Application Report

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Texas Instruments DLP® Spectrometer Design Considerations

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ABSTRACT

DLP® technology enables new functionality, performance, and tradeoffs in spectrometer design. For an overview of spectroscopy and how DLP compares to existing technologies, please see the DLP Technology for Spectroscopy white paper. In order to take advantage of the many benefits of DLP technology in your spectrometer design, several key factors and algorithms must be considered.

This application report describes the operational theory of a DLP spectrometer, discusses key component and system tradeoffs, and describes algorithms which are integral to obtaining accurate spectral output.

Topic **Page**

1 Theory of Operation

The goal of a DLP based spectrometer is to measure the spectrum of light incident on an input port. In order to accomplish this, the light from an input slit is dispersed to separate the wavelengths and is then reimaged on the digital micromiror device (DMD). The processing steps necessary to measure the spectrum distributed across the DMD are depicted in Figure 1.

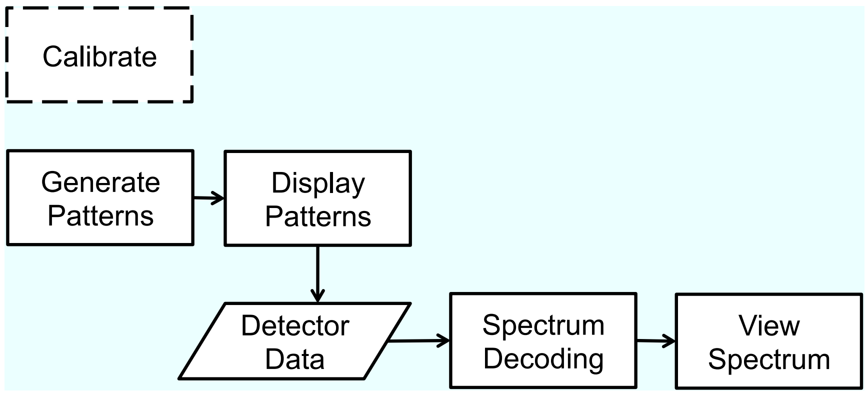

Figure 1. Data Flow

1. Pattern Generation

   Patterns are generated based upon the desired spectral filter to apply to the light at the input aperture of the system. These are typically based on several parameters: desired spectral response, outputs from calibration which relate wavelength to DMD position on the dispersion axis, and outputs from calibration which describe any optical distortion of the system.
2. Pattern Display and Detector Sampling

   Patterns are loaded onto the DLP controller and displayed on the DMD sequentially. Concurrently, values from an ADC are read into memory in such a way to keep track of which patterns were displayed during each ADC sample.
3. Signal Averaging

   ADC values occurring at each pattern are windowed to reject samples during transition events. The length and properties of this window depend upon the detector, analog front end, and ADC. The valid samples are then averaged to yield a single value for each displayed DMD pattern.
4. Spectrum Decoding

   Averaged detector values are then processed to yield a spectrum. The type and complexity of this processing is different depending on the encoding scheme (scanning column of mirrors, Hadamard patterns, or other multiplexed scanning method). The ratio of two scans is taken for transmission or absorbance spectroscopy, while a radiometric calibration would be applied if a calibrated spectrum in radiance is desired.

2 System Considerations

A few key metrics are necessary to set forth in order to properly evaluate design options: resolution, stray light, and signal to noise ratio (SNR). A typical application will drive these requirements as well as the spectral band of interest. Choosing the correct components and methods of operation is critical to meeting the system requirements and performance targets.

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2.1 Resolution

Resolution is defined as the spectral width measured by the instrument of an impulse spectrum, that is a signal with zero width. It is typically specified in full-width half-max (FWHM), defined as the width of the spectral peak when its height is 50% of the peak value. It is commonly quoted in units of nanometers or wave numbers. This definition is convenient, as it also describes the minimum distance required between two zero width input wavelengths of the same amplitude before an instrument can detect two distinct peaks instead of one broad peak.

Light received at the detector when only a single column width of pixels is turned on is a convolution of the input slit width, the optical transfer function in the dispersion axis, and the DMD pixel pitch in the dispersion axis. When designing the system, it is useful to convert these three quantities into the same domain for analysis. For an example optical design, the nominal parameters are shown in Table 1.

Table 1. Example Optical System Parameters

Parameter	Value
Magnification from slit to DMD	1.6
Dispersion at the DMD	0.122 nm/µm
Pixel pitch	7.6 µm, diagonal configuration

To analyze the expected resolution, we can build functions for each of these three components and use the dispersion from our optical design to put them in the same domain as shown in Table 2.

Table 2. Resolution Determining Factors

Parameter	µm	nm	Shape
Slit width	50	6.09	Rectangular
Optical transfer function		8	Gaussian
DMD pixel	7.6	1.315	Triangular

The convolution of these functions can then be used to estimate the FWHM of the system. This represents the highest resolution attainable when using single column widths of DMD mirrors. When designing a system, the optimal tradeoff of signal into the instrument and resolution is usually found when the entrance slit is matched to the exit slit. The typical tradeoffs for the three components which determine resolution are shown in Table 3.

Table 3. Resolution Trade-offs

Parameter	For Increased Resolution	Trade-off Incurred
Slit width	Minimize slit width	Decreased sensitivity and SNR
Optical transfer function	Use improved optical design, higher quality / higher tolerance optics and mechanics, or additional optical elements	Increased cost
DMD resolution	Choose a higher resolution DMD so there are more pixels per wavelength	Increased cost and optical engine size

Because of the small pixel size of the DMD, the DMD is usually not a large factor in the determination of resolution.

2.2 Stray Light

Stray light is a term used in spectroscopy to describe errant signals caused by misclassifying a signal's wavelength. For instance, in an array based spectrometer, if 1% of wavelength λ_1 images onto the detector pixel associated with λ_4, this light would be misclassified. This leads to inaccurate spectrum output: wavelengths with low energy are measured higher than reality. In absorbance spectroscopy, this limits the linearity of absorbance units (AU) you can reliably measure. Some handheld systems are only linear up to 1.5 or 2 AU, while some high end stationary double monochromator systems can measure up to 6+ AU.

In general, DLP systems can be less sensitive to stray light than array detector based systems. In order for stray light to strike the detector, rays must traverse through not only the optical path from the slit to the imaging plane, but they also must enter the collection optics between the DMD and single point detector at an angle such that it strikes the detector surface.

Still, the replacing of an array detector or output slit with a DMD and single point detector introduces new light paths that must be analyzed. The opto-mechanical design should be modeled by FRED, ASAP, or other stray light analysis software to minimize the paths listed. The categories of stray light described below incorporate the following naming conventions:

Static— Unchanged over time, or unaffected by DMD state

Dynamic— Changes over time, or affected by DMD state

Imaging— Incorrect imaging at the DMD (wavelength in the wrong location on DMD)

Detector— Energy incident on detector from a path other than striking an on state DMD mirror

2.2.1 Static Imaging

Incorrect imaging at the DMD which is unaffected by DMD state (wavelength in the wrong location at the DMD)

This is the classic stray light phenomenon also present in array based and monochromator systems. There are three primary causes of this: ghost images from optics, glancing angles from mechanics, and window reflections.

Ghost images from optics occur from reflections off optical surfaces (lens flats, filter), and are reimaged onto the DMD. This occurs most often when unused orders of the grating reflect back toward the illumination where they encounter an optical flat causing a ghost image displaced by some small angle.

Glancing angles from mechanics can also illuminate the DMD in the wrong location for a given wavelength. This is common in lens mounts with deep inserts, and chassis side walls parallel to the optical path.

Window reflections can also affect this. Using the DMD in the appropriate designed wavelength region will minimize these effects, as different window coatings are optimized to transmit specific wavelength regions.

2.2.2 Dynamic Imaging

Light which is imaged onto the DMD correctly, but then reflected back onto different on-state DMD pixels and then reflected to the detector. Dependent on the DMD state

Illumination which strikes the imaging plane at the correct location but later will strike a different array detector pixel or a different DMD pixel can also cause an incorrect measurement. The DMD adds an additional constraint: the illumination must strike a DMD mirror at the right angle such that DMD mirror's output angle allows illumination to enter the collection optics and be imaged onto the detector.

In order for this to happen in a DMD system, it requires an extra reflection off the window as compared to an array detector system, and two extra reflections off the DMD mirrors. For a 1% reflective window, the magnitude of this error would be at least two orders of magnitude lower with a DMD system as compared to an array detector system with a similar window. The probability of this occurring is also reduced because the state of the mirrors the illumination strikes must be in a particular relative configuration, otherwise the output rays will not enter the collection optics and get to the detector.

2.2.3 Static Detector

Energy incident on detector from a path other than striking an on state DMD mirror which is unaffected by the DMD state

In a DLP spectrometer, it is possible for light which never strikes the DMD to still get to the single point detector. In this case, the magnitude of this signal contribution at the detector is the same value for any DMD pattern displayed. Therefore, this contribution can be removed in processing.

2.2.4 Dynamic Detector

Energy incident on detector from a path other than striking an on state DMD mirror which is affected by the DMD state

Light can also be imaged onto the DMD in the correct location, strike an off-state pixel of the DMD, and still find its way to the single point detector. This is due to either scatter from the pixel structure itself, or mechanics which allow a reflection into the collection optics.

