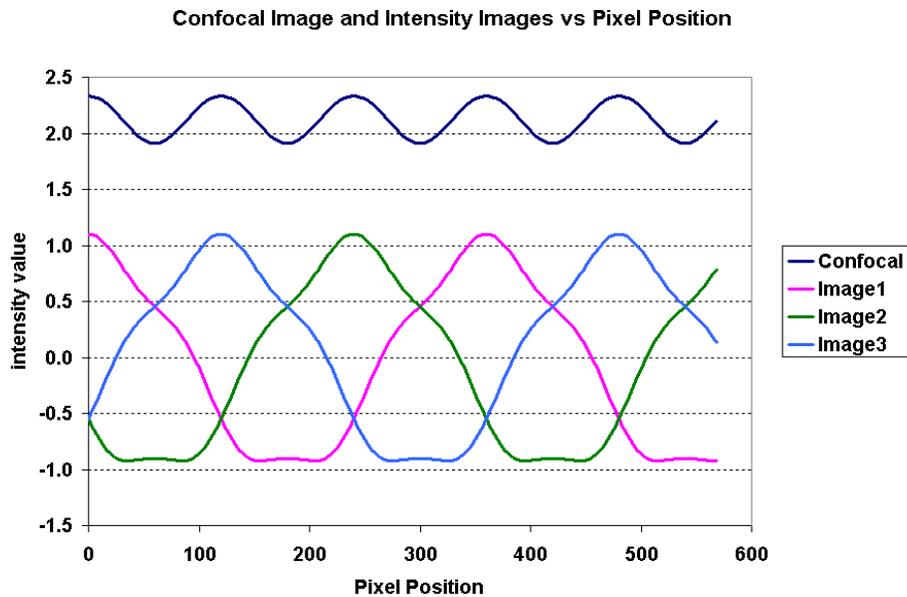
2.1.1.3   Effects of Higher Order Nonlinearities

As the order of the harmonic nonlinearity increases, the residual lines manifest themselves as higher harmonic disturbances. For instance the fifth and seventh harmonic nonlinearities cause sixth harmonic residual lines. Once again the sixth harmonic nonlinearity has zero effect on the residual lines since we employ a three-bin algorithm. This pattern repeats going to still higher nonlinearities, the third harmonic multiples cause zero effect and the neighbors cause the identical higher frequency residual lines. In all cases the magnitude is 2% residual lines per 1% harmonic disturbance.

2.1.1.4   Nonlinearity Data vs. Theory from Opti-Grid

The following validates the modeling by plotting the third harmonic residual lines content in a processed image vs. the second harmonic nonlinearity of the acquisition system. Both data and theory are shown. The degree of nonlinearity was created using various cameras with various amounts of electronically induced distortion. This data also suggests that the DVC camera is not an appropriate choice for the Opti-Grid system. We need to find a high resolution CCD with the performance of the Sony.

Residual Lines Nomalized PV Third Harmonic Content vs Nonlinearity
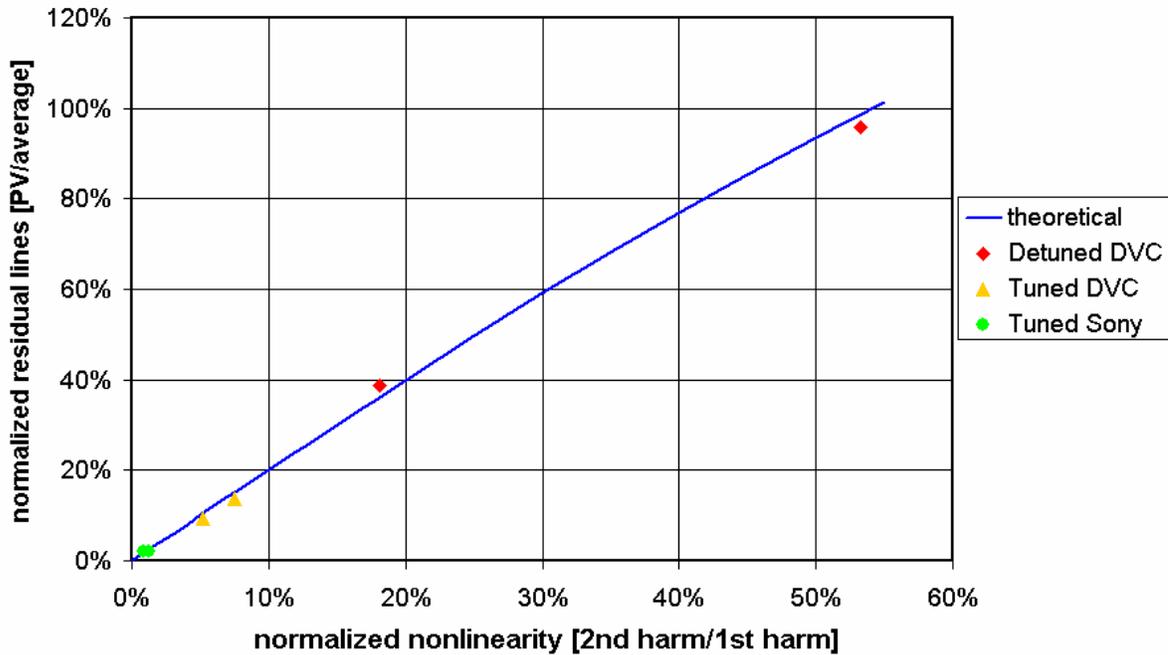
2.1.2 Residual Lines Caused by Calibration Error (second harmonic error)

This section will describe the residual lines problems that result from calibration errors in the position of the mask for the 3-bin algorithm. The plot below shows that residual lines result at the **second harmonic of the mask pattern spatial frequency**. The magnitude of the residual lines is 1.166%/degree of phase error. Shown is a 10-degree calibration error. **This data suggests that analyzing the second harmonic content of the processed Opti-Grid data could be a very effective way of estimating the calibration error.** Since there are two phases, the direction of the correction is probably indeterminate from this single piece of data.

Confocal Image and Intensity Images vs Pixel Position
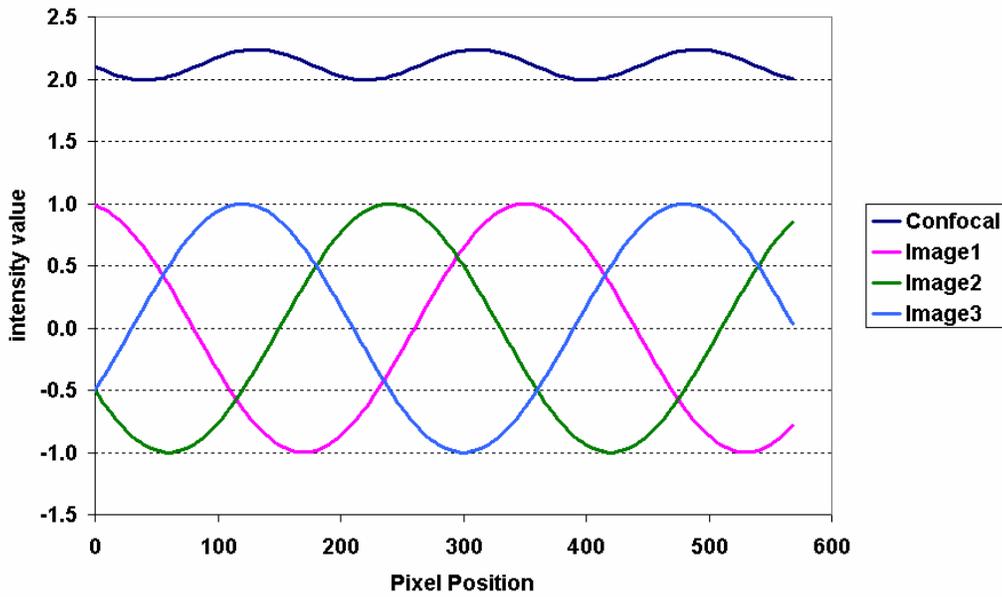
2.1.2.1 Residual Lines Magnitude vs. Calibration Detuning

This plot is from the calibration section (much more detail can be found there). The residual lines magnitude can be characterized by a merit function that is the ratio of the second harmonic content of the OptiGrid data normalized to the first harmonic magnitude of the intensity data. When this value is 1% or less, the residual lines are not noticeable.

Merit Function - Cross Section

slope = 0.0155/degree
= 0.8856/radian

slope = 0.0123/degree
= 0.7059/radian

slope = 0.0087/degree
= 0.4991/radian
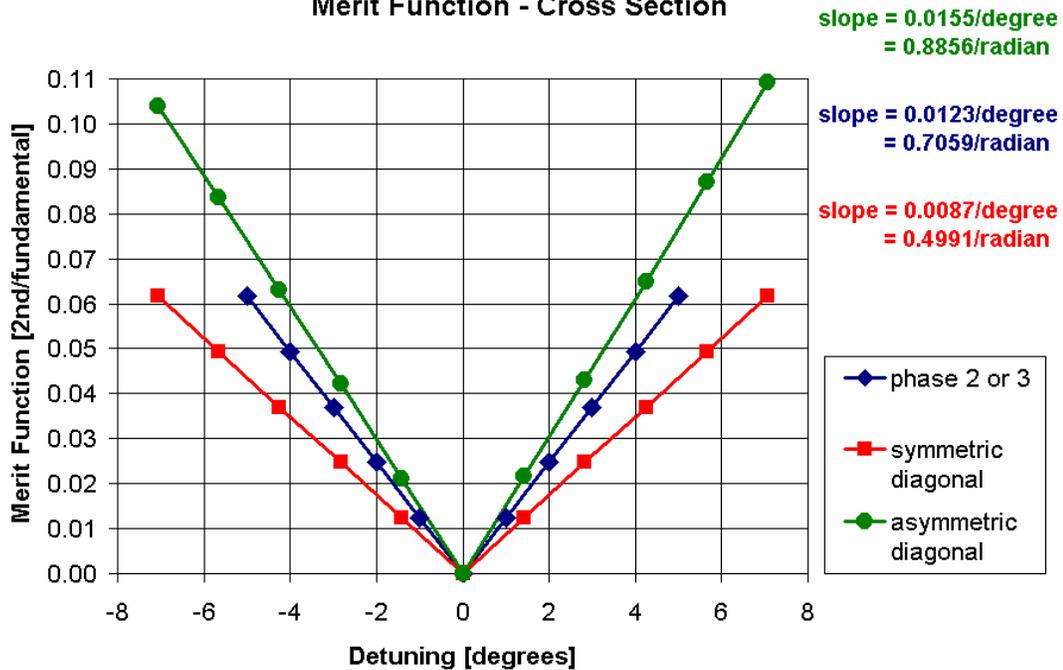
2.1.3 Transient Residual Lines

TRANSIENT RESIDUAL LINES

JAN 21ST '05

LIGHTING $\Rightarrow$ 1ST ORDER

GRID STEPS $\Rightarrow$ 2ND ORDER

PATTERN $\Rightarrow$ 3RD ORDER

KEEP THE ROOM DARK

TRANSIENT LINES

1) LIGHTING CAUSES A B' C

HAS AN OFFSET ASSOCIATED W/ IT

SAY...

A	0 → 1
B'	0.1 → 1.1
C	0 → 1

VERIFICATION

NOMINAL   A B C

LIGHT 1   A' B C $\Rightarrow$ IMAGE 1 + 1ST ORDER LI

     2   A' B' C $\Rightarrow$ IMAGE 2 +

- SPREAD SHEET (OPTIGRID.XLS)
  INDICATES TRANZ LINES OF IMG#1 + IMG#2
  TO BE 60° OUT OF PHASE
- USING "HISTO - LINE" PROFILES FROM ImagePro, THESE
  DATA WERE FEED INTO XLS.
  > A BEST FIT SINE WAS DONE FOR IMAGE #1 + #2
  Ø WAS A VARIABLE ; $\boxed{\phi_1 - \phi_2 = 60° \text{ ← PROOF}}$

2) MISSED "HOME"

HOME GETS MISSED

INCREASE t_{HOME}
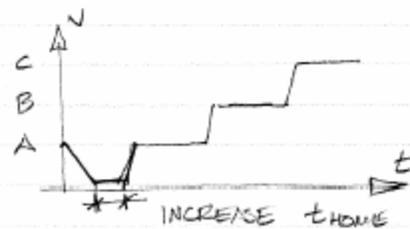
3 Subsystem Specifications

3.1 Camera

3.1.1 Camera Specifications Table

The following table contains the specifications for a good Opti-Grid camera. Some specifications are driven directly y the customer while others flow down from the various error budgets derived from the customer specifications.

Attribute	Specification	Comments
Sampling	1k x 1k minimum	
Pixel Depth	10 bit minimum	Needed for dynamic range
Non-linearity	<0.5%	Driven by residual lines budget
Pixel readout noise	TBD	Will produce grainy images and affect Opti-Grid data
Spectral sensitivity	TBD	
Blooming	TBD	
Digital	Yes	Necessary to obtain >9 bits

3.1.2 Camera Evaluation Plan

The following sections detail the camera evaluation plan needed to ensure compliance with the Opti-Grid camera specifications

3.1.2.1 Camera Evaluation Summary

The data resulting from the camera evaluation plan is collected in a summary table (example shown below). The following table represents the data for the Retiga 1300C camera. Some significant manufacturer's specifications are included along with the necessary test data.

Sample table filled out for Retiga 1300C camera

Attribute	Result	Comment
Specs		
Manufacturer	Q-Imaging	
Model	Retiga 1300C	
Cooled	Verified	TEC to 25 C below ambient
Bits	12	
Type	2/3" progressive scan interline CCD	Monochrome version for Opti-Grid
Pixel Size	6.7μm x 6.7 μm	
Light Sensitive Pixels	1280x1024	
Quantum Efficiency	400nm 30%; 500nm 43$; 600nm 30%	
Frame Rate	12 fps full resolution in 8-bit; 6 fps in 12 bit; higher rates with binning and ROI	

|			
Integration time	40 μs to 15 minutes	1 μs increments
Interface	Fire wire	
Offset		Manufacturer's range is 0-4095
Min Setting	1600	This value ensures no saturated pixels up to gain=3500 with no signal
Max Setting	4095	This would be a waste of bits
Gain		Manufacturer's range is 0-4095
Min Setting	1000	Less than this allows the pixels to saturate before the digitizer. This causes a severe nonlinearity.
Max Setting	3500	Nonlinearity and camera noise increase beyond this level
RMS noise		Cannot be determined for individual pixels without calibration software.
Opti-Grid Performance	<1.5% nonlinearity ratio	This level is actually at the system noise floor.

