Printalyzer Densitometer

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Contents:

The Printalyzer Densitometer is an affordable reflection and transmission densitometer intended for photographic dark-room use.

CHAPTER 1

Introduction

Dear Customer,

Thank you for purchasing the Printalyzer Densitometer. If you want to take a more analytical approach to testing your photographic film or paper, a densitometer is one of the best pieces of equipment you can have. This device is designed to be that nifty little gadget you can always have available, and don't need to dedicate much space for. It supports both reflection and transmission measurements, and works across the full range of densities common for testing of black and white photographic materials.

Thanks, Dektronics, Inc.

1.1 Getting Started

The package should contain the following items:

- Printalyzer Densitometer
- User Manual
- USB-C to USB Cable
- Calibrated reflection step tablet
- Calibrated transmission step wedge

Due to broad availability of USB power adapters, and the international nature of the analog photographic community, a power adapter is not included in the package. To power the device, use the provided cable and any standards compliant USB power adapter or host computer.

1.2 Device Overview

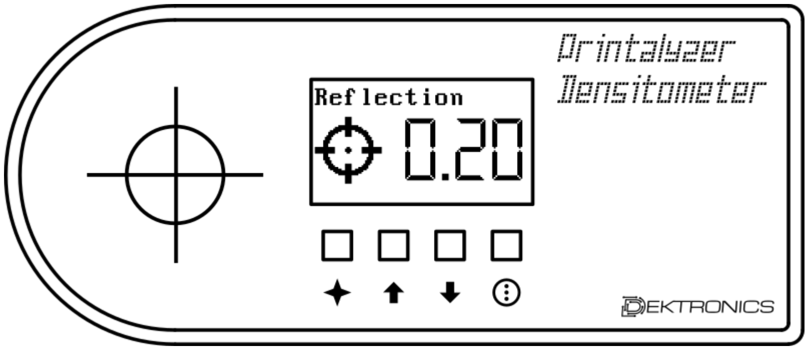

Fig. 1.1: Top of device

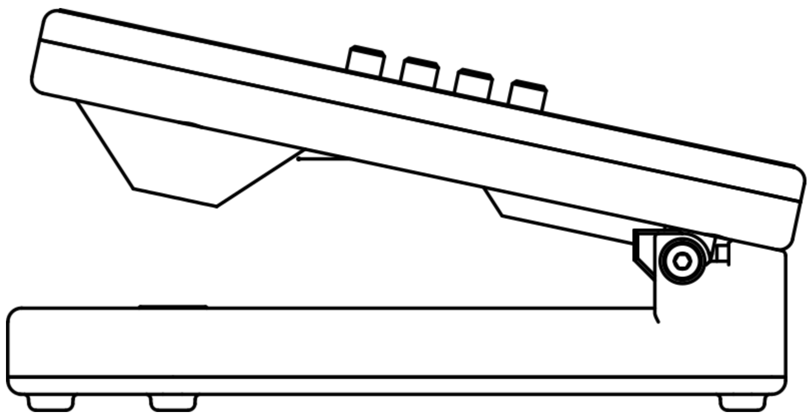

Fig. 1.2: Side of device

- ✦ **Action button** - Used to take measurements or select menu items
- 🡅 **Up button** - Long press to clear a zero offset, or press in combination with the down button to activate the menu
- 🡇 **Down button** - Long press to set a zero offset, or press in combination with the up button to activate the menu
- ⓘ **Mode button** - Used to switch measurement modes or to go back from a menu item
- **Detect switch** - Triggered by pressing down on the front of the device, this switch typically activates the measurement target light

CHAPTER 2

Calibration

The Printalyzer Densitometer uses components that should provide stable readings over the lifetime of the device. However, to ensure measurement accuracy, calibration should be checked periodically.

A transmission step wedge, and a reflection step tablet, have been provided with the device for the purpose of performing and verifying calibration. These materials must be kept clean and should be stored in their envelopes when not in use. The basic layout of these materials, and their expected measurement locations, can be seen in Fig. 2.1.