The magnitude of light which follows this path is a function of the amount of light striking the DMD off-state pixels. Because different encoding patterns have different combinations of pixels off, the method to properly account for this stray light path varies depending on the pattern being shown. Still, careful characterization of the system and processing of the data can mitigate this path.

2.3 SNR

The SNR of a system is dependent on the systems design and use. Design factors can be optimized for cost and expected use case; while use factors determine what the SNR will be for a particular datapoint of a scan.

2.3.1 Design Factors

The following factors should be optimized to maximize system SNR. The intended use model, form factor, and cost will be limiting constraints.

- Maximize illumination optical power through slit

  This is a function of the optical efficiency of the sampling instrument, the intensity of the source, and the size of the slit. Special attention should be paid when coupling systems together via fibers, in order to match the étendue to minimize the losses before the light enters the system.

- Minimize noise from Illumination instability

  In systems that include illumination sources, illumination stability is very important. Since DLP spectrometers collect spectral data based on sequential patterns, variation in the source power or spectrum could affect the accuracy of the output spectrum. For applications where source variation or sample consistency cannot be controlled, displaying patterns as fast as possible may be useful in addition to averaging multiple scans rather than displaying patterns slowly.

- Maximize slit to detector optical efficiency

  This is the core of the optical design. The tradeoff with optical efficiency is usually spectral resolution, as the optical transfer function typically suffers when using a lower f-number.

- Minimize detector and analog front end noise

  A low noise detector should be used and paired with a low noise amplifier. The gain should be set to maximize the available dynamic range, and the bandwidth of the amplifier should be met or exceeded by the ADC sampling rate so that higher frequency noise can be averaged out.

2.3.2 Use Factors

Once the system is designed and built, the type of scan and properties of the point in the spectrum being inspected will determine the SNR of that data point. It is important to understand these factors so that the flexibility of the DLP solution can be used to optimize these tradeoffs for the particular scan or situation.

- Wavelength

  The system has a wavelength sensitivity, which is a combination of how the following change as a function of wavelength: the detector's D*, the expected illumination source power, and the system optical efficiency.

- Pattern encoding used

  Different pattern encoding types can be more appropriate for certain types of scans. For very low signal scans looking at emission peaks, using the DMD to display multiplexed patterns, for instance, can increase the SNR dramatically.

- Spectral resolution

  The required spectral resolution will drive the width of the exit slit image displayed on the DMD. In practice, there may be little advantage to reducing the width of the exit slit image displayed on the DMD, so this is usually matched to the input slit.

- Scan time

  Increasing scan time or the number of scans to average will allow random noise to be averaged out and mitigated.

3 Hardware Considerations

Having introduced the key system metrics and tradeoffs, we will now inspect the system and components in more detail.

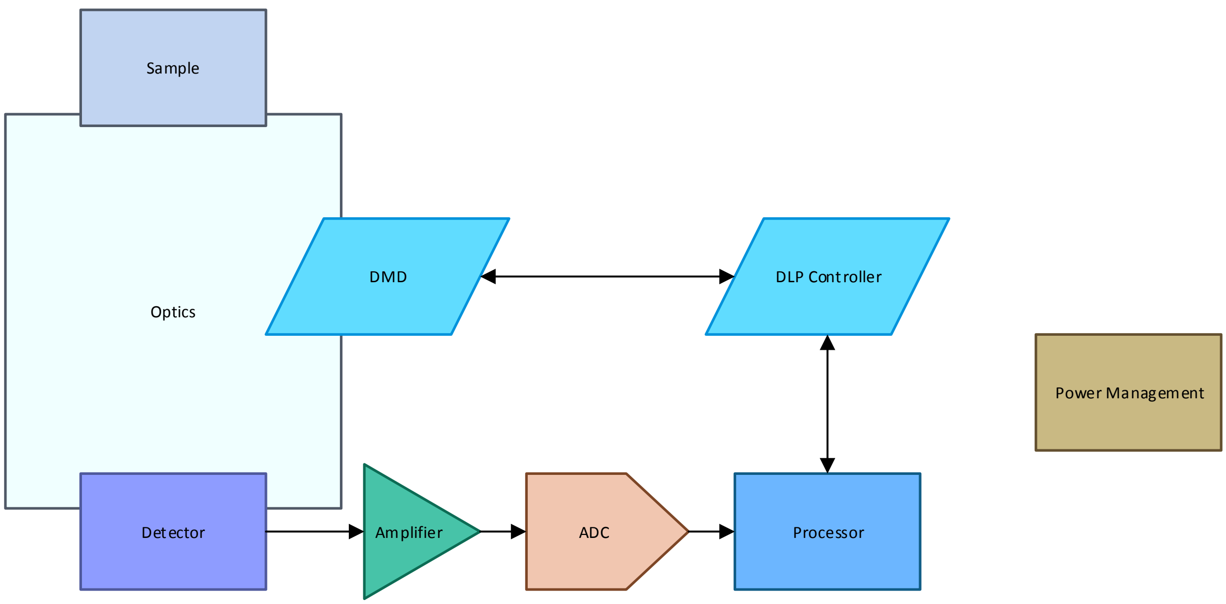


Figure 2. Basic Block Diagram

3.1 DLP Chipset

DLP Advanced light control controllers include time accurate triggers, which allow synchronization between a particular DMD pattern and other system events. In a DLP spectrometer, these triggers can be used by the system to maintain a relationship between particular ADC samples of a detector signal and the patterns displayed on the DMD. That relationship is required for this application.

Considerations for choosing a DMD include:

- Spectral bandwidth

  Each DMD is optimized for specific wavelengths. For details, see Wavelength Transmittance Considerations for DLP® DMD Window . This should be the determining factor in DMD selection. Choosing a DMD designed for the wavelengths of light to be used in the system reduces potential stray light issues and increases the optical efficiency of the system, allowing more optical power to reach the detector.

- Pixel size

  As the wavelength of light approaches the pixel size, diffraction efficiencies play an increasingly large role in the overall optical efficiency.

- DMD array size

The increased etendue of larger DMDs allows more light to enter the system, which allows more light to get to the detector. Because of this, systems based on larger DMDs will have higher SNR than a comparable system built with a smaller DMD. Using a larger DMD also increases the size of the optical module.

- Illumination direction

  DMDs which are meant to be illuminated from the side keep the optical path in plane with the DMD, therefore reducing the overall size of the optical module.

- Pattern rate

  The maximum binary pattern rate of the chosen chipset and the number of patterns required for a given pattern sequence will determine the minimum scan time. In applications where the sample or the instrument may be in motion during scanning (for instance, in a factory automated or hand-held system), it may be beneficial to operate at a high pattern rate even if fast output is not required. This allows the system to perform multiple scans and average away any inconsistencies due to sample motion.

3.2 Opto-mechanics

The optics design is crucial to maintaining high resolution by minimizing stray light and optimizing the optical transfer function to provide sharp focus of the slit onto the DMD. In a DMD based dispersive spectrometer, we can use the programmability of the DMD to calibrate any distortion of the slit image. This is fortunate, since the grating in a dispersive system tends to curve the image of the slit at the DMD.

The curvature of the slit images is caused by the oblique (out of plane) incident illumination on the grating. Therefore, point sources from locations in the slit further from the center of the slit tend to be curved more. Additionally, optics or mechanics tolerances can rotate the slit's image in relation to the DMD pixel array orientation. The most common way this occurs is by physically rotating the slit, grating, or DMD. Fortunately, the DMD gives off a programmable modulator which is an option for correcting these, and any other distortions as long as the focus remains sharp.

3.2.1 Design For Minimum Alignment

Several factors can translate or displace the image of the slit on the DMD from the images nominal position:

- Slit position

  Slit translation or rotation in plane will directly influence the position of the intended wavelength passband on the DMD, and the rotation of the slit image.

- Grating angle

  The grating angle and rotation will also shift or rotate the image of the slit on the DMD. This component is particularly sensitive, and manufacturing tolerances in this location are typically the most stringent.

- DMD position

  If the DMD mirrors are shifted or rotated with respect to the nominal design due to package and chassis mechanical tolerances, the image of the slit relative to the DMD pixels will devate from the model.

Typically, the slit image on the DMD is underfilled in the dispersion axis and overfilled in the orthogonal axis as shown in Figure 3. This allows the proceeding factors to be calibrated out electronically, greatly reducing production time. The degree of underfill chosen should be matched to a tolerance analysis which shows the expected location of the image of the slit. In most cases, the resolution of the DMD far exceeds the required measurement resolution. If your application requires a spectrum of fewer points than 80% of the number of columns of the chosen DMD, nominally undersizing the image of the slit on the DMD allows for electronic calibration with no adjustments to position the DMD or grating.