3.1.2.2   Evaluate Manufacturer Specification

A copy of the manufacturer specs should be included in permanent files. Significant characteristics recorded in an online database. It may be possible to record all quantitative specifications along with the measured attributes in the camera evaluation data table shown in the last sub-section of this section of the SRD.

3.1.2.3   Establish Valid Offset Range

The goal is to find the minimum setting at which the camera experiences clipping of signal at the low end of the digitization range. A valid minimal setting is where there are no zero digitization count readings for any pixel on the camera. The consequence of a zero digitization reading will cause intensity clipping and severely nonlinear response.

Here is an example of an improperly set offset causing clipping at the low end of the digitization range:
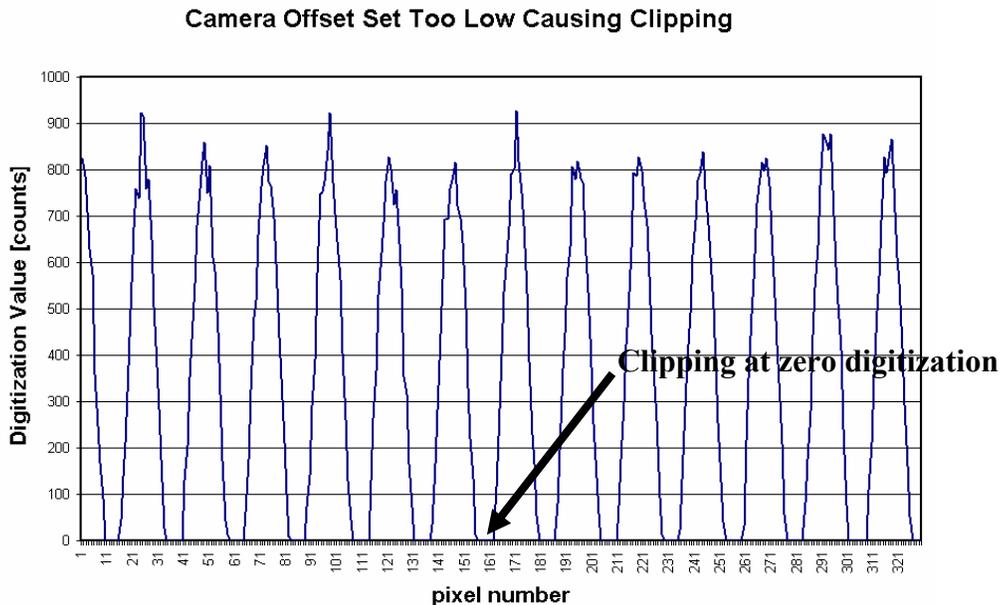
Simple (in the field) Offset Determination Instruction:
1. Turn off the light source and make sure no light enters the system.
2. Set the integration time to minimum if available.
3. Set the gain to maximum value to be used.
4. Vary the offset parameter and record the minimum value that yields no pixels with zero digitization value are observed. To verify the max digitized value bring up the histogram tool in the software and turn on the statistics setting in the tool.
5. The proper offset setting is the minimum setting at which no zero digitized pixels are detected.
6. Record this value in the camera evaluation data table.

Detailed (factory) Offset Determination instruction:
1. Set up the system as described in the simple procedure.
2. Record the digitization values near the offset value that causes the camera digitization to start responding above zero counts.
3. Vary the gain to assemble several data files over various gain settings.
4. Plot the data on one graph to determine the best-offset value over all gain settings.

As an example of the technique described in step 4 above, here is a graph that depicts an offset scan for various gain values for the Retiga camera. It is clear that an offset value of about 1600 should be the minimum for this camera.

Average Signal vs Offset [Gain=2000]
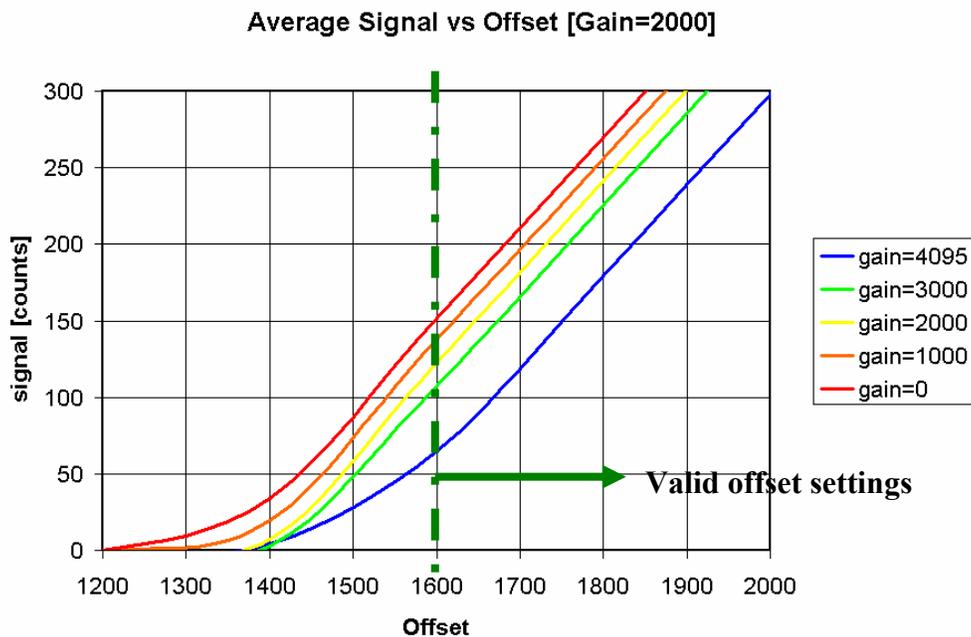
3.1.2.4 Camera Response vs. Gain

Once the valid minimum offset value is established, the camera's response (digitization vs. gain setting) may be established. This allows us to understand the actual effect of the gain knob. This data is most valuable for cameras that are integrated into the Opti-Grid software for automated control.

The procedure:
1. Offset is set to ideal value for the camera (as determined in previous procedures).
2. Set the integration time to a small value (~1ms) to minimize ambient light effects.
3. A light level is established that does not saturate the digitizer at the maximum gain setting of 4095. The max pixel reading can be seen using the histogram tool with show statistics selected.

4. The digitization value is recorded at a series of gain settings from minimum to maximum.
5. A background value (with the light blocked) is recorded at minimum gain setting and is subtracted from all the recorded digitized values.
6. The data is plotted below to show the function relating the gain setting to the actual signal multiplier.

The data is plotted below to show the function relating the gain setting to the actual signal multiplier. The signal-to-noise ratio actually represents the spatial variation of response across the array since a spatial ensemble was used for the evaluation. The per-pixel SNR is probably much better. We need calibration software to determine this parameter separately.

DC Signal and DC SNR (spatial) vs Gain
for fixed light level [1 ms exposure]
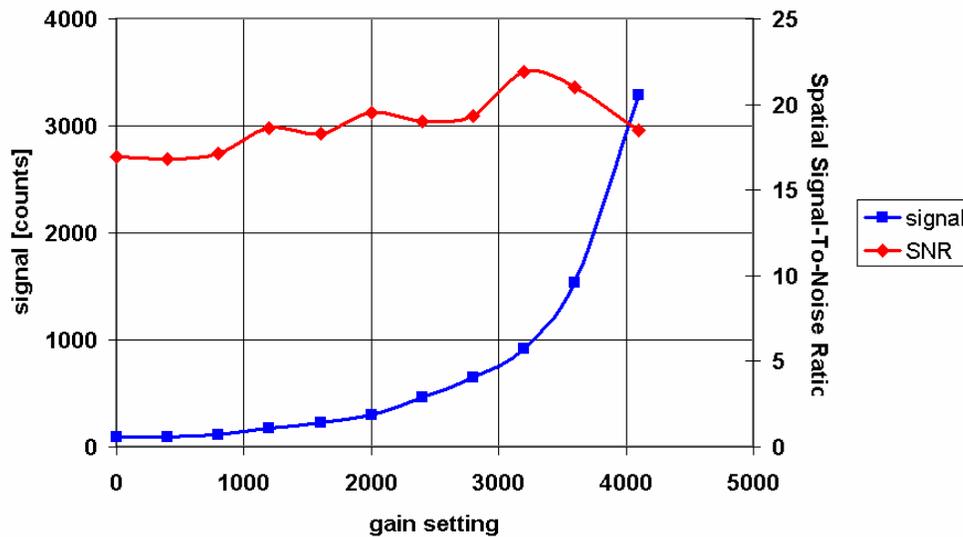
The signal data on the plot above is now shown on a log scale:

DC Signal and DC SNR (spatial) vs Gain
for fixed light level [1 ms exposure]
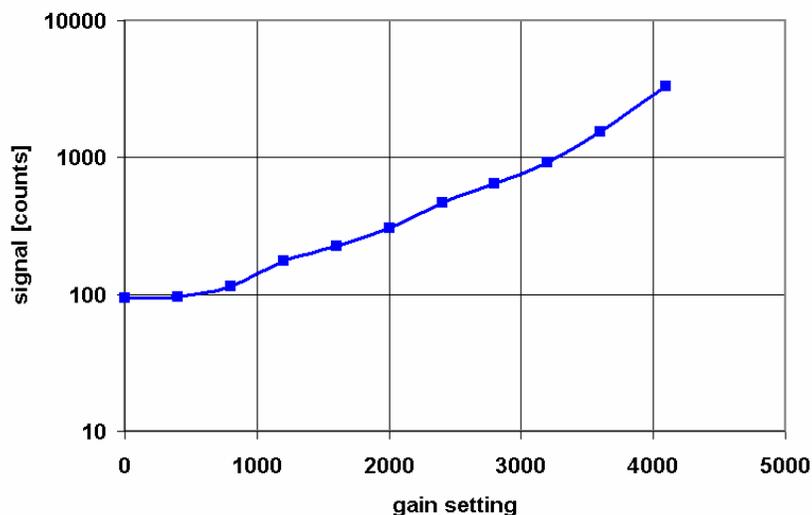
3.1.2.5 Establish Valid Gain Range (simple)

This step is needed to evaluate the minimum valid gain setting. If the camera gain is set too low then when enough light hits the sensor plane the silicon detector will reach a saturation level before the analog-to-digital converter reaches the maximum count value. When this happens the response of the pixels become nonlinear and the response saturates causing a flattening of the tops. An example of this condition is shown below:

Instruction:
1. Set offset value to its minimum value
2. Crank the light level or the integration time and adjust the gain until saturation is observed just below max A/D value. This can be done with a cross section tool. The cross section will appear flat with little or no noise since the pixels and electronics are saturated.
3. Decrease light level or the integration time to achieve average signal of 50% of the max A/D value. As the light level is decreases the cross section will decrease and signal variation (normal noise) will be observed across the field since the electronics are no longer saturated.
4. Now increase gain until the digitization value is once again near max A/D value. This effectively sets that gain to 2x the level where saturation is observed.
5. Record this value for the gain in the camera evaluation data table. This gain setting and higher should be used for linear camera operation.

The table below shows an example of a sine wave illumination with the camera's gain setting too low, causing saturation at high exposures. This condition leads to sever nonlinear response and is undesirable.
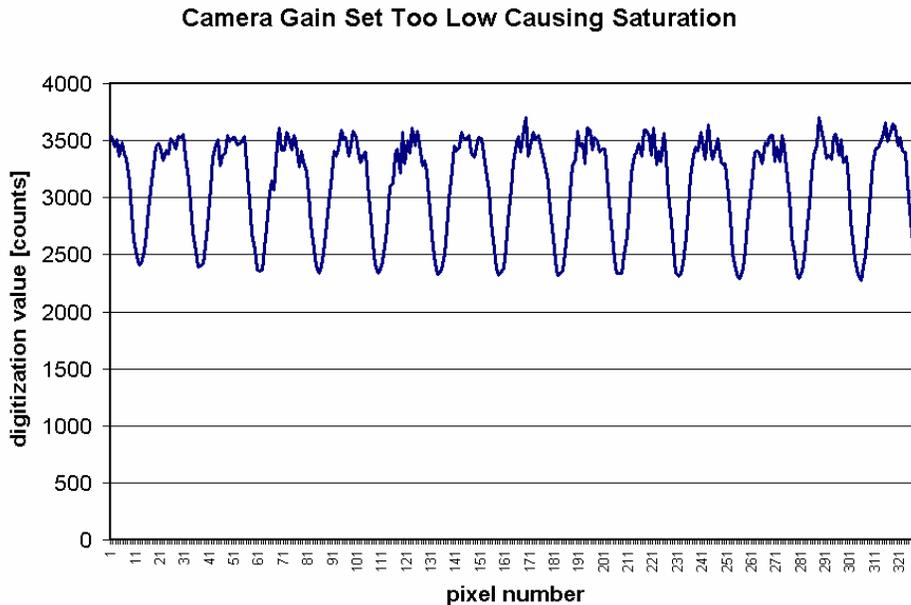
3.1.2.6 Camera Linearity Evaluation (precision gain determination)

This test establishes the linearity or nonlinearity of the camera once the camera. This test can also be used to determine the best range of gain settings for a camera. By evaluating the linearity of the camera with near-saturating exposures at various gain settings the behavior of the linearity of the camera as a function of gain can be determined.
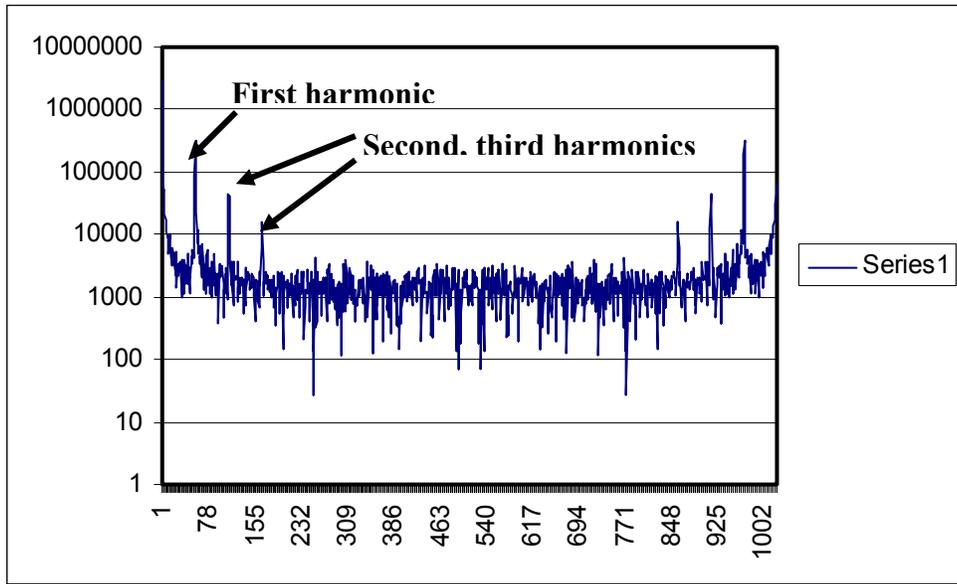
Instruction:
1. Set the camera at the minimum valid offset setting as determined by the offset procedure.