Note: The read head must be firmly held down during all measurements to ensure accurate results. If the head is released during the process, calibration will fail.

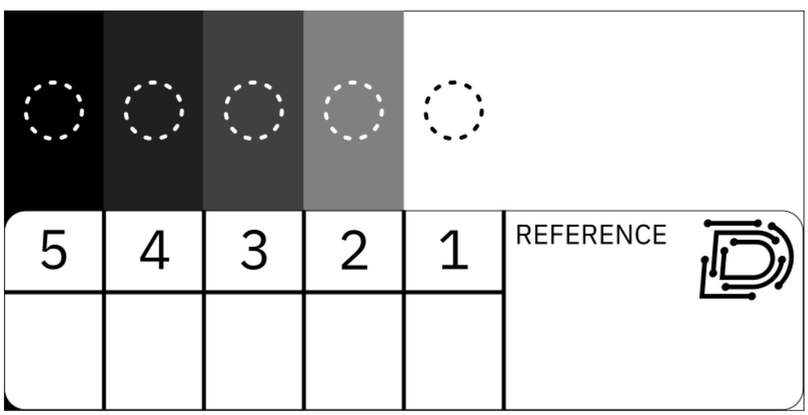

Fig. 2.1: Calibration strip layout, showing measurement locations

2.1 Reflection Calibration

- Press the [↑ ↓] buttons together to open the device menu
- Select "`Calibration`" and press ✦
- Select "`Reflection`" and press ✦
- Make sure that the numbers after "`CAL-LO`" and "`CAL-HI`" match the corresponding numbers on the provided reflection step tablet's label
  - If either of these numbers do not match, then adjust them accordingly
  - Select with ✦
  - Adjust the value with ↑ and ↓
  - Accept with ✦
- Select "`** Measure **`" and press ✦
- Follow the on-screen instructions:
  - Position the center of the reflection step tablet's **CAL-LO** patch in the read area, firmly hold down the sensor head ⌖, and press the ✦ button
  - Position the center of the reflection step tablet's **CAL-HI** patch in the read area, firmly hold down the sensor head ⌖, and press the ✦ button

If using 3rd party calibration materials, the following guidance should be taken into account:

- The **CAL-LO** patch should have a marked density of `0.10` or less.
- The **CAL-HI** patch should have a marked density roughly within the range of `1.50` through `1.90`.
- If the material was marked for color densitometer calibration, then use the values labeled as "visual" or "black."
- The material must be held perfectly flat against the bottom of the sensor head to ensure accurate measurement. This is easy if the material is made from photographic paper, however it can be quite difficult if the material is made from a thick piece of painted metal.

2.2 Transmission Calibration

- Press the [↑ ↓] buttons together to open the device menu
- Select "`Calibration`" and press ✦
- Select "`Transmission`" and press ✦
- Make sure that the number after "`CAL-HI`" matches the corresponding number on the provided transmission step wedge's label
  - If the number does not match, then adjust it accordingly
  - Select with ✦
  - Adjust the value with ↑ and ↓
  - Accept with ✦

- Select "`** Measure **`" and press ✦
- Follow the on-screen instructions:
  - With the read area empty, firmly hold down the sensor head ⌖ and press the ✦ button
  - Position the center of the transmission step wedge's **CAL-HI** patch in the read area, firmly hold down the sensor head ⌖, and press the ✦ button

If using 3rd party calibration materials, the following guidance should be taken into account:

- The **CAL-HI** patch should have a marked density roughly within the range of `2.90` through `3.00`.
- If the material was marked for color densitometer calibration, then use the values labeled as "visual" or "black."
- The material must be measured with the emulsion side facing upward towards the sensor. Whether or not the material is labeled this way may depend on the design of the densitometer it was originally intended for use with.

2.3 Measurement Light

Measurement light calibration is a process normally performed as part of device assembly. As it should not normally need to be repeated by the user, the desktop companion software is required to perform it.