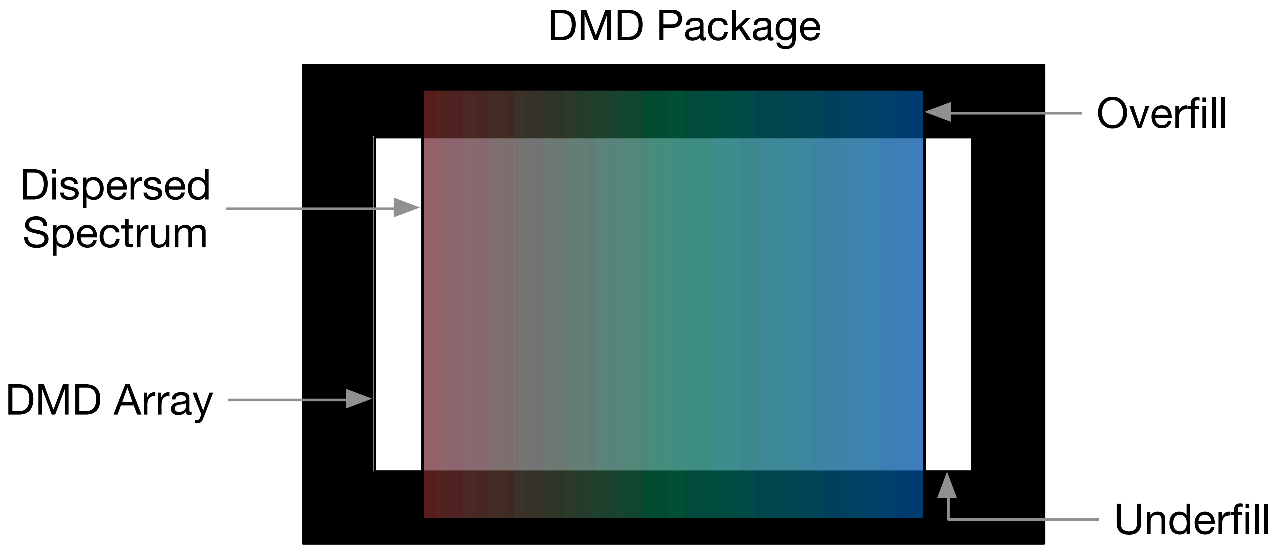


Figure 3. Typical DMD Underfill / Overfill Pattern

The following two items may need to be actively aligned. Whether or not to align these depends on the cost and performance targets of the system:

- Slit focus

  In some optical designs, adjustment may be necessary to focus the slit on the DMD, while in others, this can be fixed depending on optics and mechanics tolerances.

- Detector position

  Since detector noise and cost is proportional to size, it is usually beneficial to use as small as a detector as possible, and then actively align the detector for each system. If detector cost is not a large cost factor in the system, the detector could be oversized in order to reduce the amount of active alignments necessary.

3.2.2 Light Blocks

Mechanics should be designed with features to serve as light traps in critical areas including:

- Reflected light from any band-blocking filter

  If a bandpass filter is included in the system, rejected light may be significant.

- Unused grating orders

  Reflections from the grating which are in orders not intended to be imaged onto the DMD.

- DMD off-state light

  Light which strikes DMD off pixels is scattered somewhat, but the majority of this energy is directed in a particular direction.

Various mechanical features can be designed which require these rays to undergo multiple reflections before they can get back to the detector. In order for these light blocks to be most effective, coat the chassis with a wavelength absorbing coating; this coating is expected to enter the instrument. Care should be taken to select appropriate coatings in the near infrared region, as certain coatings like standard black anodization are nearly 70% reflective in the NIR. Analysis with stray light software tools like FRED or ASAP can provide insights into how to optimize these mechanical features.

3.3 Detector and Analog Front End

Noise from the detector and analog front end directly translates to noise in the spectrum. Good mixed-signal design strategies should be employed in order to minimize any noise coupled into the detector signal before it is converted.

3.3.1 Detector

Noise at the current output of the detector is a function of the optical power at the detector, the detector's specific detectivity (D*), and the area of the detector. This includes Johnson noise, shot noise, and dark current. It is important to note that both the power at the detector and the detectivity of the detector are a strong function of wavelength.

Because noise increases with increased detector area, it is beneficial to focus light from the DMD intended for the detector into as small a spot as possible. As the DMD active area increases and the f number of the system decreases, a larger detector may be required.

Detector noise can be reduced by cooling the detector with a TEC. Typically, less power is required to cool a single point detector than an array detector to a given temperature, because there is less mass which needs to be cooled.

3.3.2 Amplifier and ADC

Amplifier noise is usually modeled into an output noise spectral density plot, from which a total integrated RMS noise value can be computed. Amplification is typically provided by an transimpedance amplifier (TIA) in either photoconductive or photovoltaic mode.

In most applications, a photovoltaic mode TIA will provide the lowest noise analog front end. If there is need to sample very fast (faster than the 100 KHz), a photoconductive approach may be necessary.

Designed bandwidth should be high enough to allow the signal to fully settle within about a third of the pattern exposure period. If bandwidth is lower than this, the signal read from the ADC for each pattern will be influenced by the previous pattern, producing an inaccurate spectrum. If the bandwidth is much higher, the ADC may have to be faster and more expensive in order to average out additional noise which is not filtered before the input to the ADC.

3.4 Lamp and Lamp Driver

3.4.1 Coupling Efficiency

Typical slits in DLP spectrometers are taller than array detector spectrometers because the DMD is taller than most array detectors. Because of this, the coupling of light into the input slit should be designed to fill the taller slit. Given this, here are some considerations to follow with a few common illumination methods:

- Transmittance

  When using a transmittance attachment which might hold a cuvette or solid transmissive sample in a collimated space, the lamp should be sufficiently large to fill the height of the slit, but focussed onto the slit to maximize throughput into the spectrometer.

- Diffuse reflectance

  Diffuse reflective attachments should be designed to concentrate illumination onto the sample at a high intensity. The diffuse reflected light should then be focussed onto the slit, while the specular reflection should not be directed toward the slit. The illumination spot on the sample should be sufficiently large so that when focussed on the slit, the entire slit is filled.

- Fiber coupling

  If the system is designed for fiber-coupled input, major improvements may be realized by shaping a fiber bundle to approximate the slit shape. On standard array based systems, the useable slit height is no taller than a standard 600 µm fiber. In DMD based systems, this height could be several millimeters, depending on the DMD and magnification used. Therefore, shaping a fiber bundle from a standard circular fiber bundle into a shape mimicking the slit can allow a much greater percentage of the illumination to enter the instrument.

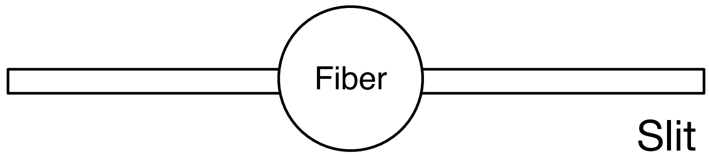


Figure 4. Slit Fill Factor with Standard Fiber

3.4.2 Stability

For units designed with an integral light source, source stability is also very important. Any noise at the source will show up as noise at the detector. Since the likelihood of this noise being fairly slow is probable, any variance in this signal could manifest errors in output spectrum. Possible drive methodologies include:

- Constant voltage

  This method is usually the least expensive, but suffers from one main drawback: any change in contact resistance or resistance of the wires leading to the lamp will change the drive current. As a result, the brightness of the lamp is no longer constant in these conditions.
- Constant Current

  This is usually the preferred method due to simplicity. Implementations can vary from simple constant current supplies to more complex sources with current monitoring through a sense resistor.
- Optical Feedback

  For particularly demanding applications, the source can be actively monitored and fed back into the drive strength. The optical feedback method introduces an additional source of noise, however, any environmental or electronic noise in the optical feedback signal will induce noise in the source brightness.

3.4.3 Protection

Another reason to prefer current sources when driving filament lamps is that the resistance of the filament changes dramatically as the lamp heats up. The cold filament resistance can be as little as 10% of the hot filament resistance, which can allow an inrush current of 10 times or greater when operating from a constant voltage supply. For this reason, a soft-start or maximum current clamping function in the lamp driver is advisable.

3.5 Processor

3.5.1 Processor Selection

The following features are always required:

- Command the DLP controller (USB, I^2C, or other, depending on the DLP controller)

  The processor will have to send commands to the DLP controller. Most DLP controllers support I^2C and USB, see respective datasheets for details.
- GPIO for triggers on DLP controller

  Triggers to and from the DLP controller are used to maintain real-time control and knowledge of the pattern display state on the DMD. For this reason, using a real-time operating system or having dedicated hardware subsystems on the processor to handle trigger status is required.
- Collect ADC samples

  A protocol compatible with the chosen ADC (usually SPI) must be supported at the required speed. Additionally, the processor must be able to collect these samples concurrently with monitoring triggers from and/or sending triggers to the DLP controller.
- Communication / Interface to user

  Specific end product requirements will drive additional interfaces and processing needs for communication to a host machine or an included user interface

Two main factors determine the additional features needed from the processor for a particular DLP spectrometer implementation. Once these are decided, the necessary features for the processor are shown in Table 4.

- Pattern source

  Patterns may be streamed from the processor to the DLP controller over a parallel RGB bus or stored in flash directly connected to the DLP controller.

- Pattern generation

  Patterns may be generated internally by the processor, or externally by a different system.

Table 4. Processor: Additional Requirements Matrix

	Flash	Streamed
Externally Generated Patterns		• 24 bit parallel RGB port with sufficient pixel clock
Internally Generated Patterns	• Additional memory and speed to compute patterns	• Additional memory and speed to compute patterns • 24 bit parallel RGB port with sufficient pixel clock

3.5.2 Pattern Source

Another key factor to determine is the method of getting patterns into the DLP controller. The DLPC350 controller which controls the DLP4500NIR DMD has two methods of pattern input: streaming from a display controller of an embedded processor to the parallel RGB input port of the DLPC350, and storing the patterns in flash memory which the DLPC350 accesses directly. Other DMD chipsets have similar options for loading pattern data into the controller. Selection of the pattern input method as well as the number of scan patterns determines the fastest possible scan time. Table 5 shows how this comparison is computed for the DLPC350. For other DLP chipsets and specific pattern rates, see the datasheet for those DLP controllers.