2. Set the camera to a valid gain setting.
3. Put in the DIC interferometric objective with a flat reflector in focus.
4. A 10nm filter should be used to that a large interferometric fringe envelope can be seen as shown below.
5. Increase the intensity to a near maximum level (do NOT saturate the camera digitization!). Use the area histogram tool to view the full frame statistics. Max value should not be less than the camera's max-digitized value (1024 for 10 bits, 4095 for 12 bits).
6. Grab a frame and use the line-sectioning tool to acquire an intensity cross-section. Save this data to a file for analysis in excel.
7. Analyze the intensity data by taking an FFT (excel can be used for this).
8. The ratio of the second harmonic spike with respect to the first harmonic is the harmonic distortion (or nonlinearity ratio) of the camera at this gain and offset setting. Finding the first harmonic spike and then going to the proper frequency bin for the second and higher harmonics can determine these values. The ratio of each harmonic with respect to the first harmonic is the harmonic distortion ratio for that harmonic.

The figure below shows the screen in image pro used for this procedure.
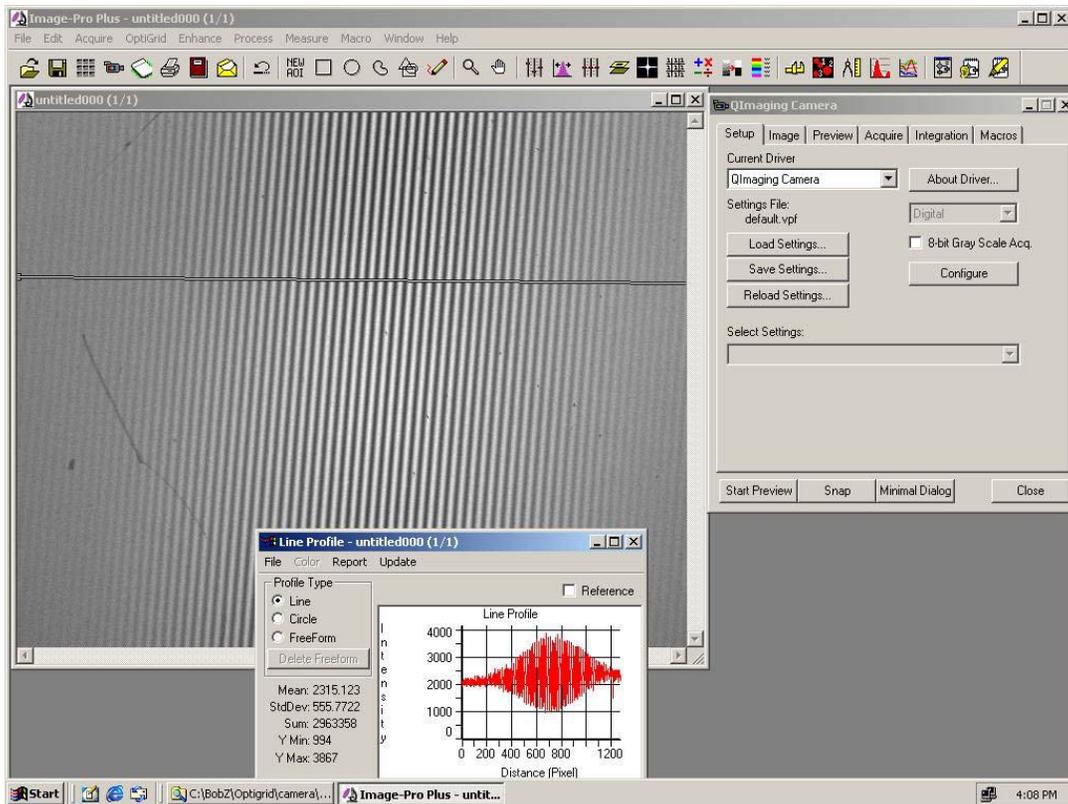
The following graph shows an example of nonlinear (poor) behavior showing the first harmonic as well as the second and third harmonics.

This data is processed to produce the ratios described in the instructions. With data from several gain settings, we produce the following graph for the Retiga camera. The graph shows that the gain should be operated between the settings of 1000 and 3500 for this camera (the 3500 gain setting reading was limited by the spectral noise floor- if this were not the case, the max gain setting would be closer to 3000 as shown by this data).
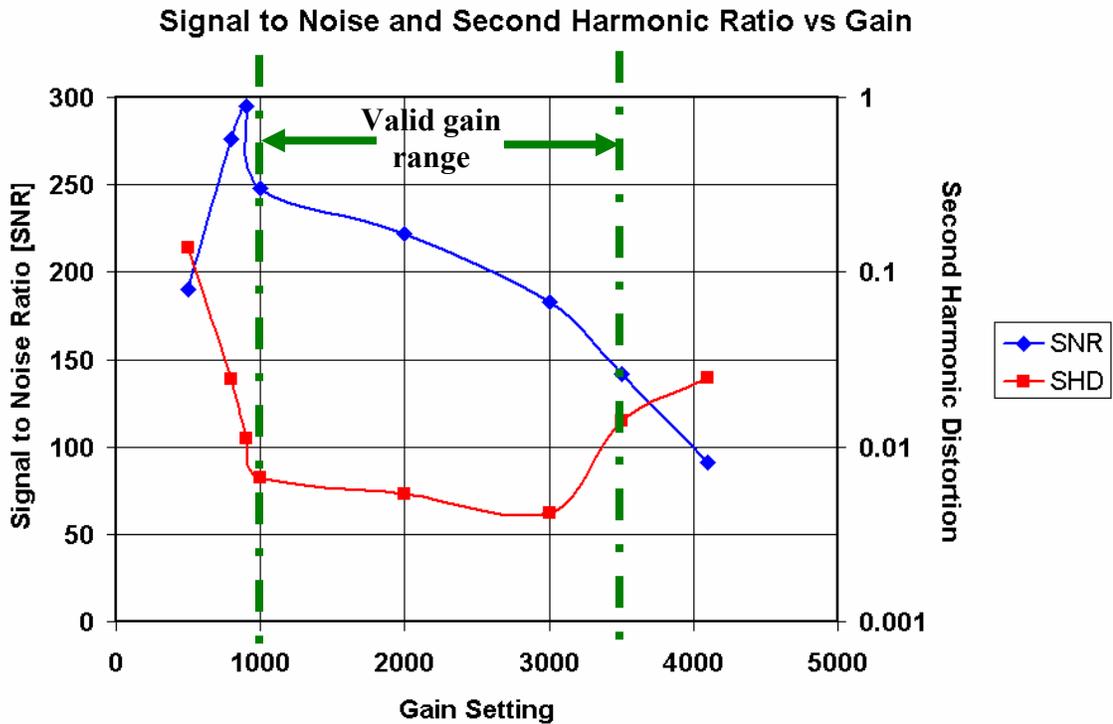
### 3.1.2.7 Evaluation of Opti-Grid Performance (full system verification)

Now that we have shown the valid gain and offset ranges we can evaluate the Opti-Grid performance with the camera operating with these parameters. The graph below shows the Fourier transform of the intensity pattern and the Opti-Grid data for the system operating at an offset setting of 1600 and a gain setting of 2000.

Procedure:
1. Snap a frame of intensity data with a non-saturating exposure. Non-saturating exposure is determined using the area histogram tool; show statistics, using the max value readout to reduce light level so this value is just below the maximum digitization value for the camera.
2. Use the line section tool to record and save data representing as long a section as possible across the field of view of the camera. Try to record at least 1024 pixel section for a good FFT.
3. Use Excel or other software tool to establish the spectral intensity of the first harmonic of the mask's transmitted intensity. This is 362547 for the data shown below.
4. Repeat steps 1-3 except with Opti-Grid processed data to establish the spectral intensity of the second harmonic (calibration error) and third harmonic (nonlinearity error) distortion of the Opt-Grid data. If the data section is recorded similarly then the harmonics will be located in a relative position in the Opti-Grid FFT to the first harmonic location on the intensity FFT.
5. Take the ratio of these values to the first harmonic intensity of the grid intensity data. Acceptable performance is obtained when this ratio is below 2%.
6. Repeat these procedures for various gain settings.
7. Construct nonlinearity plot from intensity data by comparing first harmonic Fourier magnitude with second harmonic magnitude. Also construct SNR plot by taking ratio of first harmonic to Fourier noise floor.
8. Construct residual lines plot vs. gain by taking ratio of third harmonic Fourier component from OptiGrid cross section to first harmonic of intensity FFT. Also extract SNR by taking first harmonic of intensity to noise floor of OptiGrid cross-section.

Both the second and third harmonic power spectral values are below the 5000 level. These levels at near the noise floor of the Opti-Grid data. We can establish a normalized Peak-to-Valley residual line intensity ratio of about 1.5% from these values. The actual values may be lower since the noise floor of the Opti-Grid data may be obscuring the actual performance level.

Fourier Spectrum of Intensity Signal
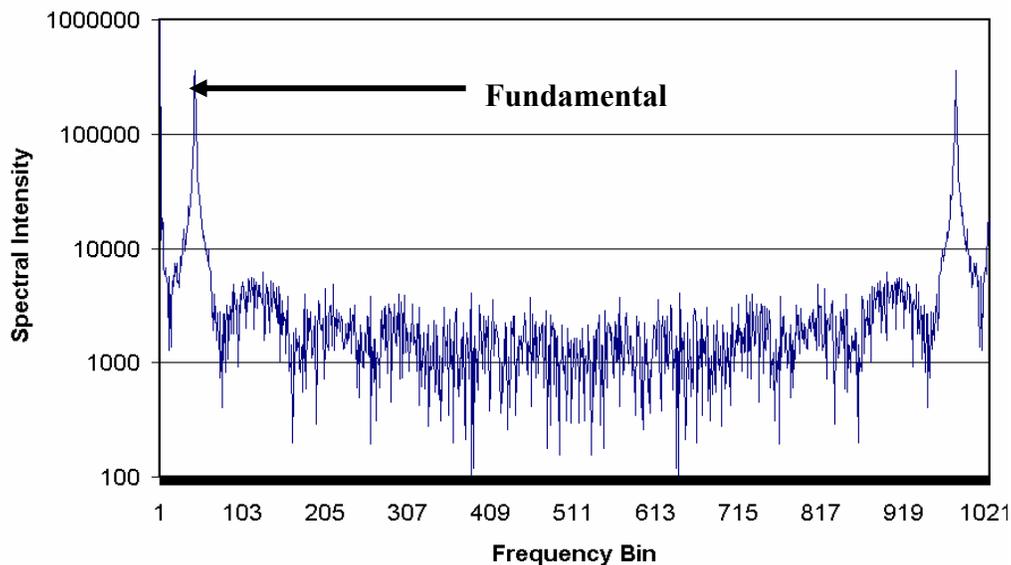
Fourier Transform of Opti-Grid Data

Second harmonic < 5000

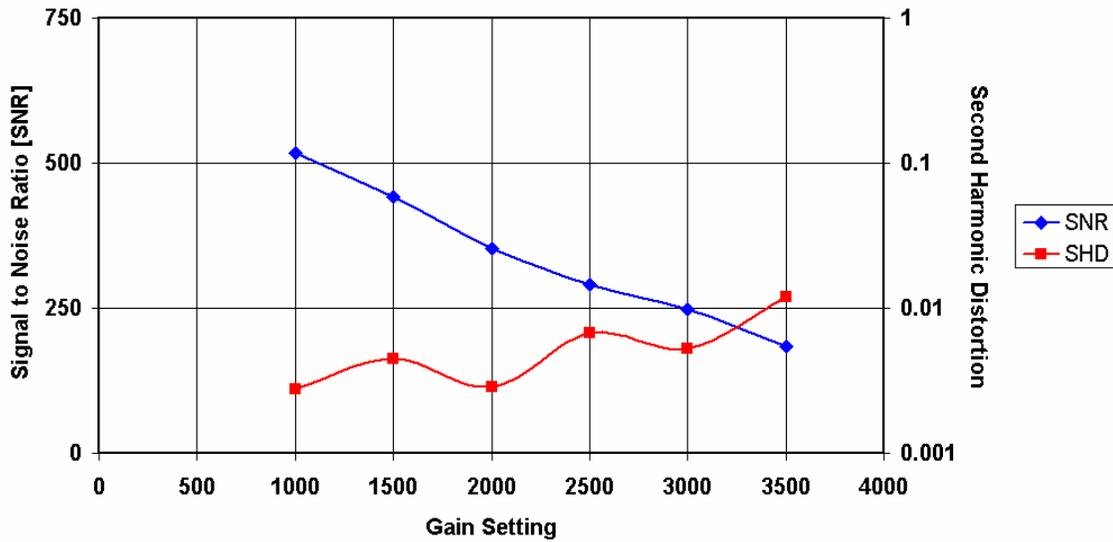**Third harmonic <5000**
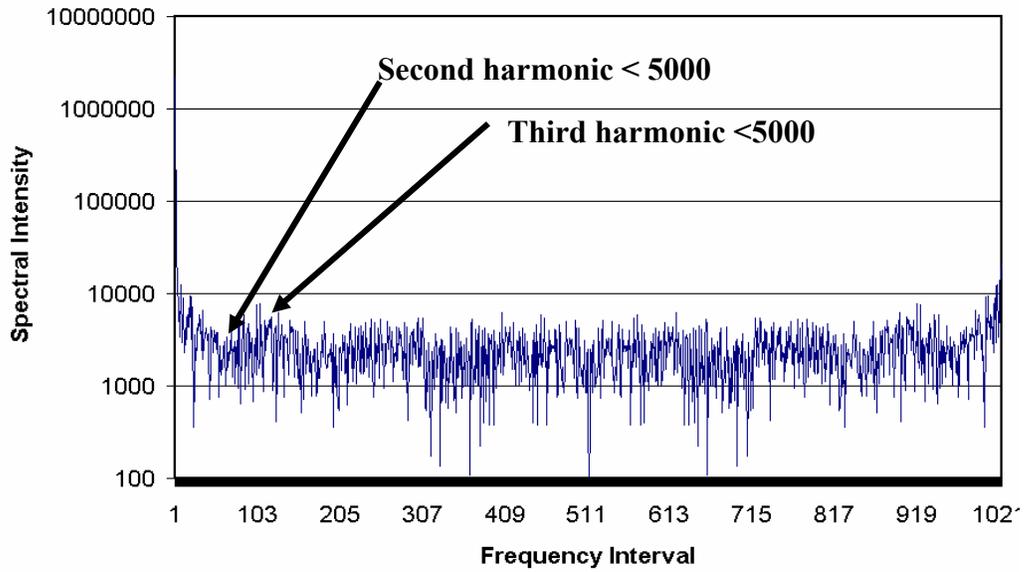
The following is the plot of the SNR and SHD derived from an intensity cross section of the sinusoidal mask. The SNR is that ratio of the first harmonic of the intensity to the noise floor of the intensity FFT. The second harmonic ratio is the second harmonic normalized to the first harmonic.