The purpose of measurement light calibration is to determine the optimal brightness of the device's light sources for measuring density targets. This is necessary because manufacturing variation in several components can lead to significant device-to-device differences in measurement light output. If these differences are too great, then target calibration alone cannot easily compensate for them.

The process of actually performing measurement light calibration involves the desktop software and is currently beyond the scope of this manual.

2.4 Sensor Gain

Sensor gain calibration is a process normally performed as part of device assembly. As it should not normally need to be repeated by the user, the desktop companion software is required to perform it.

The purpose of sensor gain calibration is to determine the actual relationship between the various gain settings of the light sensor used by the device. This is necessary so that target readings taken at different levels of sensitivity can be accurately compared.

Sensor gain calibration is discussed in more detail in the *Theory of Operation* section, later in this manual. The process of actually performing sensor gain calibration involves the desktop software and is currently beyond the scope of this manual.

2.5 Sensor Slope

Sensor slope calibration is a process normally performed as part of device assembly. As it should not normally need to be repeated by the user, the desktop companion software is required to perform it.

The purpose of sensor slope calibration is to compensate for a slight non-linearity in the sensor's response curve. This is necessary to ensure accurate readings at both low and high densities, while still only requiring two points to be measured as part of the user calibration process described above.

Sensor slope calibration is discussed in more detail in the *Theory of Operation* section, later in this manual. The process of actually performing sensor slope calibration involves the desktop software and is currently beyond the scope of this manual.

CHAPTER 3

Operation

3.1 Mode Selection

Reflection or Transmission modes are switched between by pressing the ⓘ button. The name of the active mode will be shown on the display, as will the last measurement result from that mode.

3.2 Taking Measurements

To take a measurement, follow these steps:

1. Select the desired measurement mode
2. Center the area to be measured over the target area, emulsion side up
3. Lower the sensor head and hold it firmly closed
4. Press the ✦ button and wait for the result

Note: When the sensor head is pressed down partway, the read light for the current mode will turn on at a moderate brightness. This can be used to help better position the material area to be measured.

3.3 Setting a Zero Offset

It is common to want to take measurements relative to a film or paper base. The Printalyzer Densitometer provides a convenience feature to make it easier to take such relative measurements, without having to do math on the results.

After measuring the base area of a piece of film or paper, long-press the ⬇ button. This will set the result to 0.00 and display a ⬇ icon in the upper-right corner of the display. From this point forward, all displayed measurements will be relative to this zero offset.

To clear the zero offset, long-press the ⬆ button. The indicator icon should disappear.

CHAPTER 4

Settings

To get to the settings screen:

- Press the [⬆ ⬇] buttons together to open the device menu
- Select "`Settings`" and press ✦

To leave the settings screen, simply press ⓘ until you return to the main screen. Alternatively, if you wait long enough, you should be returned to the main screen automatically.

4.1 Target Light

This settings menu is for configuring the behavior of the read light before and after taking measurements. This light state is normally triggered by pressing the sensor head down partway.

The settings for this feature are as follows:

- Refl. - Brightness for the reflection light
- Tran. - Brightness for the transmission light
- Timeout - Amount of time the light should remain on after the sensor head is released

The default settings are "Medium" for the reflection light, "Low" for the transmission light, and "None" for the timeout.

4.2 Display Settings

This settings menu is for configuring the format with which density readings are displayed. Selections here will affect both the local on-device display as well as characters generated by the *USB Key Output* feature as described in the following section. They do not affect the behavior of the *Remote Interface* or the *Desktop Application*.

The settings are as follows:

- Number - Display format for density values
- `#.##` - Use a period as the decimal separator
- `#,##` - Use a comma as the decimal separator
- Units - Display units for density values
- `D` - Display values in the standard log_{10} density units
- `F` - Display values in camera f-stop style log_2 units

Note: While changing the decimal separator affects the entire system, changing the density units only affects active measurements. It does not change the units used for entering calibration values.