Table 5. Minimum Scan Times for DLPC350

	Flash	Streamed
≤48 Patterns	1/4225 Hz x N Patterns (236 µs - 11.4 ms)	1/2880Hz × N Patterns (350 µs - 16.7 ms)
≥49 Patterns	(N Patterns / 24) × pattern load time *pattern load time typically between 80 ms and 300 ms* (160 ms+)	1/2880 Hz × N Patterns (17 ms+)

Streaming patterns to the DLP controller also enables faster updates and changes to the patterns as compared to storing them in Flash.

3.5.3 Pattern Generation

One consideration which impacts processor selection is whether patterns need to be computed by the embedded processor after the unit is deployed into the field. There are three different pattern generation use cases as shown in Table 6. The optimal use case will vary depending on the application.

Table 6. Pattern Generation Use Cases

Use Case	Potential Requirements
Fixed pattern	Minimal
Externally generated pattern	Faster communication protocol between embedded processor and external host to transfer patterns
Internally generated pattern	Faster embedded processor with sufficient RAM and storage to compute and store the patterns in a reasonable amount of time

4 Algorithms

4.1 Calibration

Accurate and stable calibration are key to providing wavelength accuracy and resolution over time in a spectrometer design. The high resolution and two dimensional nature of the DMD allow the following calibration techniques to reduce production time and manual adjustment steps without sacrificing wavelength accuracy or resolution.

These routines are designed to be used when the optical design under-fills the DMD in the dispersion dimension and overfills the DMD in the other spatial dimension (see Section 3.2.1). This procedure assumes that the main sources of optical or mechanically induced distortion can be constrained to a second order two dimensional polynomial. If the magnitude of higher order distortions is expected to be greater than one pixel due to a different optical configuration, adjustments to the procedures listed here may be required.

The figures in this procedure assume that the dispersion dimension of the DMD is in the width or long axis of the array. Likewise, the terminology used explains DMD columns as being primarily single wavelength. If the optical design uses the DMD in a 90 degree rotation, where the dispersion axis is on the short axis of the array, these calibration instructions will need to be read with row and column terminology interchanged.

4.1.1 Scan Procedure

Prior to calibration, there may be an unknown wavelength position, distortion, and rotation on the DMD as shown in Figure 5 (Distortion exaggerated).

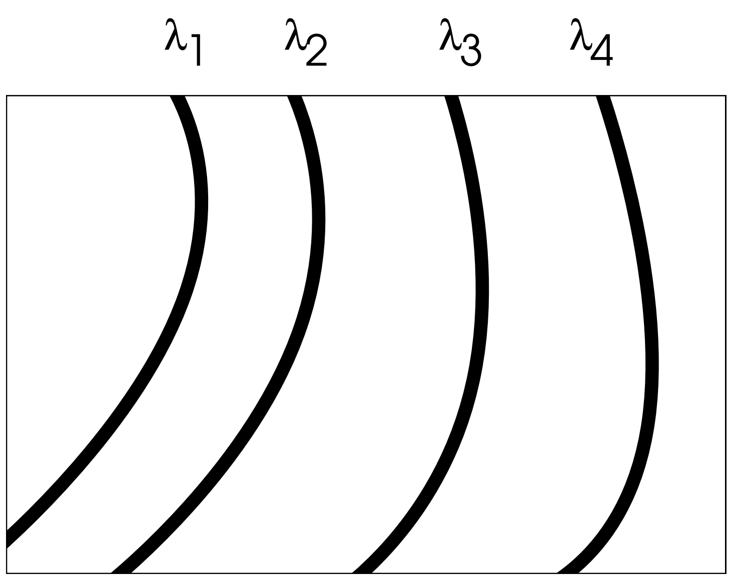


Figure 5. Unknown Wavelength Position, Distortion, and Rotation

For wavelength calibration, we illuminate the slit with a spectrum with known emission or absorption peaks. We can then take scans where only small rectangular regions of DMD mirrors are turned on. This block of mirrors is then scanned across the DMD in small increments as shown in Figure 7.

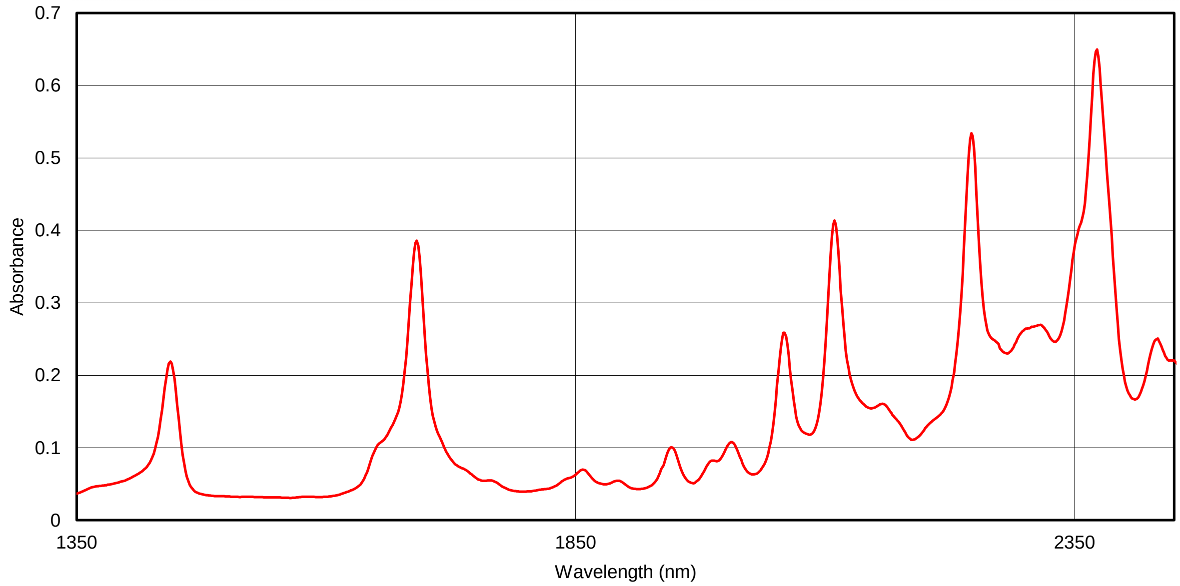


Figure 6. Example Spectral Standard

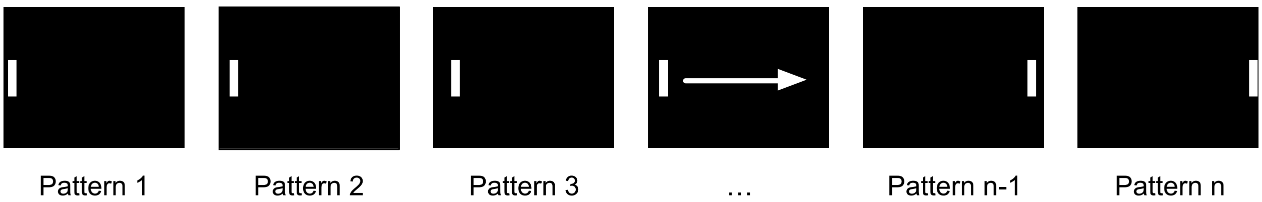


Figure 7. Calibration Scan

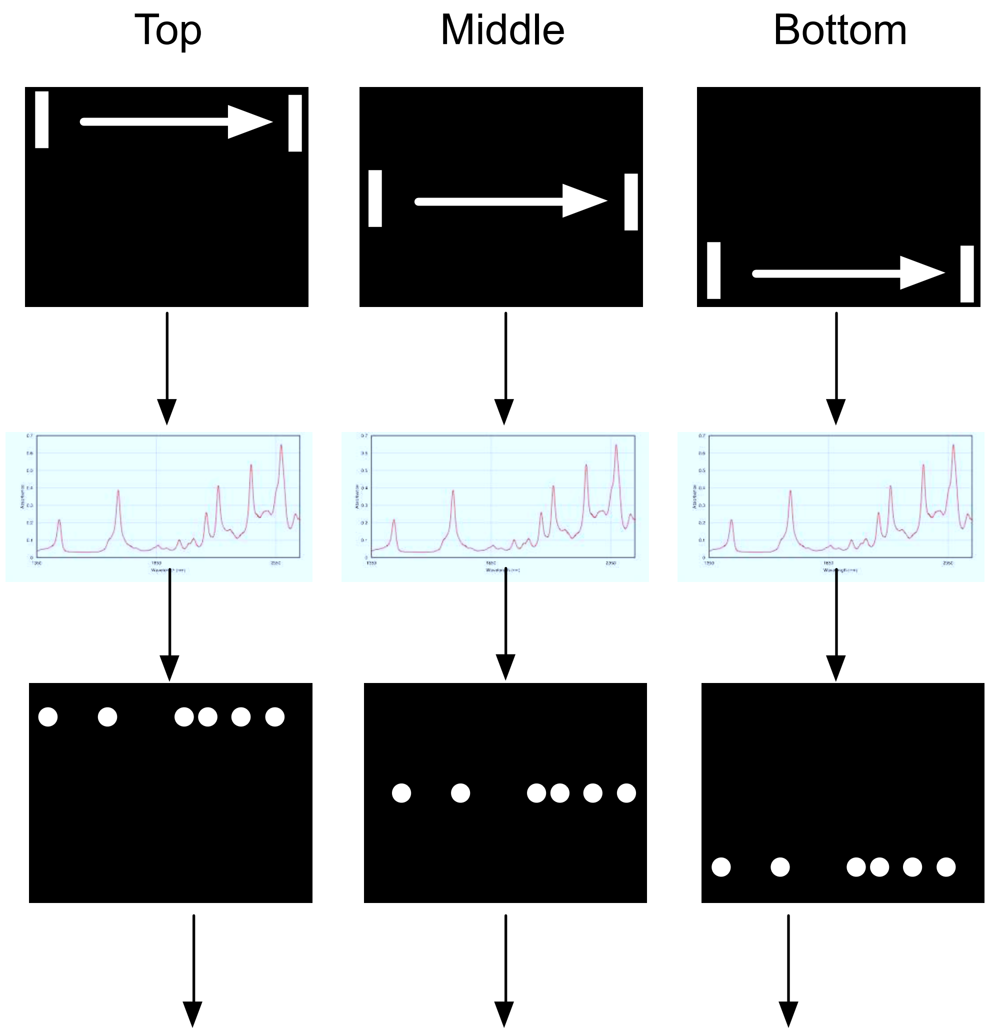
These rectangles of on-state pixels should have the following properties:

- Height

  This should be short enough such that the expected distortion is relatively minimal within this region. Typically, 1/5 to 1/9 of the non-dispersion dimension of the DMD is used.
- Width

  This should be narrow enough to get accurate peak locations from each of the calibration peaks, but wide enough to get enough signal to reduce noise. In practice, this rectangle of on-state pixels should be the same width or narrower than the image of the slit on the DMD.

Scanning this pattern across the DMD centered near the top, middle, and bottom rows of the DMD yields three spectrums. A peak finding algorithm should then be used to locate the DMD columns which correspond to the known wavelength peaks of the calibration source. Specifics of this peak finding algorithm are beyond the scope of this document since the spectrum different calibration sources may differ. The output should be a list of known wavelengths and corresponding known DMD column positions for the scan centered near the top, middle, and bottom of the DMD. This process is shown in Figure 8. This data will later be used to transform vertically consistent patterns which are uniform in column into wavelength consistent patterns which may be curved.



$$\begin{pmatrix} \lambda 1_{top} & x1_{top} \\ \lambda 2_{top} & x2_{top} \\ \vdots & \vdots \\ \lambda n_{top} & xn_{top} \end{pmatrix} \begin{pmatrix} \lambda 1_{mid} & x1_{mid} \\ \lambda 2_{mid} & x2_{mid} \\ \vdots & \vdots \\ \lambda n_{mid} & xn_{mid} \end{pmatrix} \begin{pmatrix} \lambda 1_{bot} & x1_{bot} \\ \lambda 2_{bot} & x2_{bot} \\ \vdots & \vdots \\ \lambda n_{bot} & xn_{bot} \end{pmatrix}$$

Figure 8. Top, Middle, and Bottom Calibration Scan Process

4.1.2 Wavelength Location

This procedure describes how to take known x locations of λ wavelengths on the DMD from the calibration scan across the middle of the DMD and yield 2nd order polynomial coefficients for wavelength calibration. These coefficients can then be used to find the DMD column at the middle row of the DMD relating to a particular wavelength, or find the wavelength of a particular column of the DMD along the middle row. This enables creation of patterns from wavelength inputs, as well as computing accurate wavelength centers for particular patterns.

We need to compute the coefficient vector β_X which will allow us to easily find the wavelength of a particular X location on the DMD:

$$\mathbf{X}\beta_X = \lambda \quad (1)$$

The format for the matrix $\mathbf{X}$ is:

$$\mathbf{X} = \begin{bmatrix} 1 & x_{1_{mid}} & x_{1_{mid}}^2 \\ 1 & x_{2_{mid}} & x_{1_{mid}}^2 \\ \vdots & \vdots & \vdots \\ 1 & x_{n_{mid}} & x_{n_{mid}}^2 \end{bmatrix} \quad (2)$$

To solve for β_X , we employ least squares by using the pseudo inverse in the following way:

$$\beta_X = \left(\mathbf{X}^T\mathbf{X}\right)^{-1}\mathbf{X}^T\lambda \quad (3)$$

From β_X , we can compute the wavelength of a known column as such:

$$\lambda = \begin{bmatrix} 1 & x & x^2 \end{bmatrix}\beta_X \quad (4)$$

A similar transform can be built for transforming from wavelength to column.

4.1.3 Image Distortion

To correct for image distortion, the calibration data can be used to transform images into the measured distortion.

This can be done by computing a polynomial with 2 dimensional least squares similar to the wavelength calibration step, or by using an existing tool. In the DLP® NIRscan™ Evaluation Module we used imagemagick for this computation.

$$\begin{pmatrix} x1_{mid} & y_{top} \\ x1_{top} & y_{top} \\ x2_{mid} & y_{top} \\ x2_{top} & y_{top} \\ \vdots & \vdots \\ xn_{mid} & y_{top} \\ xn_{top} & y_{top} \\ x1_{mid} & y_{mid} \\ x1_{mid} & y_{mid} \\ x2_{mid} & y_{mid} \\ x2_{mid} & y_{mid} \\ \vdots & \vdots \\ xn_{mid} & y_{mid} \\ xn_{mid} & y_{mid} \\ x1_{mid} & y_{bot} \\ x1_{bot} & y_{bot} \\ x2_{mid} & y_{bot} \\ x2_{bot} & y_{bot} \\ \vdots & \vdots \\ xn_{mid} & y_{bot} \\ xn_{bot} & y_{bot} \end{pmatrix} \tag{5}$$

When control_points.txt is a CSV text file in the format in Equation 5, transformation of an input bmp file can be accomplished with the following command. For details, refer to the imagemagick documentation.

```
convert INPUTFILE.bmp \
        -virtual-pixel black \
        -interpolate NearestNeighbor \
        -distort polynomial “2 $(cat control_points.txt)" \
        OUTPUTFILE.bmp
```

4.1.4 Radiometric Calibration

In certain instruments, it is desirable to have a radiometrically calibrated output. If this is done, similar care should be taken as when calibrating other spectrometer instruments to ensure the calibration source input is spatially and angularly uniform at the slit.

4.2 Pattern Generation

Since we will develop a calibrated correlation between wavelengths and their column numbers on the DMD across the middle row, we can build pattern sets by defining the middle row, expanding to fill the whole height of the DMD, and then transforming the image to adjust for any optical distortion or rotation.

It is common that the number of columns between the minimum and maximum wavelength to scan is not evenly divisible by the number of wavelength groups desired. In this case, there are a few ways to proceed:

- Keep the column width constant, and step the on pixel group by an amount different than the column width.
- Change the column width throughout the scan, in order to distribute extra columns
- Enforce a constant column width and step size, allowing only certain numbers of patterns in scans of certain wavelength regions.

The second option where the column width changes is depicted in Figure 9. Because the column width is changing, the magnitude measured at the detector will contain discontinuities. However, computing the transmission or absorption ratio between a sample and reference scan will still yield a smooth spectrum absent some other source of noise.