Spatial Signal to Noise & Second Harmonic Ratio vs Gain

The following plot is the SNR and third harmonic residual lines as derived from the OptiGrid processed cross section. The SNR is the ratio of the First harmonic spike from the intensity data to the average of the FFT noise floor of the OptiGrid cross section. The Third harmonic is the ratio of the third harmonic for the OptiGrid data to the first harmonic of the intensity FFT data.
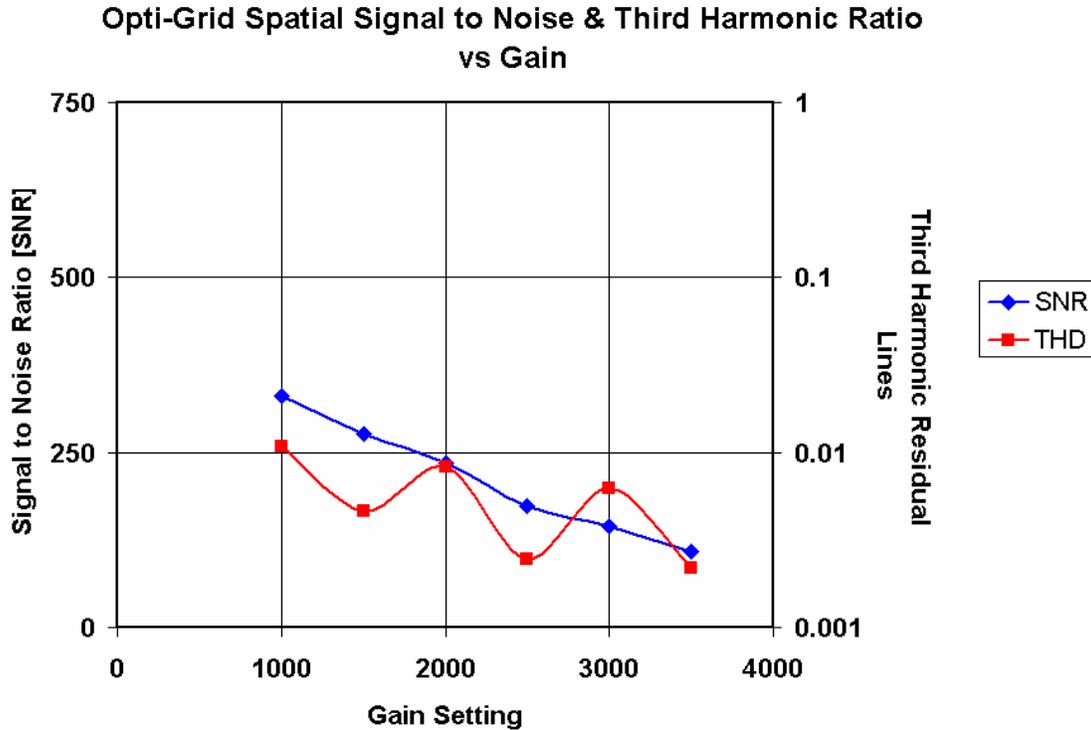
3.2 Calibration

The fidelity of the calibration can be determined by analyzing the second harmonic content of the residual lines. We found that the calibration error is the only thing that produces second harmonic residual lines. Therefore, the second harmonic content of the residual lines can be a metric function for the calibrations. The algorithm could be a damped optimization routine based on this merit function.

There is also the possibility of computing the phase for each of the three bins as a means of calibration. This technique is totally analytic and should converge quickly if the 0, 120, 240 phase condition actually minimized the residual lines. At this point there is no reason to suspect otherwise.

3.2.1 Calibration Merit Function

Since the fidelity of the calibration is known to directly affect the second harmonic content of the OptiGrid data, we will take a detailed look at this function vs. detuning of the calibration phases of the OptiGrid. We will also show a detailed procedure for evaluating the merit function from actual OptiGrid data in this section.

3.2.1.1 Merit Function for Small Detuning

This first plot shows the behavior of the second harmonic (normalized to the fundamental) for small deviations from the ideal calibration condition of $\Phi_1 = 0$ degrees, $\Phi_2 = 120$ degrees, $\Phi_3 = 240$ degrees. The second and third phases were varied over a range of +/- 5 degrees in 1-degree increments to form this 3D plot of the proposed merit function.
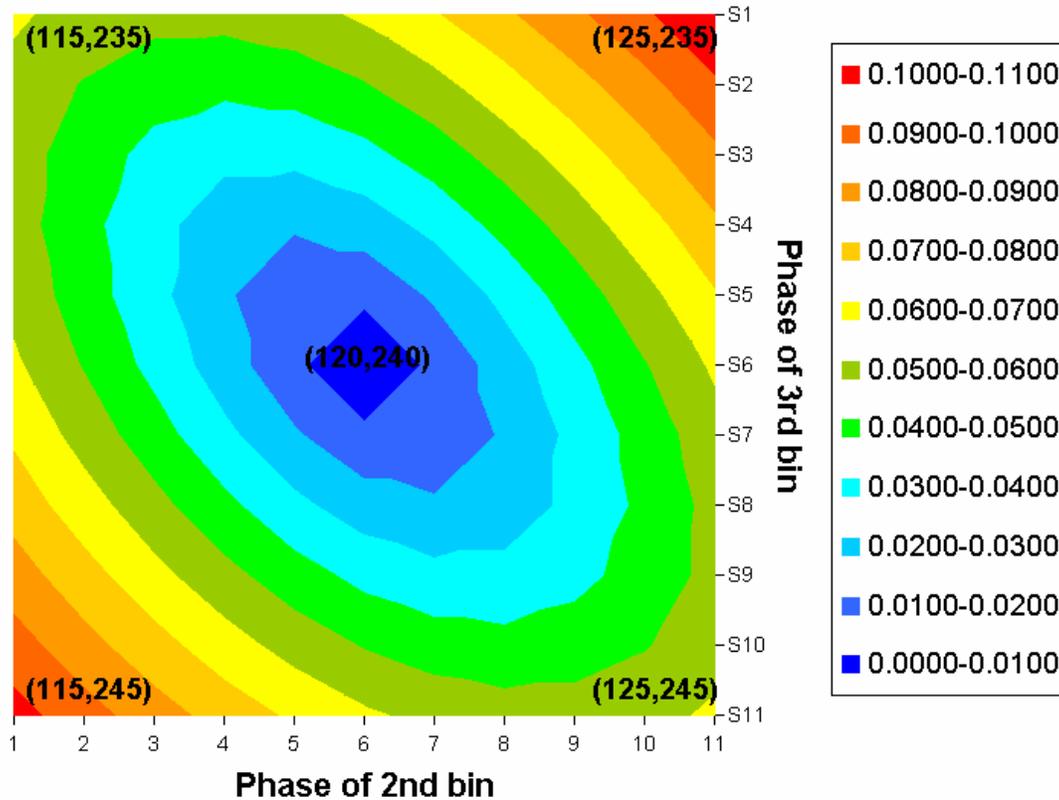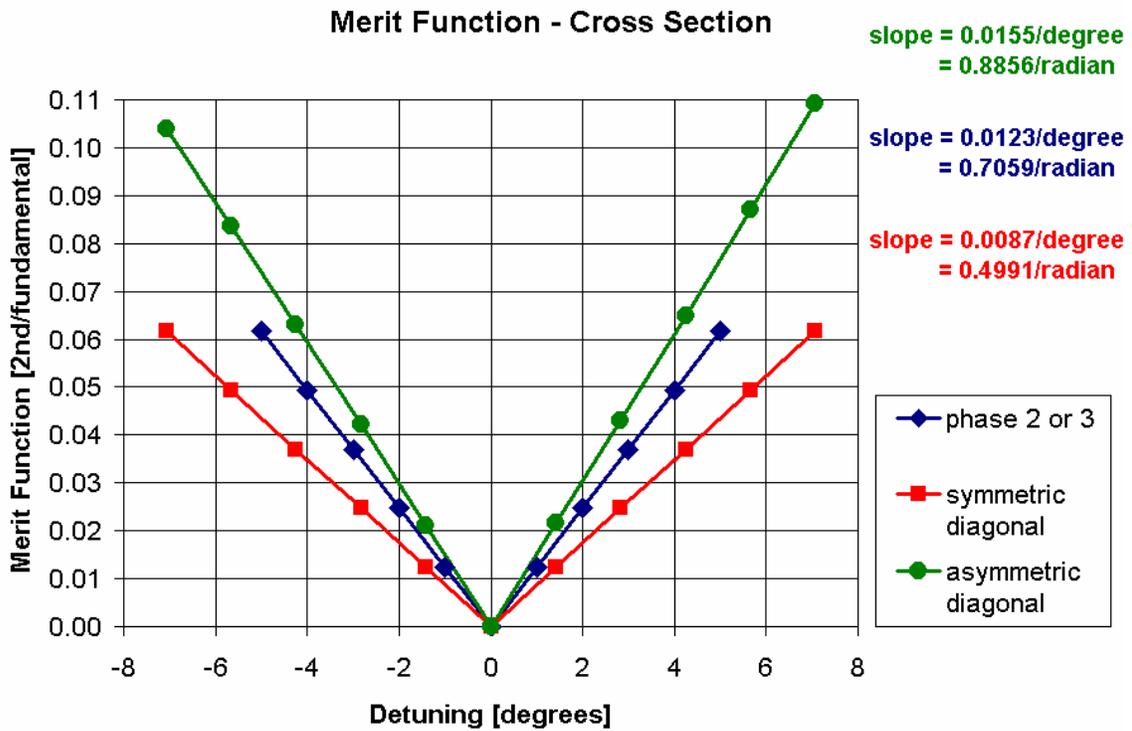

This curve shows that the merit function is a smooth function in the neighborhood of the ideal calibration solution.

3.2.1.1.1 Merit Function Cross Sectional Behavior

The trajectory through the solution on the merit function surface is V-shaped. That is to say that there is a linear dependence of the merit function toward the solution. The following plot illustrates this point. Shown are cross sections through the plot for small phase variation. Cross sections that correspond to varying either phase 2 or phase 3 alone are the same. Cross section along the minor and major axes of the function are also shown. This data is useful in establishing the step sizes to take when establishing the derivative as well as the correction of the function.

Since the maximum slope is 0.0155/degree, this should be used to determine the step size taken to determine the derivative. Since we do not want to go through the solution when establishing the slope, we want to take a step size that is smaller than the step that would zero out the merit function. We also want this step size to be small enough so we do not cross into the nonlinear region or exit the basin of attraction.

Merit Function - Cross Section

slope = 0.0155/degree
= 0.8856/radian

slope = 0.0123/degree
= 0.7059/radian

slope = 0.0087/degree
= 0.4991/radian

Merit Function [2nd/fundamental]

Detuning [degrees]

- phase 2 or 3
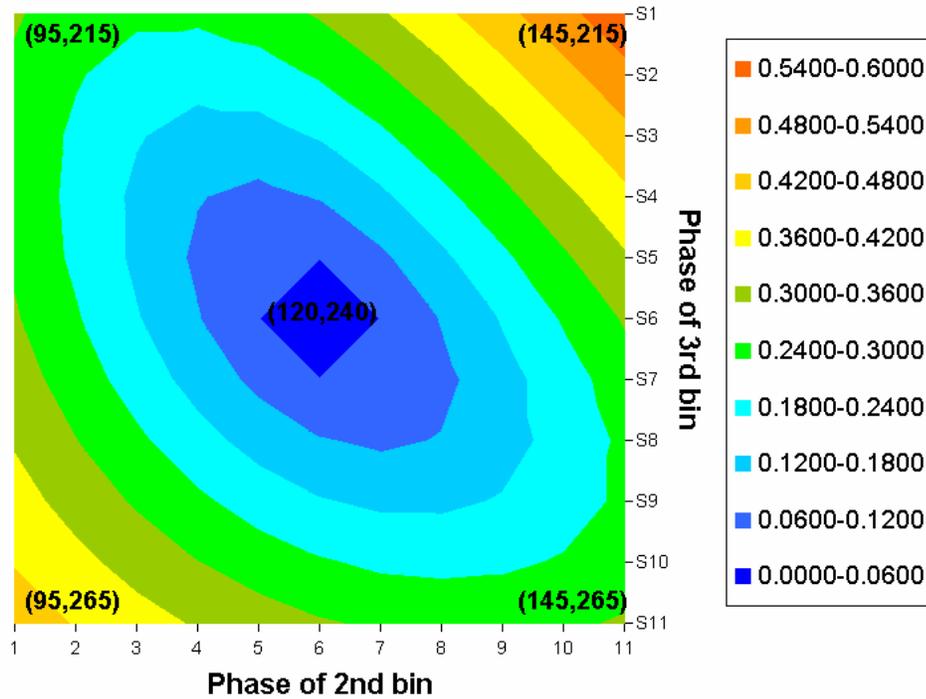- symmetric diagonal
- asymmetric diagonal

3.2.1.2 Merit Function for Medium Detuning

This second plot shows the behavior of the second harmonic (normalized to the fundamental) for larger deviations from the ideal calibration condition of $\Phi_1 = 0$ degrees, $\Phi_2 = 120$ degrees, $\Phi_3 = 240$ degrees. The second and third phases were varied over a range of +/- 25 degrees in 5-degree increments to form this 3D plot of the proposed merit function.