(This feature was added in firmware v1.1.0)

4.3 USB Key Output

This settings menu is for configuring the USB Keyboard Output feature of the device. When connected to a computer, if this feature is enabled, the device will appear as an additional keyboard. Then, whenever a measurement is taken, it will “type” the result on the computer. It is designed to be a very convenient way of getting measurements into analysis applications on a computer, without the need for specialized software.

Note: This feature is temporarily disabled whenever connected to the *Remote Interface* to avoid conflicts between applications.

The settings for this feature are as follows:

- Enabled - `Yes` to enable this feature, `No` to disable it.
- Format (Fmt.) - Desired format for typed measurements:
  - `#.##` - Just type the raw number (e.g. `0.24`)
  - `M+#.##D` - Type a fully formatted sequence, which contains the measurement mode. This is the same format used by the *Remote Interface* (e.g. `T+2.85D`).
- Separator (Sep.) - Character to send after a measurement, to advance to the next line or field (i.e. Enter, Space, Comma, etc.)

4.4 Diagnostics

This settings screen is for exercising direct control over the device's sensor and light sources, for testing and diagnostic purposes. It may be removed or disabled prior to final release.

CHAPTER 5

Remote Interface

5.1 Basic Usage

To interface with the Printalyzer Densitometer from a host computer, use the provided cable to plug the device into a USB port on that computer.

The device will appear on the computer as a serial (COM) port, and can be connected to via any typical serial terminal application. The expected communications parameters are 115200 8n1.

Under normal usage, every time the device takes a measurement, the result will be transmitted via this interface.

The typical format for measurements is:

`<R/T><+/->#.##D<CR><LF>`

An example of a density reading would be something like `R+0.20D` or `T+2.85D`.

5.2 Control Interface

There is also an extensive control interface provided via the USB port. It allows for remote configuration and control, as well as device logs and higher precision raw sensor and measurement data. It is primarily intended for use by the provided desktop application, and for functions that are part of the device manufacturing and testing process.

This interface is described separately in the following document:

https://github.com/dektronics/printalyzer-densitometer/blob/master/docs/protocol.md

5.3 Desktop Application

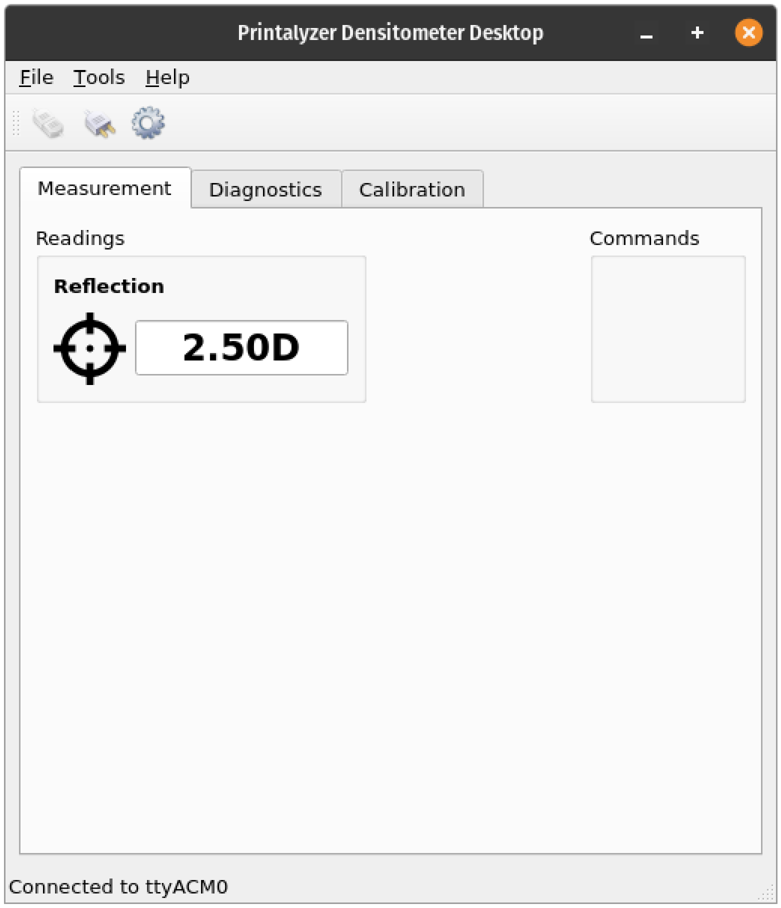

Fig. 5.1: Printalyzer Densitometer Desktop

CHAPTER 6

Maintenance

6.1 Cleaning

Whenever required, the device may be wiped clean with a lint-free cloth. The sensor head may be cleaned by lightly blowing compressed air into its openings.