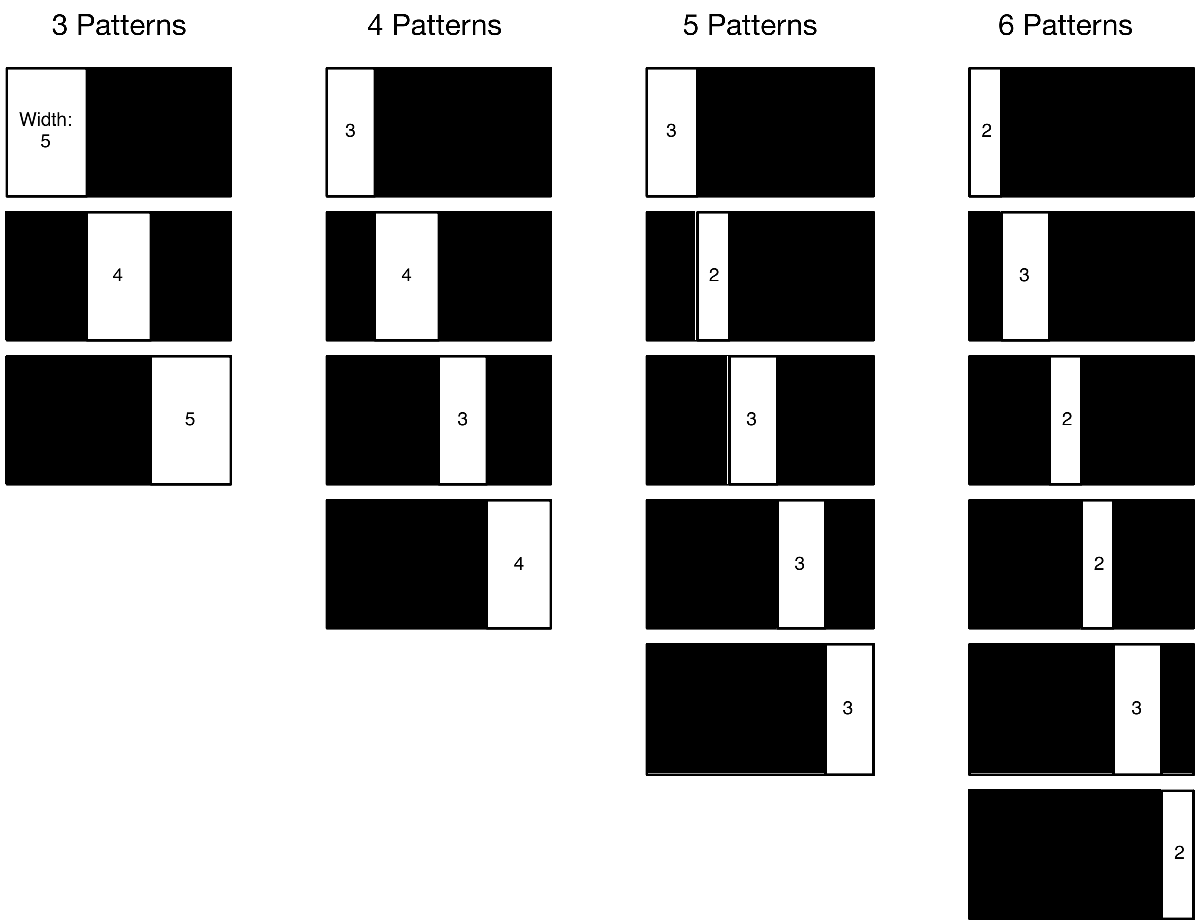


Figure 9. Pattern Distribution

These methods of distribution may be used with either a line scan or multiplexed pattern set. If there is overlap between patterns (some pixels are in multiple regions of DMD pixels assigned to a particular wavelength block), they will first need to be separated into multiple groups which have no overlap within each group. Once the individual multiplexed scans are finished, the results can be composited.

4.2.1 Line Scan Patterns

In line scan pattern sets, the energy at a particular wavelength is sent to the detector only while a single pattern is displayed on the DMD. There is, therefore, a 1-to-1 correspondence between the pattern number, and the wavelength which is being measured. This can be represented mathematically as shown in Figure 10 in a 3 pattern sequence by a 3×3 matrix where each row contains a representation of the pattern to be displayed on the DMD, and each column contains the state (on or off) of a particular band of pixels representing one wavelength region.

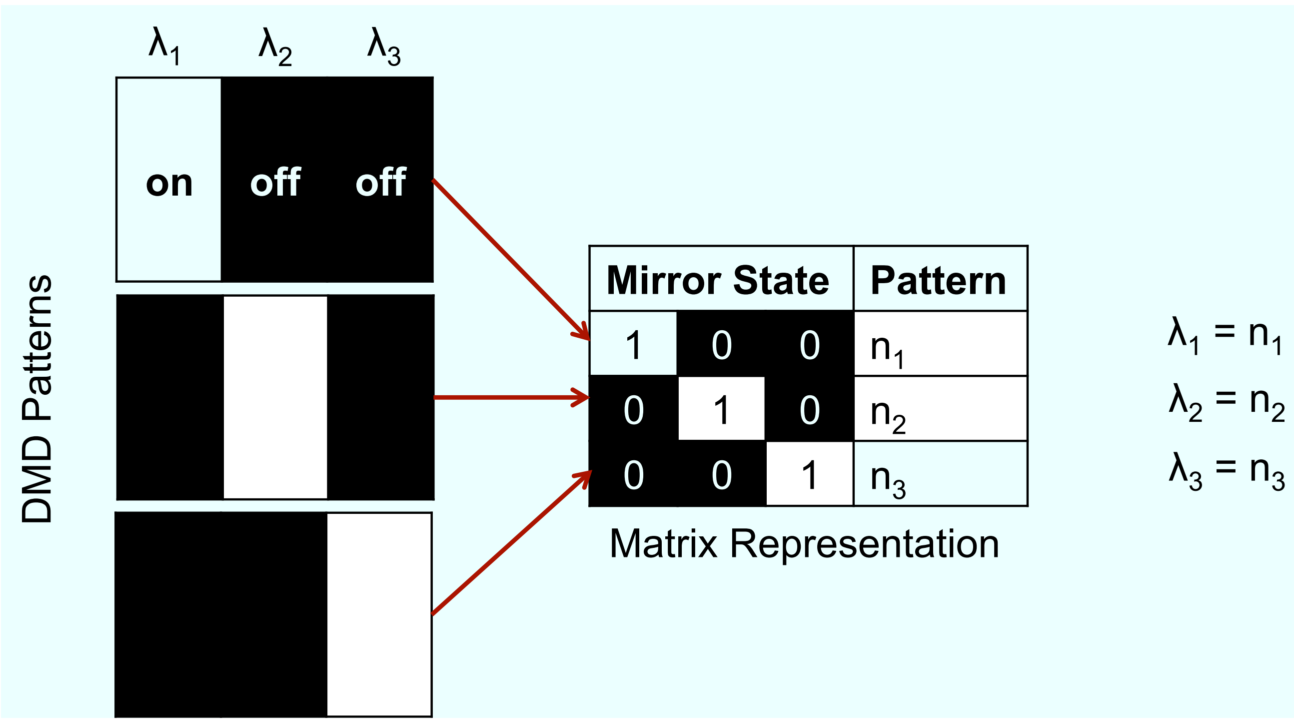


Figure 10. Line Scan Patterns

In this line scan case, an identity matrix can define the scan, regardless of the width of each individual band of pixels.

4.2.2 Hadamard Scan Patterns

A similar pattern definition can be created for Hadamard matrix or other multiplexed patterns. The following is one method which can be used to compute the pattern definition for a scan, based on a Paley constructed matrix:

1. Find next largest valid Paley construction Hadamard matrix
   - Size must be ≥ n+1 (n = desired number of patterns)
   - Size must be an even multiple of 4
   - Size - 1 must be prime
2. **P** = Generate Hadamard matrix via Paley construction
3. Trim first row and column of **P**
4. Trim columns > n of **P** (set width of matrix to be equal to the number of desired patterns)
5. **S** = -1/2 * (**P** - 1) (Convert -1 and +1 representation to 1 and 0. Negating is necessary because each row must contain n/2 + 1 ‘on’ pixels, and n/2 - 1 ‘off’ pixels.
6. Shuffle matrix columns to equalize diffraction efficiencies of patterns (each column of the matrix gets swapped with a random other column)

The resulting matrix can then be used to describe the patterns to be displayed on the DMD.

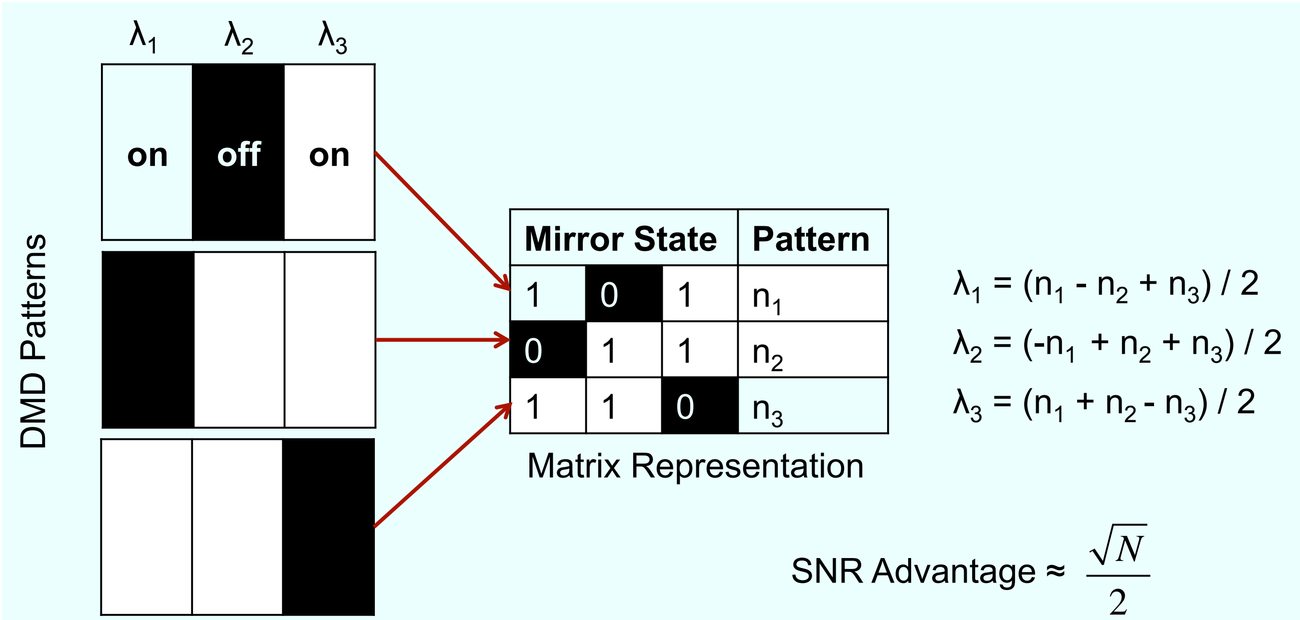


Figure 11. Hadamard Patterns

One challenge with multiplexed patterns is that there is a boundary diffraction effect at the edge of a group of on-state pixels. Because of this, the energy collected at the detector from two adjacent bands of on-state pixels is not necessarily equal to two independent measurements of those two bands of pixels. As described above, the Hadamard patterns which turn on a particular band of pixels may or may not turn on adjacent bands of pixels. This means the whole width of a region of on-state pixels varies from pattern to pattern, leading to the measurements for each pattern not being simple summations of the independent on-state bands' value. This can lead to an inaccurate spectrum when performing the inverse Hadamard transform, so a workaround is necessary. One possible method is to split the region into two separate Hadamard scans, such that no two bands within a specific Hadamard pattern are adjacent. In this way, the summation of individual bands for each Hadamard scan is maintained. This is depicted in Figure 12.