This plot shows that in this range the merit function still converges monotonically on the solution. However, we start to see some deviation in the way the function behaves in the upper right corner of the plot.

Merit Function = (2nd harmonic/first harmonic)
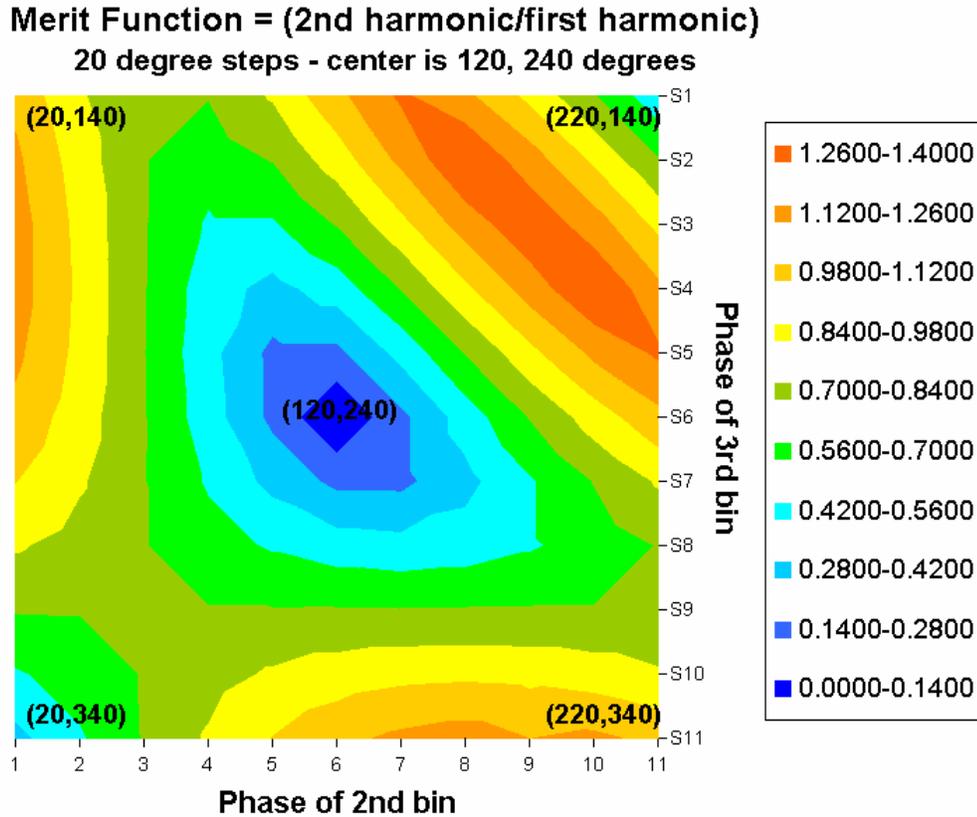### 5 degree steps - center is 120, 240 degrees

3.2.1.2.1 Merit Function Cross Sectional Behavior

Once again we plot the cross sections of the merit function. We start to see some non-linearity of the cross sections. One side of the merit function is obviously higher than the other. Notice that the magnitudes of the slopes are different than for the previous small detuning plots.
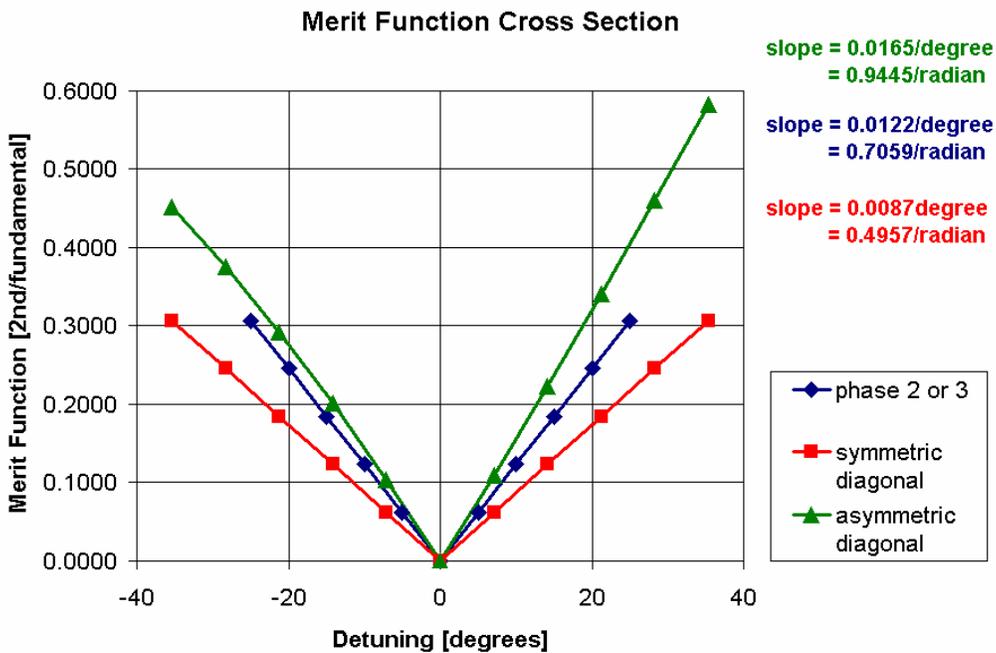
3.2.1.3 Merit Function for Large Detuning

This third plot shows the behavior of the second harmonic (normalized to the fundamental) for larger deviations from the ideal calibration condition of $\Phi_1 = 0$ degrees, $\Phi_2 = 120$ degrees, $\Phi_3 = 240$ degrees. The second and third phases were varied over a range of +/- 100 degrees in 20-degree increments to form this 3D plot of the proposed merit function.

Merit Function = (2nd harmonic/first harmonic)
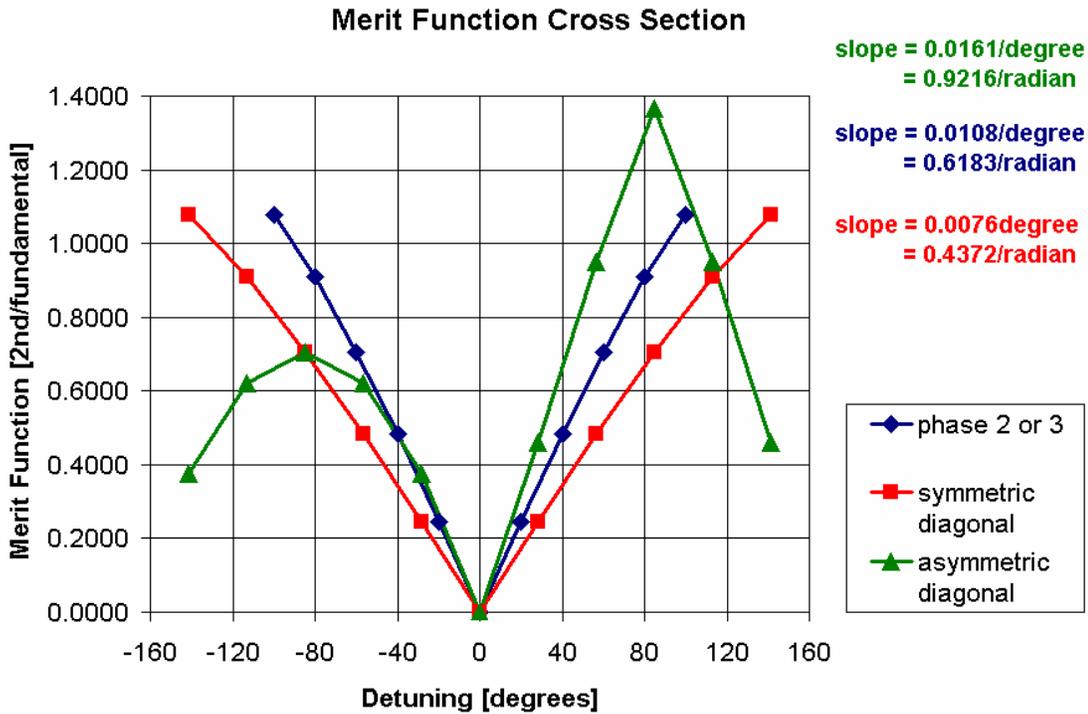**20 degree steps - center is 120, 240 degrees**

This plot shows that as you expand the initial error from the ideal solution you run into the possibility of going down hill in the wrong direction. By this most lenient criterion, I would define the basin of attraction of the best solution as a detuning that produces a merit function value of no more than 0.7. At that point the downhill direction would be away from the desired solution where all the phases are in order (i.e. 0,120,240).

3.2.1.3.1 Merit Function Cross Sectional Behavior

Once again we plot the cross sections of the merit function. We see severe non-linearity of the cross sections. One side of the merit function is obviously higher than the other. Notice that the magnitudes of the slopes are different than for the previous small detuning plots. The slopes were calculated for the right side of the curves where they are the largest.

The other take-away from this plot is that any value of the merit function near 0.7 could indicate that the errors may be outside of the basin of attraction. It is important that all data be taken for angular errors less than 80 degrees and merit function values not approaching the 0.7 ratio.

Merit Function Cross Section

slope = 0.0161/degree
= 0.9216/radian

slope = 0.0108/degree
= 0.6183/radian

slope = 0.0076degree
= 0.4372/radian

3.2.1.4 Experimental Merit Function Behavior

The following plot is Merit function data taken from an instrument by varying the detuning and recording the Merit Function.


Experimental Merit Function = (2nd harmonic/first harmonic)
~6 degree steps - center is 0, 120 degrees
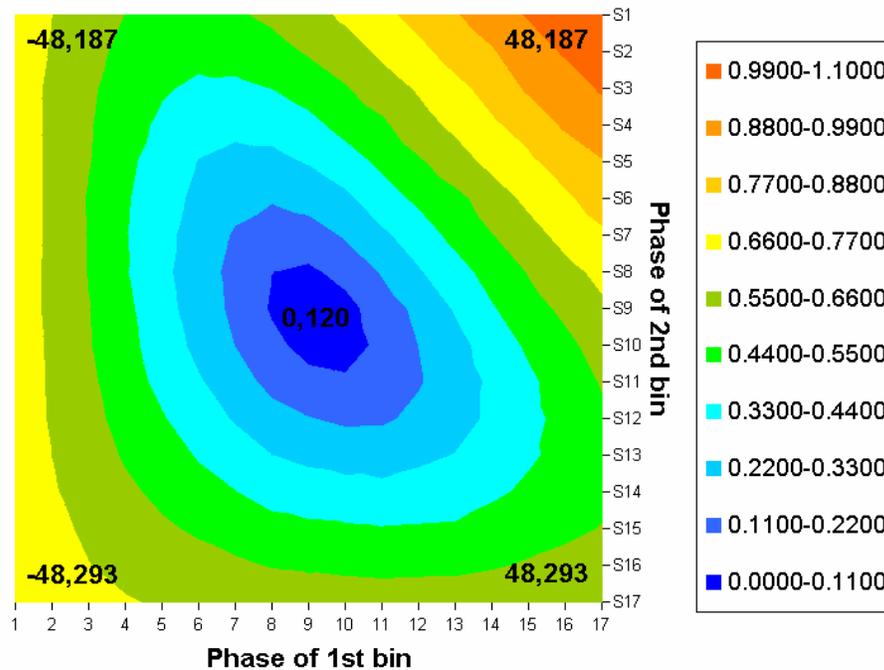
3.2.1.4.1 Experimental Merit Function in 3D

This plot shows the oblate conical shape of the merit function. The direction directly down hill is linear in all directions for small offsets from the solution.


Experimental Merit Function = (2nd harmonic/first harmonic)
~6 degree steps - center is 0, 120 degrees
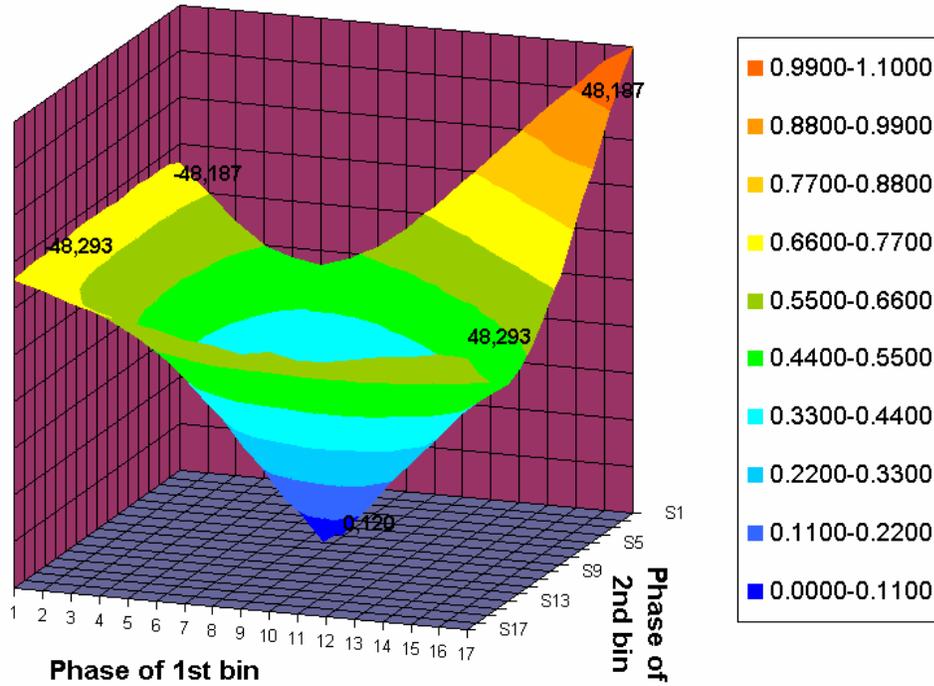
3.2.1.4.2 Experimental Merit Function Cross Sections

The chart below shows the cross sections through the experimental merit function. Even though there were some hysteresis issues while taking this data the slopes agree with those of the theoretical model.

Experimental Merit Function Cross Sections
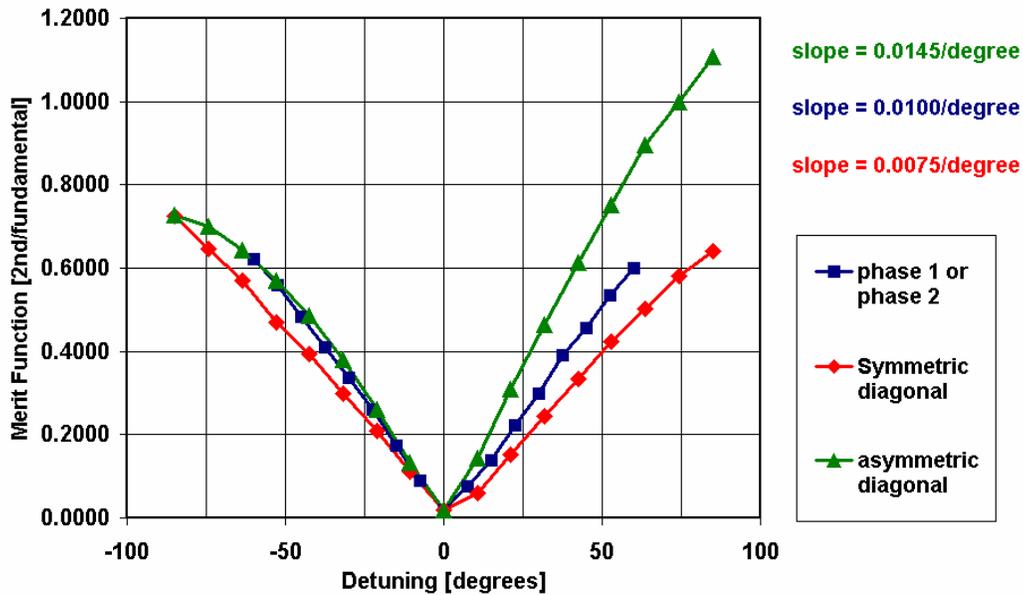
3.2.2 Merit-Function-Optimization Calibration Procedure

The following procedure is an outline for the software calibration of the OptiGrid using Merit function minimization.

Starting point characterized by:
Phases: Phase1, Phase2, Phase3
Voltages: Vphase1, Vphase2, Vphase3

1) Take OptiGrid trio of frames at current phase 1,2,3 settings
2) Use one intensity frame for normalization
   a. Average 10 cross sectional lines in center of frame. Should be 1024 point data sets for FFTs.
   b. Take FFT of resulting average
   c. Find fundamental peak @ point f
   d. Average the peak and two neighbors = fundamentalaverage
   e. Find Intensitynoise floor = average (point 4f to point 512)
   f. If fundamentalaverage/Intensitynoise < 50 ; then error   (not enough contrast calibration error)
3) Process OptiGrid trio of frames
4) Find Second Harmonic and Merit Function
   a. Average same 10 cross sectional lines in center of frame
   b. Take FFT of resulting average
   c. Average second harmonic plus two neighbors (SH @ point 2N)
   d. Find OGnoise floor = average (10 points on either side of points used for SH peak)
   e. Find STD deviation over same region.
   f. SHaverageAbsolute = SecondHarmonicAverage - NoiseFloorAverage
   g. If result < N sigma then the system is calibrated   **(exit criterion – N~1-2 works)**
   h. Calculate the MeritFunction0 = SHaverageAbsolute/fundamentalaverage

Comment: We are taking the derivative at the current point (point0). We will always perform corrections from this point. We have to keep track of changes from where we are (i.e. on the derivative phases or on the current solution phases).

Taking the Derivative of the Merit Function at the current calibration setting (see figure below)
5) Determine the phase and voltage step sizes
   a. Pull up current Merit Function Value (as calculated in previous steps)
   b. PhaseStepsize = Stepfactor * MeritFUnctionValue/(maxslope = 0.0165 per degrees)
      i. We do not know what Stepfactor is. For now lets go with 0.5.
   c. Voltagestepsize = phasestepsize / phasepervoltageslope   (phase/voltage slope is entered parameter for now)
      i. In general there may be a different slope for phase1 and phase 2
      ii. These could be provides from derivative of phase vs. voltage plot.
6) Calculate Differential phase values
   a. Current phases are phase1, phase2, phase3
   b. Derivative phases are phase1d, phase2, phase 3 for phase1 derivative
      i. Phase1d = phase1 + phaseStepSize
   c. Derivative phases are phase1, phase2d, phase2 for phase2 derivative
      i. Phase2d = phase2 + phaseStepSize
7) Calculate Derivative voltage values
   a. Current voltages are vphase1, vphase2, vphase3
   b. Derivative voltage settings are vphase1d, vphase2, vphase3 for phase 1 derivative
      i. Vphase1d = vphase1 + Voltage1stepsize
   c. Derivative voltage settings are vphase1, vphase2d, vphase3 for phase 1 derivative
      i. Vphase2d = vphase2 + Voltage2stepsize
8) Take OptiGrid Data for phase 1 derivative

   a. Take 3 frames at Vphase1d, Vphase2, Vphase3
   b. Use procedure in step 4 to calculate Meritfunction1.
9) Take OptiGrid Data for phase 2 derivative
   a. Take 3 frames at Vphase1, Vphase2d, Vphase3.
   b. Use procedure in step 4 to calculate Meritfunction2.
10) Calculate Gradient Differences and Correctionfactors
   a. Calculate Delta1 = (MeritFunction1 − MeritFunction0)
   b. Calculate Delta2 = (MeritFunction2 − MeritFunction0)
   c. Calculate Deltamag = sqrt(Delta1^2 + Delta2^2)
   d. Correctionfactor1 = Delta1/Deltamag
   e. Correctionfactor2 = Delta2/Deltamag
11) Calculate new values for phases and voltages to start step 1 again (steps are from point0)
   a. PhaseCorrection1 = Correctionfactor1 * MeritFunctionValue/(maxslope)
     i. VoltageStepSize1 = PhaseCorrection1/ phasepervoltageslope
   b. PhaseCorrection2 = Correctionfactor2 * MeritFunctionValue/(maxslope)
     i. VoltageStepSize2 = PhaseCorrection2/ phasepervoltageslope
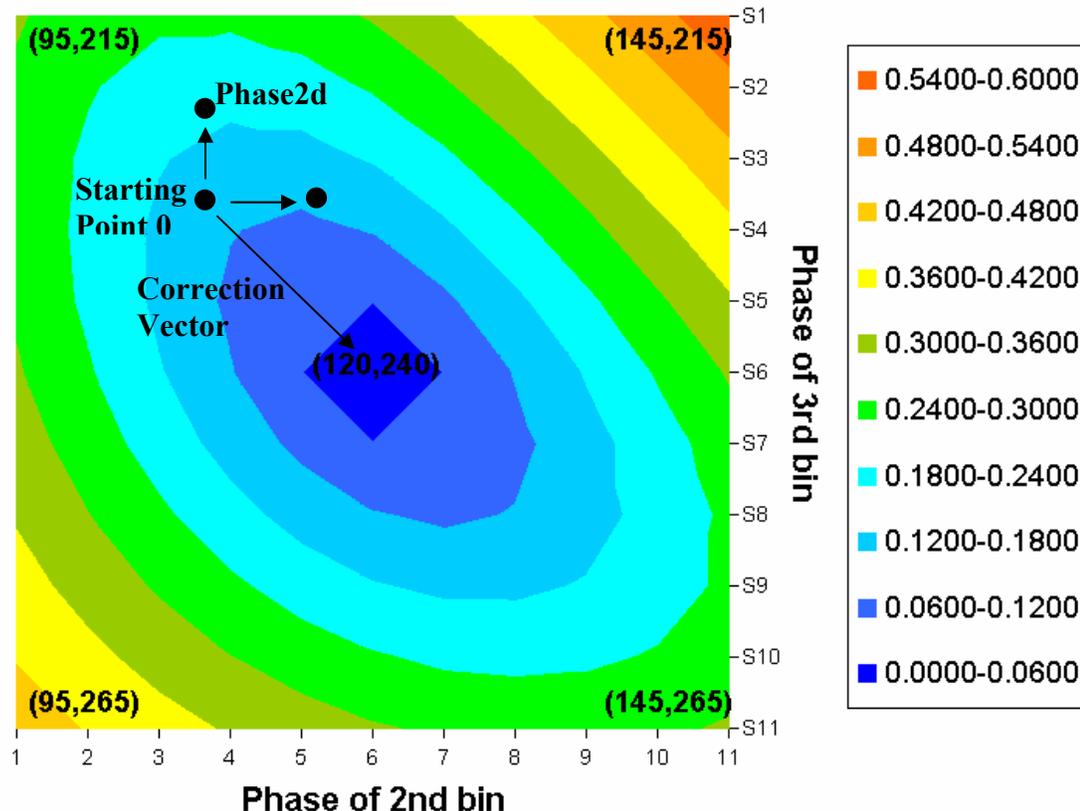

New point is characterized by:
Phases: Phase1- PhaseStepsize1, phase2 - PhaseStepsize2, phase3
Voltages: Vphase1 - VoltageStepSize1, Vphase2 - VoltageStepSize2, Vphase3

Iterate the entire sequence until exit condition (see step 4 g) is met.
SecondHarmonicAbsolute < N * Sigma, where Sigma is standard deviation of OptiGrid FFT noise floor near the second harmonic.

3.2.3   Calibration of OptiGrid via Phase Calibration

This calibration method is more deterministic based on a measurement of the phases instead of an optimization technique. This section is put together to provide a theoretical background and a detailed procedure for this calibration technique.

3.2.3.1   Intensity Cross Section

The basis for the phase calibration technique is the intensity cross section and its Fourier Transform. Although we are familiar with this cross section and its transform, we will review here for completeness. Shown below is a cross section of a single intensity frame taken across the grid. In the calibration this data will be the average of 10 or so such cross sections for the purpose of noise reduction. Notice that we will be taking 2^10 point = 1024 points in order to leverage Fast-Fourier Transform software.


Intensiy vs Pixel Number
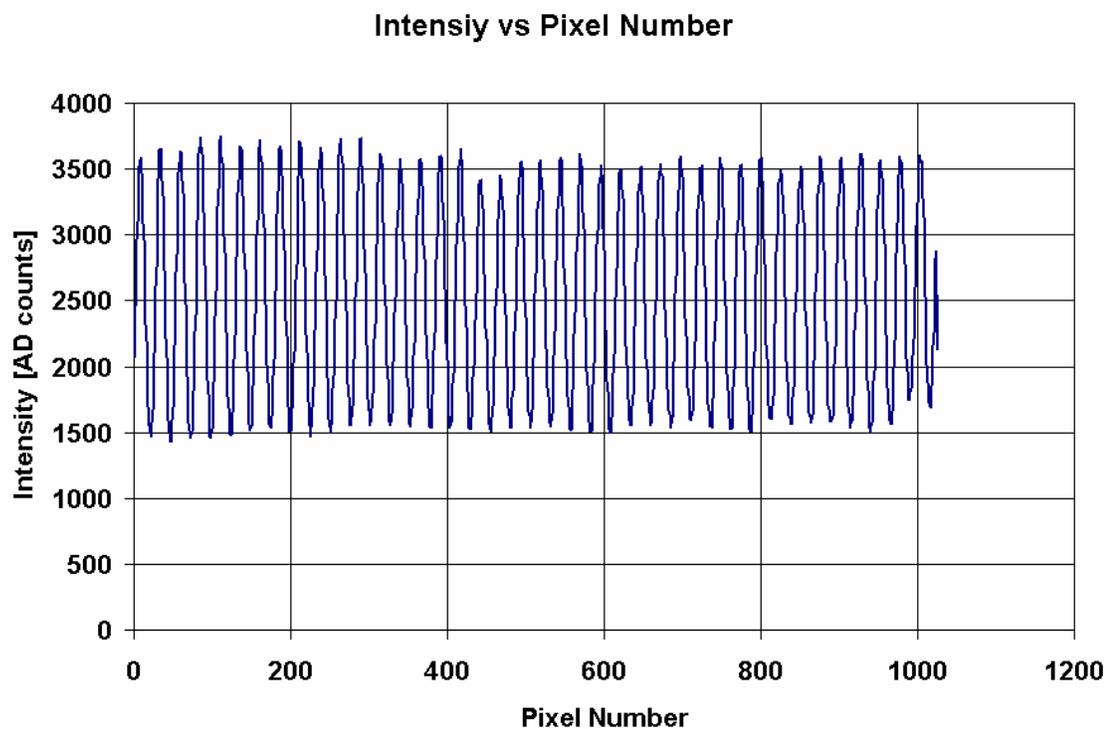
3.2.3.2   The Fourier transform of the Intensity

These section provide a basic coverage of the FFT of the intensity cross section that will be used for the phase calibration. The phase of the FFT is used for the calibration but we will utilize the magnitude in order to determine the location of the fundamental in frequency space.

3.2.3.2.1 Magnitude of Intensity FFT

The plot shown below is the Fourier Transform of the Intensity cross section of OptiGrid. The Fourier Transmorm will have 1024 points. The spectrum starts at DC on the left and goes to maximum positive frequency at 512, then the negative portion of the spectrum starts at point 513 to point 1024 where it ends with low negative frequency. We can concentrate on the left half of the curve since the right half contains redundant information.