Additionally, it is possible to generate Hadamard scans of a number of bands which do not correspond to the size of a Hadamard S-matrix. Scans of this type still require showing the number of patterns which would be required for the full S-matrix scan, but the unused values in the S-matrix can simply be ignored. Since the pixels corresponding to these other columns of the S-matrix are never turned on (and may not even exist), their detector readings will be zero once we perform the inverse transform. At that point, these values can be truncated before the spectrum is reported to the user. This method when desiring an 8 band scan is shown in Figure 12, along with the method of splitting them up into two different Hadamard matrix scans.

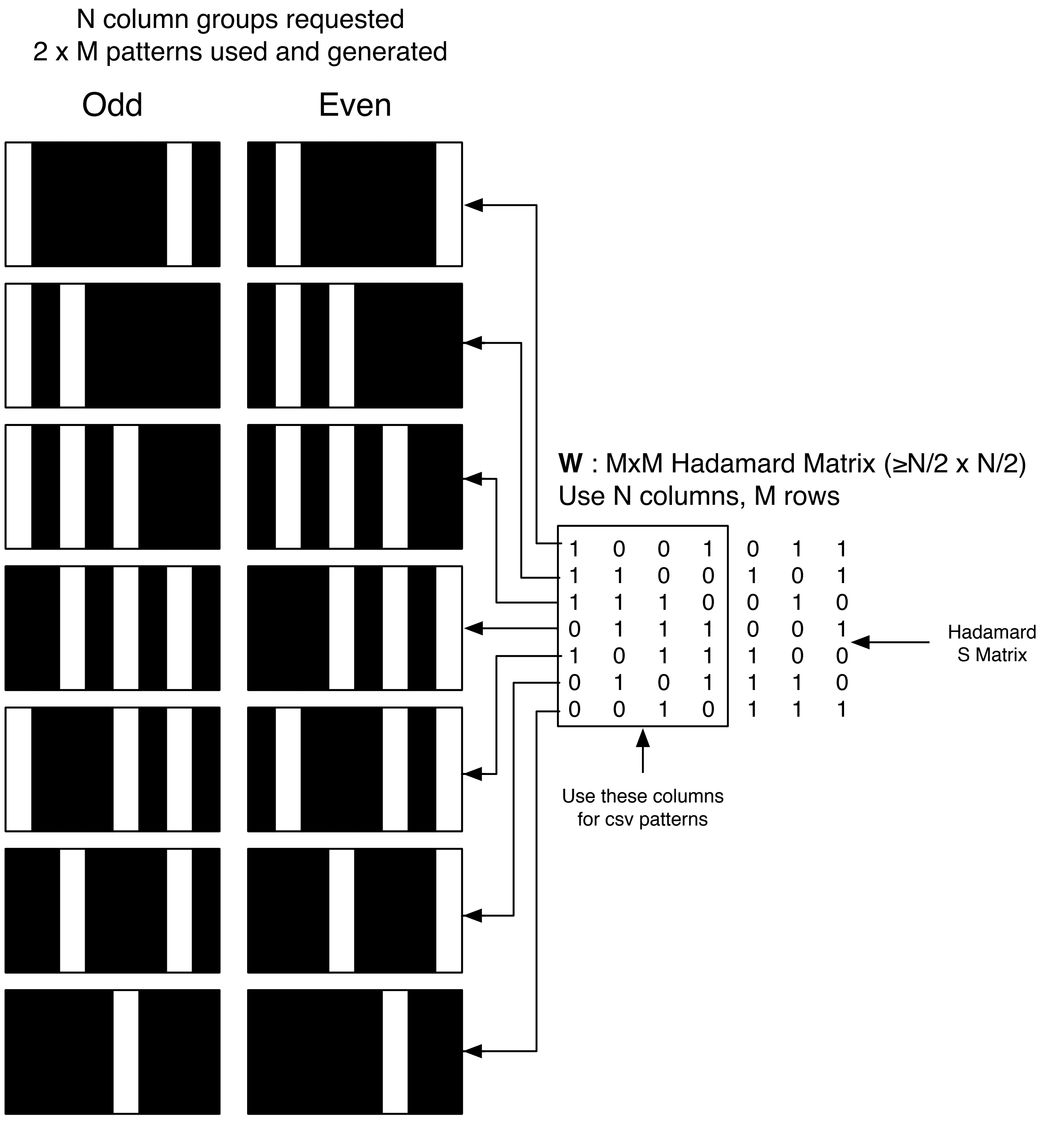


Figure 12. Split Hadamard Scan to Mitigate Diffraction Errors

4.2.3 Wavelength to Column Mapping

For either pattern mode (line scan or Hadamard), transforming each column of the pattern definition matrix to a specific region of columns for the DMD resolution pattern can be done in a number of ways. For instance, starting and ending at specific wavelengths with a certain number of steps evenly distributed may be sufficient. If greater control is necessary, patterns can be defined in the wavelength domain and then transformed into the DMD column domain.

When the desired pattern set applies attenuation to each individual band, a pseudorandom pattern of off pixels within the on band should be applied. The percentage of off-state pixels will then correspond to the desired attenuation.

4.2.4 Image Composting

Once the binary patterns are generated, up to 24 binary patterns can be combined to form a 24 bit composite image. These composite images are what will be streamed over the 24 bit parallel RGB bus to the DLP controller, or stored onto the flash attached to the DLP controller. For details on this process, see the respective controller datasheet for the chipset you are using.

4.2.5 Image Warping

As described in the calibration section, these images should then be warped to compensate for any rotation or distortion of the slit image caused by the optomechanics.

4.2.6 Row Interleaving for Diamond DMD Arrays

When using a chipset which has a diamond array configuration (DLP4500NIR, DLP3000, for example), the rows and columns should be used in a manner to maximize the resolution in the dispersion axis to maximize the resolution of the spectrometer. The rows and columns in the DLP4500NIR chipset are numbered every other column and every row, yielding a 912 × 1140 pixel numbering scheme. Greater horizontal resolution can be attained by swapping this to conceptualize the array as numbering every column and every row, yielding a 1824 × 570 pixel numbering scheme.

Referring to the mirror orientation as shown in the DLP4500NIR Datasheet, the top left pixel of the 912 × 1140 source image is actually shown on the second half-column at DMD pixel (0,911). That is, DMD pixel (1,911) is to the left of DMD pixel (0,911). This means we want the even rows of the DMD pattern image to be sourced from data that is one pixel to the left of the odd rows. Therefore, we arrive at the following pseudocode, loading pattern_image of size 912 × 1140, from warped_image of size 1824 × 570:

```
 For each image:

Read pattern_image into array

pattern_image[0…911][0,2,…1136,1138] = warped_image[1,3,…1821,1823][0…569]
pattern_image[0…911][1,3,…1137,1139] = warped_image[0,2,…1820,1822][0…569]

save warped_image to BMP file
```

The result is 912 × 1140 images which can be loaded into the DLPC350.

4.2.7 Periodic DC Measurements

To enable removal of the detector stray light as discussed earlier, it is beneficial to insert periodic patterns of all off or all on pixels within a scan. The frequency could be up to every other pattern to enable using detectors which require a chopped input signal, or as sparse as once per scan, depending on the expected change of the ambient environment during the scan. These signals can then be used as discussed in Section 4.3 to mitigate the detector stray light effects.

4.3 Spectrum Decoding

Because most applications will oversample the detector data for each pattern by running the ADC at a faster sample rate than the DMD pattern rate, we must first compute an average detector value for each scan, and then compute the spectrum from those average detector values for each pattern.

4.3.1 Sampling and Averaging

During a scan, each pattern is displayed on the DMD for the desired period, and samples are collected. There are largely two methods of collecting ADC samples and synchronizing them with the corresponding pattern which was displayed on the DMD at the time.

- Free running ADC

In this mode, the ADC is set to collect samples continuously. Incoming samples are stored along with the state of trigger outputs from the DLP controller which indicate pattern exposure status. This combined signal can later be parsed to determine which samples correspond to each pattern displayed.

- Synchronized ADC

  In this mode, the pattern trigger output from the DLP controller initiates an interrupts service routine on the embedded processor which then sends a synchronization signal to the ADC. Many ADCs enable this through a GPIO pin which discards the current sample conversion and waits until the next valid conversion before sending a data ready signal to the processor.