FFT Amplitude vs Bin Number
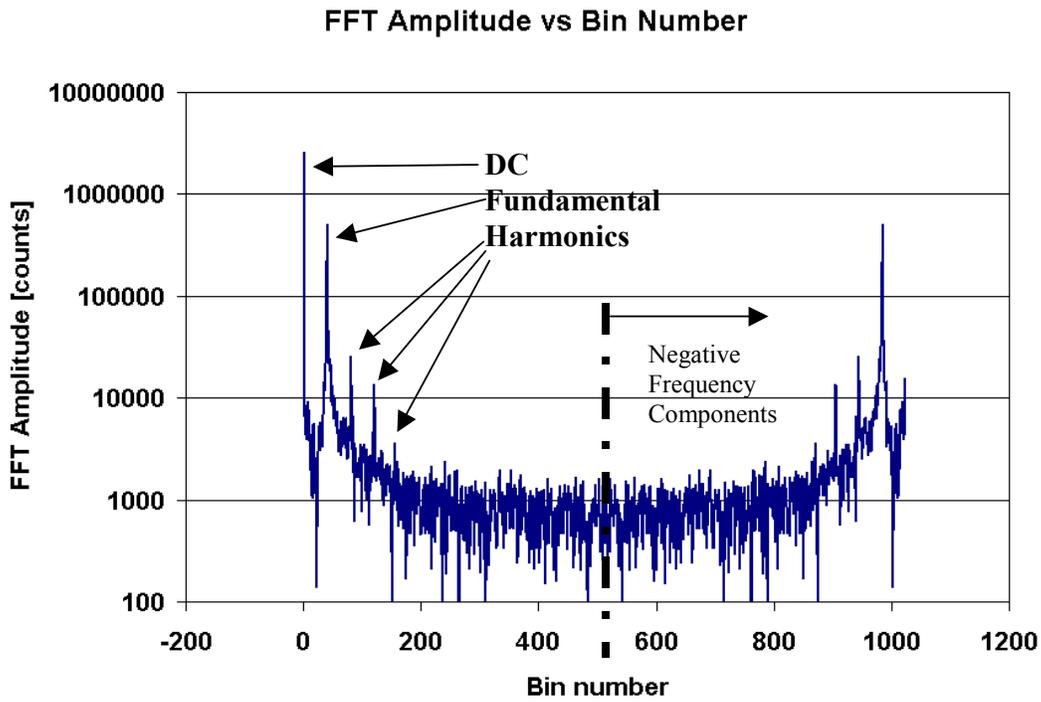
3.2.3.2.2 Phase of Intensity FFT

The phase over the entire range of frequency bins is shown below. This does not make a lot of sense except near a dominant frequency such as the fundamental bear bin 40. The next section will afford us a look near the fundamental frequency bin.

Phase vs bin number
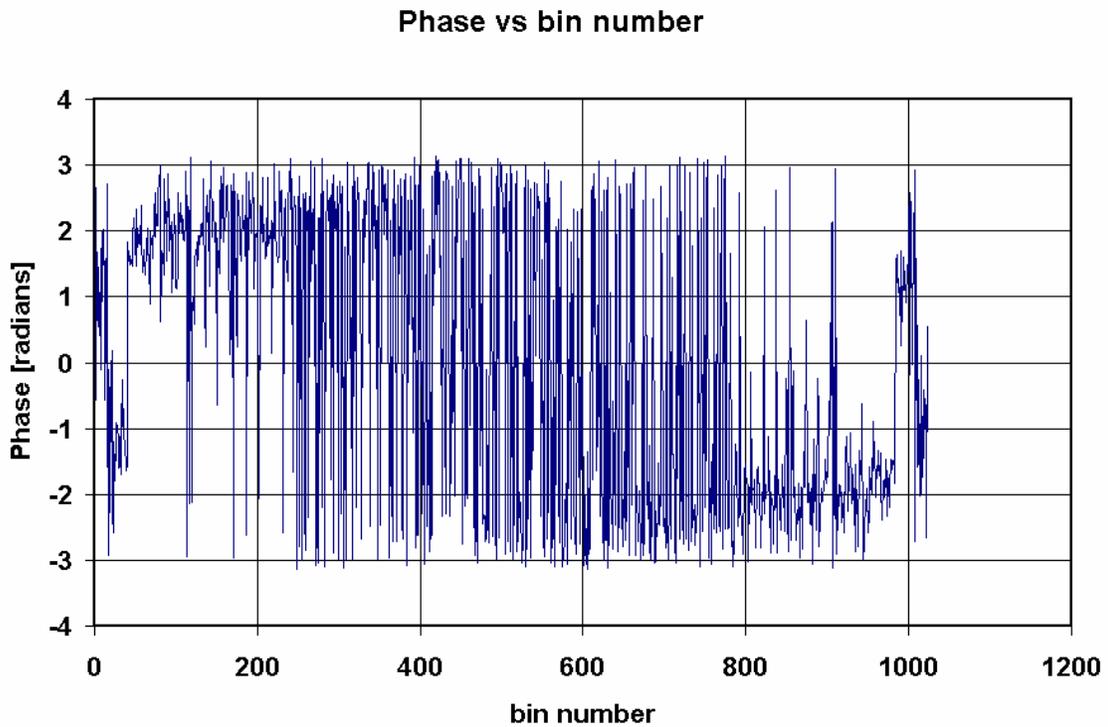
3.2.3.2.3 The Phase Near the Fundamental Frequency

This zoomed in plot of the phase shows that the phase undergoes a phase jump of PI at the fundamental frequency bin 41. The phase is a meaningful quantity only in the neighborhood of the fundamental frequency peak.


Phase vs bin number
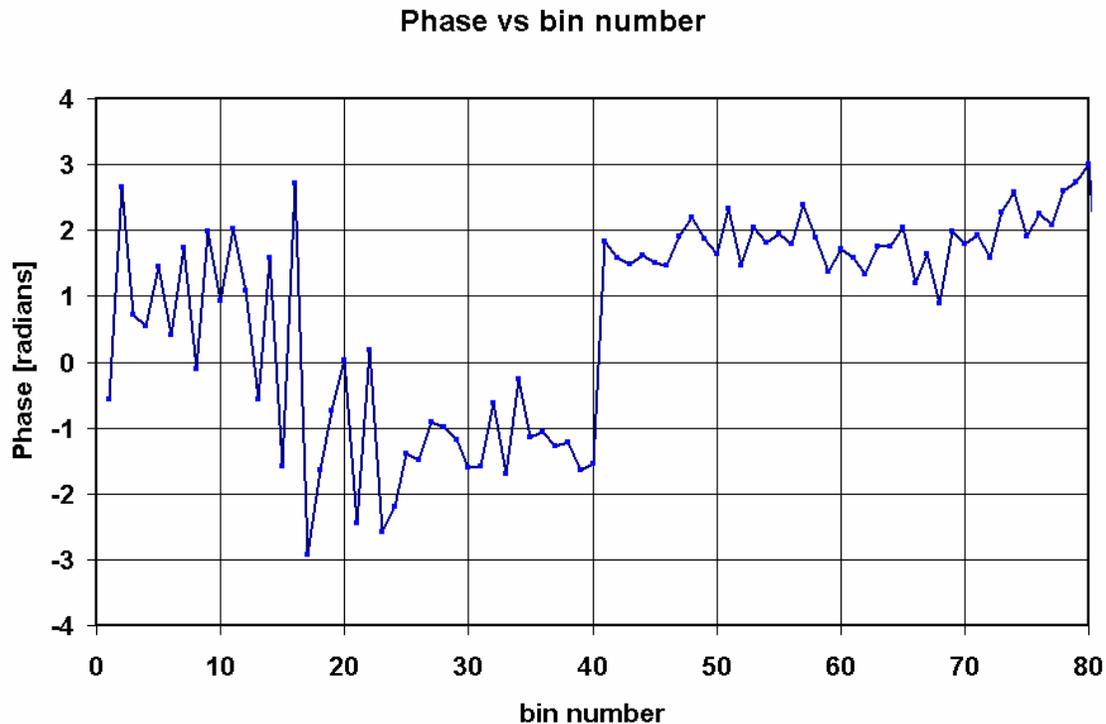
3.2.3.3   Behavior of the Fourier Coefficients with PZT voltage

In this section we show how both the amplitude and phase of the FFT behave with changing voltage (Phase) on the PZT. The magnitude should not and does not change as the voltage is varied. The phase show a correlated dependence on the PZT voltage. **The phase calibration technique is based on the change of the phase at the fundamental frequency with changing voltage.** This meaning of this statement will become obvious in this section.

3.2.3.3.1 FFT Magnitude vs. Voltage

The magnitude of the FFT coefficients is constant over changing PZT voltage (phase). This is expected, and this plot provides proof. The amplitude of the 5 Fourier magnitude coefficients (near the peak of the fundamental) are plotted vs PZT voltage. Notice that the value of the Fourier magnitude coefficients do not change as we ramp the PZT voltage. It is only the phase that changes as the next section reveals.

Fourier Amplitude vs Voltage
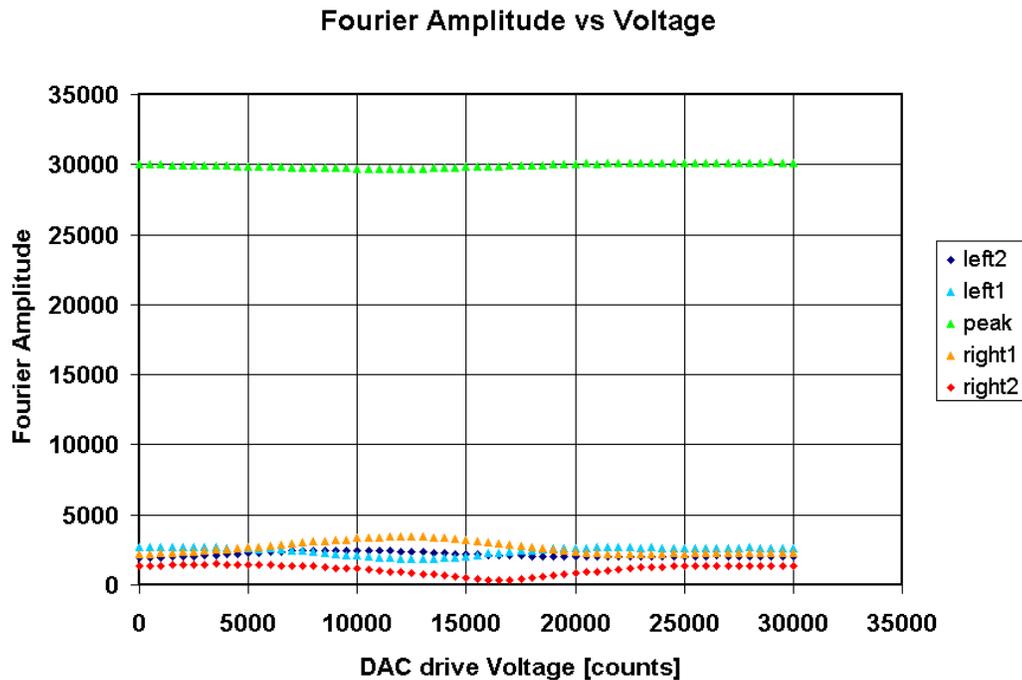
3.2.3.3.2 FFT Phase vs. Voltage

The phase of the Fourier coefficients which is the arctan(imaginary/real) is plotted in this section. The phase for the 5 Fourier components, near the fundamental frequency, are shown. There are a few important facts to learn from this plot:

1. There are regions of near-linear dependence of phase vs. voltage.
2. Points to the left of the peak differ by Pi from points on the right. (PI, or 180 degree phase shift)
3. There is a phase jump discontinuity of 2*PI so the phase is always bounded by +/- PI.
4. At high DA drive values the PZT stops moving because the high voltage Op-Amp has hit its maximum output voltage.
5. The phase at the peak is the highest fidelity signal.

Phase vs Voltage DAC Command
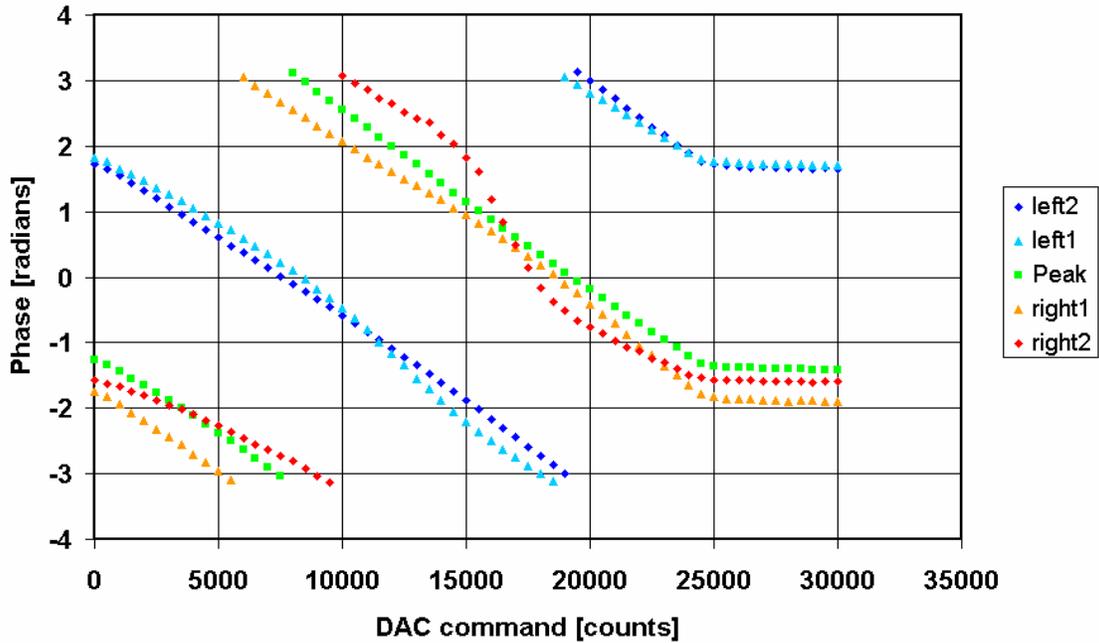
3.2.3.4 Processing the Phase Information

It seems that we only need to process the phase of the Fourier coefficient that corresponds to the peak value of the fundamental. The fundamental is located by the spatial frequency corresponding to the grid at the camera and the Fourier amplitude coefficient having the largest value is used to determine the bin number of the phase coefficient that will be plotted vs. voltage to get the calibration curve. We considered averaging various coefficients near the peak but then a complicated unwrapping routine would be needed. Furthermore, the other coefficients seem to reveal worse behavior vs. voltage.

3.2.3.4.1 The Raw Phase Data vs. Voltage

The plot below shows the phase calculated at the bin corresponding to the peak amplitude of the fundamental frequency. Notice the 2*PI phase-wrap at about 7000 counts. Also notice the zero slope near 25000 counts. Both these features need to be identified and removed from the data in order to accurately use the data for calibration. The next sections show how this will be done.

Phase vs Voltage DAC Command
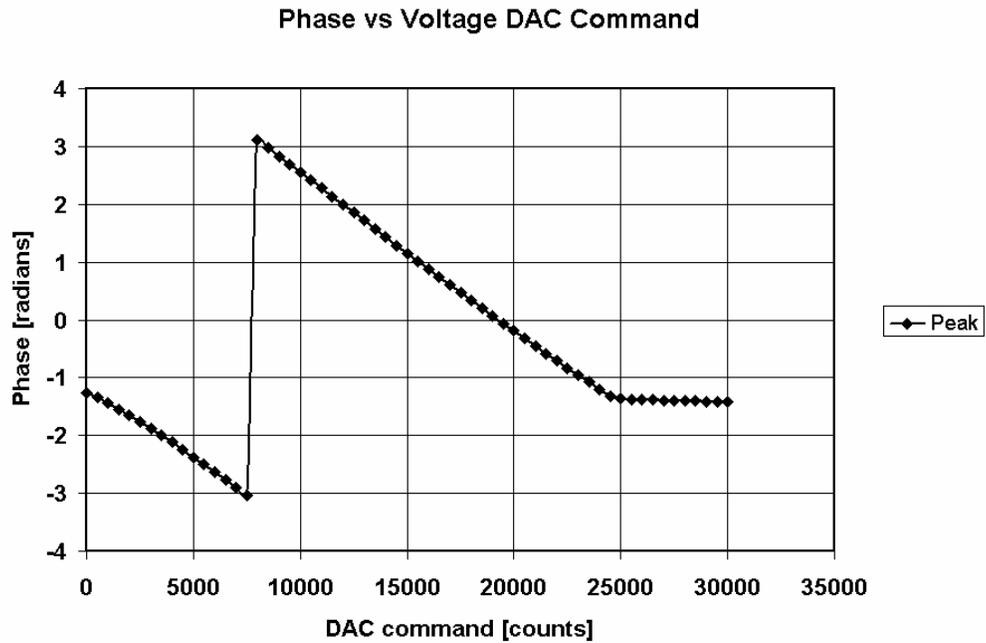
3.2.3.4.2 The Unwrapped Phase vs. Voltage Plot

The first step is to unwrap the 2*PI phase discontinuity. This is done by looking for a 2*PI phase jump and then removing it by adding or subtracting 2*PI to all subsequent data points. This is done in a software loop to produce the following unwrapped phase plot. Next we need to eliminate the region at **the large drive voltage end where the amplifier has been saturated** and no further voltage increase accompanies increasing drive counts.


Unwrapped Phase vs Voltage
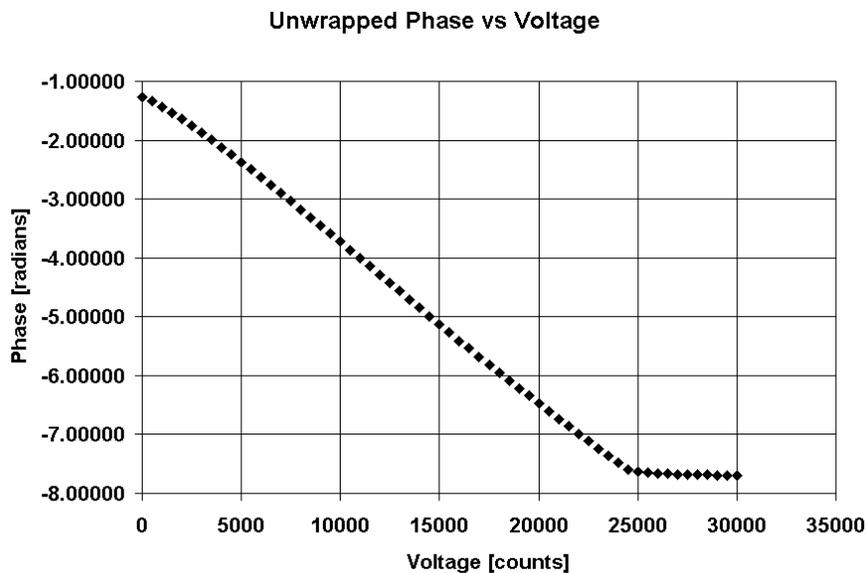
3.2.3.4.3 Using the Derivative to Eliminate Low Response Regions

To eliminate the undesirable low or zero response regions of the Phase vs. Voltage response function we take **the nearest-neighbor derivative** of the data. The plot below shows this for the data file in the last couple sections. The derivative varies slowly between 1000 and 24000 counts drive voltage. We can smooth this data find the maximum and eliminate points corresponding to derivative values that are less than say one half of the maximum slope of 0.016 on this graph. This will eliminate the first data point as well as the last several.
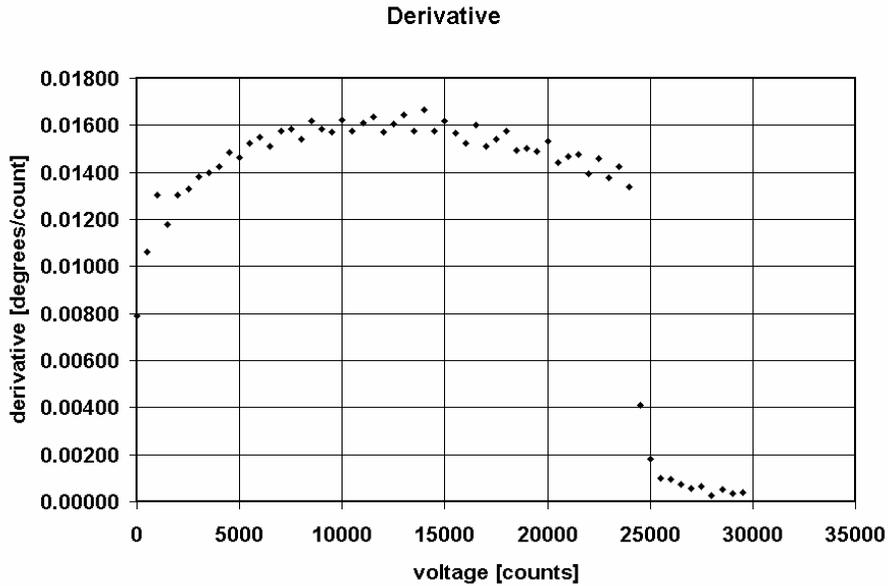
### 3.2.3.4.4 Final Processed Phase Response Function

After eliminating the low response points the remaining data is plotted below. This is the data that will be used by the phase calibration routine to determine the three voltage values for the three OptiGrid phases. To understand the nature of the curve the data is fit to a linear and cubic function and the coefficients of each are shown on the plot.
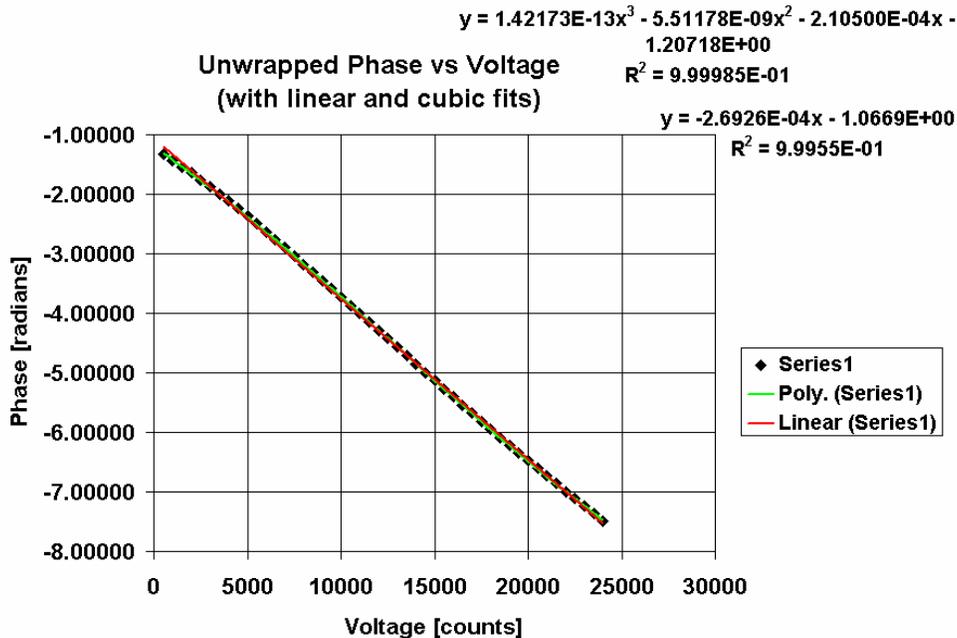
3.2.3.4.5 Deviations From Global Linear and Cubic Fits

The data from the previous section was fit to linear and cubic equations. This section shows the deviation of the global fit equations from the data. The linear fit shows deviations that are as high as 0.05 radians or about 3 degrees. This level of deviation is unacceptable since the tolerance is about 0.5 degrees for the calibration. The cubic fit shows deviations of about 0.01 radian or about 0.6 degrees. This level of fit is marginally acceptable. **The conclusion here is that if a global polynomial fit is to be used to establish the proper voltages, then the order of polynomial will have to be cubic or higher to obtain good results.**

Difference From Best Linear and Cubic Fits
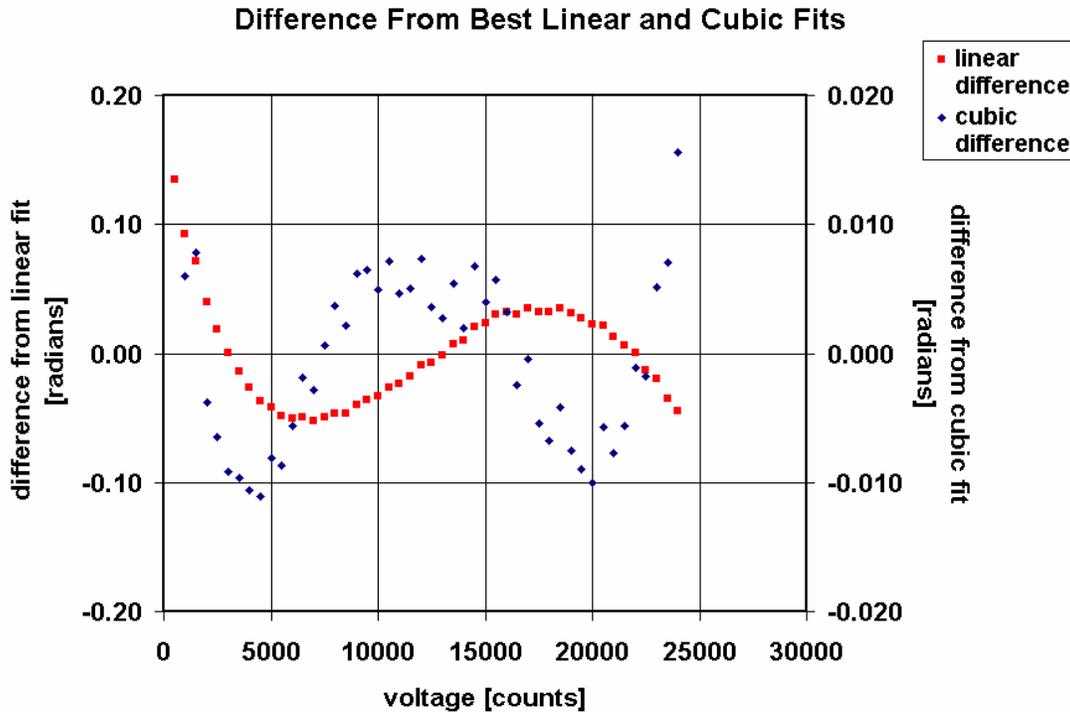
3.2.3.5 Phase vs. Voltage Calibration Procedure

1. Setup
   a. Put an optical flat in the field of view.
   b. Adjust focus and light level properly
   c. Activate calibration
2. Take 10 intensity cross section perpendicular to the lines in the image
   a. Use FFT to determine orientation of the lines
3. Average the intensity cross sections to obtain a single intensity cross section data set
4. Take FFT to obtain amplitude and phase information'
5. Find the fundamental
   a. Away from DC
   b. In neighborhood of expected grid
6. Find the noise floor
   a. Noise floor determined at 4f to infinity frequency average
7. Compute fundamental/noisefloor ratio > threshold

Take Phase data
8. Collect phase data at regularly spaced voltages

9. Phase is calculated using the phase point at the same frequency bin as the fundamental peak. This should not change over entire voltage range.

Unwrap Phase Data
10. Look at nearest neighbor changes (Derivative)
11. If change is >PI then add or subtract 2*PI and check for change < PI

Calculate Derivative vs. voltage to establish valid points
12. Take nearest neighbor differences
13. Find maximum amplitude derivative.
14. Eliminate points whose nearest neighbor derivative < 0.5 of maximum

Establish Phase 1,2,3 voltages
15. Phase 3 Voltage is largest voltage of filtered data set.
16. Find nearest data point to calculated Phase 1,2 values that differ from phase 3 by 120 and 240 degrees.
17. Perform linear regression in neighborhood of phase 1 and Phase 2 voltages with +/- 2 neighbors to interpolate exact voltages. Currently this is done by interpolation after a nearest neighbor low-pass filtering of the data.

Test Solution
18. Set voltages for OptiGrid for solution voltages and acquire OptiGrid data
19. Evaluate Merit Function.
20. Accept if Merit Function < threshold value. This should be <0.01. Typically we can achieve < 0.005.

Parameters (default or set by user in advanced diagnostic mode)
Minimum modulation = fundamental/noise floor
Voltage Step size (1000 counts over 27000 would take 27 seconds
Merit function threshold – ratio of second harmonic of OptiGrid to fundamental of intensity
Valid voltage settings (min and maximum for Phase settings)

Controls
Same as parameters?
Activation switch.
Diagnostic mode activation button

Error Messages
1. Saturation
2. Modulation too low
3. Voltage out of bound – PZT problem.
4. Merit function too high