Whichever mode is used, some samples will likely need to be discarded when the detector signal is not stable, as shown in Figure 13. The specific number and timing of these samples to use or discard will depend on the sample rate of the ADC and the bandwidth, slew rate, and rise time of the detector amplifier. The last sample is typically discarded as well, to guard against boundary effects in case the data ready signal from the ADC occurs just slightly before the end of the pattern exposure.

The remaining valid signals after stripping any invalid samples are then averaged to reduce noise to yield a single detector value for each pattern.

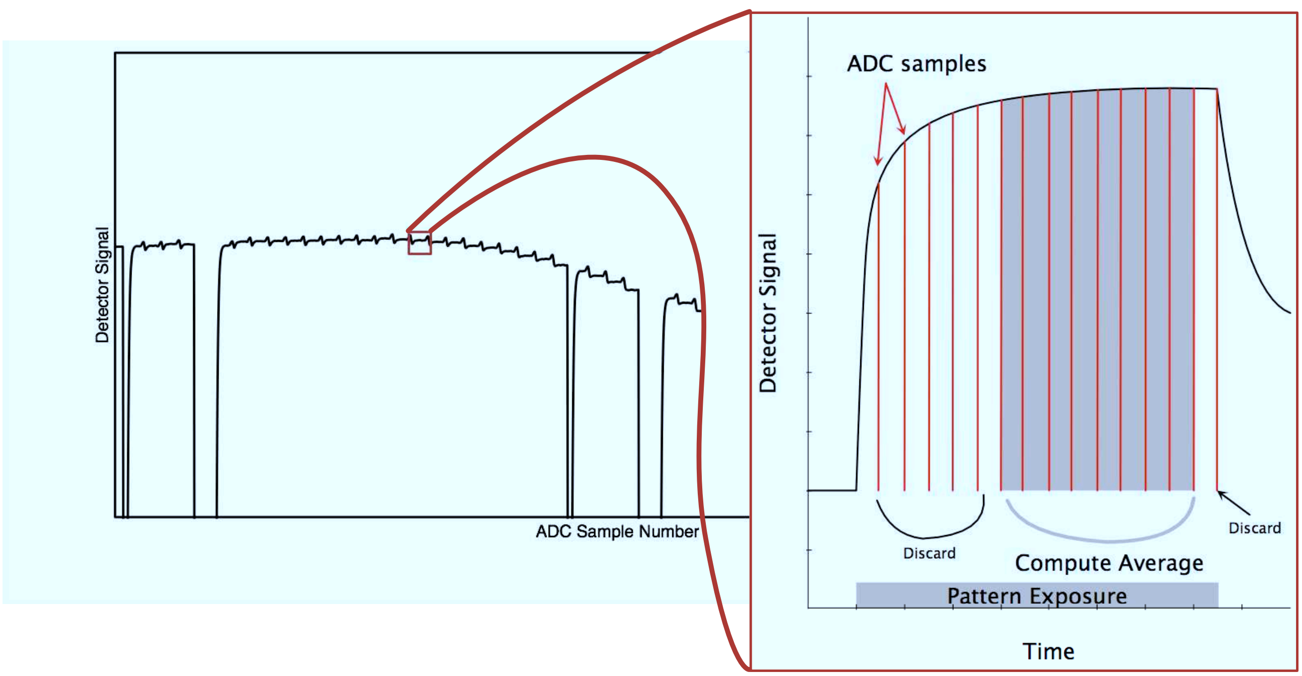


Figure 13. Averaging Samples From One Pattern

4.3.2 Line Scan

In line scan mode, there are several steps which must be performed to decode the spectrum:

- Adjust for Detector Stray Light

  During the scan, light which strikes off-state pixels or doesn't strike active DMD pixels but still makes it to the detector arbitrarily raises the measured value at the detector. In the line scan mode, typically 99% or more of the DMD pixels are set to the off-state position for each pattern. Therefore, the energy from all the off-state pixels and light not striking DMD pixels still making it to the detector for each pattern is almost exactly equal, and almost exactly equal to the value measured when all DMD pixels are in the off position. Therefore, we can average the detector value during several black patterns inserted in the scan and then subtract this DC value from all of the measurements. For certain applications, patterns with all the pixels or a certain percentage of pixels in a random pattern could be used to monitor overall illumination level. This could be used to verify sample or illumination stability in time.

- Remove Periodic DC Measurements

  The periodic DC measurements which were inserted to measure and remove the detector stray light or monitor illumination or sample stability should now be removed so that the measurement vector contains only the adjusted values from intended line scan patterns.
- Compute the Center Wavelength of Each Pattern

  For each pattern, the center column at the center row of the DMD, or more likely the data used to compute the patterns, needs to be computed. This column number can then be used to compute the center wavelength as described in Section 4.1.2.

For line scan scans, the results after this step can be plotted to view the spectrum, referenced to another scan to compute absorbance, or any other spectrum computation desired. Hadamard scans require a decoding process.

4.4 Hadamard

Hadamard scans offer the ability to increase SNR over standard scans in certain circumstances. As described in and shown in Figure 12 a Hadamard scan can be generated with two interleaved Hadamard scans. To compute the spectrum, the following is necessary:

1. Compute inverse of the S-matrix used to define the Hadamard pattern set.
2. Multiply the measurement vector of each Hadamard scan (even and odd) by the inverse of the S-matrix.
3. Truncate each resultant vector to the first N/2 entries, where N is the originally requested number of wavelength points, or banded sections of DMD pixels.
4. Interleave the two vectors in the same order that they were separated when creating the patterns.

The above process is shown in Figure 14 for the case where N = 8.

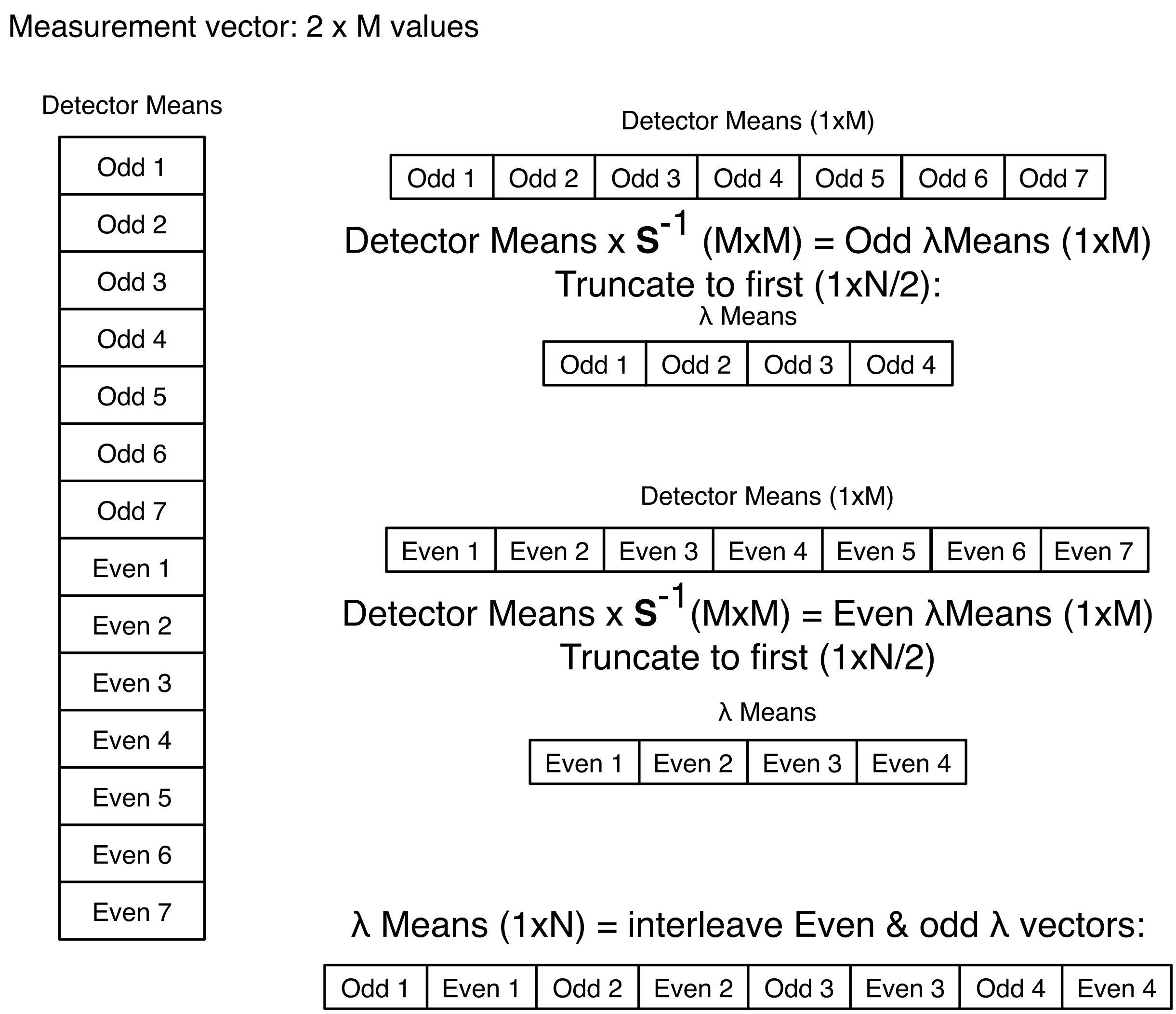


Figure 14. Computing Spectrum from Hadamard Pattern Data