Do not attempt to clean the device with alcohol or any solvent cleaners.

6.2 Updating Firmware

The Printalyzer Densitometer is designed to have firmware that can be updated. This is so that features can be added, and bugs can be fixed, after the device has shipped. The update process is designed to be as easy as possible, and can be performed from any computer that the device can be plugged into.

To update the device firmware, you will need:

- The Printalyzer Densitometer itself
- The latest firmware file, downloaded to your computer (a file with a name similar to `densitometer.uf2`).
- A cable that can connect from a USB port on your computer to the port on the Printalyzer Densitometer

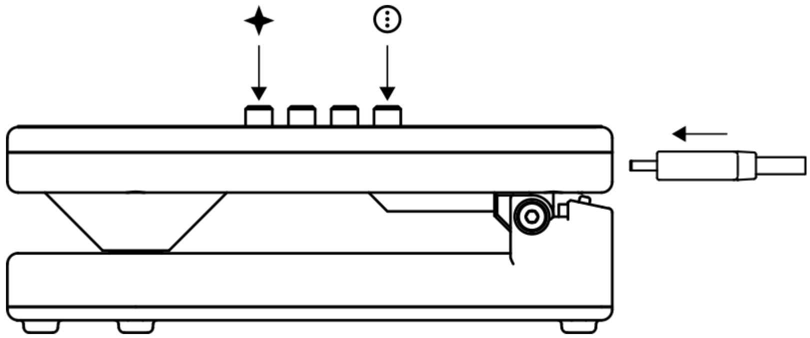

Fig. 6.1: Starting the bootloader

The update procedure is as follows:

- Make sure the USB cable is plugged into your computer, but not the device.
- While simultaneously holding down the sensor head ⌖, and pressing the ✦ and ⓘ buttons, plug the cable into the device.
- The device should now start in a special mode, with a USB logo displayed on the screen.

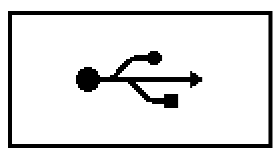

Fig. 6.2: Device in bootloader mode

- You may now let go of the device.
- On your computer, a USB disk volume named “PRDENSBOOT” should appear.
- Copy the firmware file (e.g. `densitometer.uf2`) to the “PRDENSBOOT” device,
- While the firmware is being copied, you should see a progress indicator on the device.

Fig. 6.3: Device receiving updated firmware

- Once complete, the device should automatically reset and start up with the new firmware. If it does not reset correctly, simply unplug it and plug it in again to restart it.

6.3 Updating the Bootloader

It is also possible to update the bootloader itself, which is the special piece of software that enables the user-friendly update process described above. Updates to the bootloader are expected to be infrequent, and should only be necessary to fix issues that prevent the normal update process from functioning correctly.

To update the device bootloader, you will need:

- The Printalyzer Device itself
- The latest bootloader file, downloaded to your computer (a file with a name similar to `densitometer-bootloader.dfu`).
- A cable that can connect from a USB port on your computer to the port on the Printalyzer Densitometer
- A small pin, such as a bent paperclip
- A special piece of software called dfu-util (http://dfu-util.sourceforge.net/)
  - The dfu-util website has downloadable binaries and instructions for Windows, macOS, and Linux.
  - Alternative USB DFU utilities, such as STM32CubeProgrammer (https://www.st.com/en/development-tools/stm32cubeprog.html) can also be used. However, they will not be covered by these instructions.

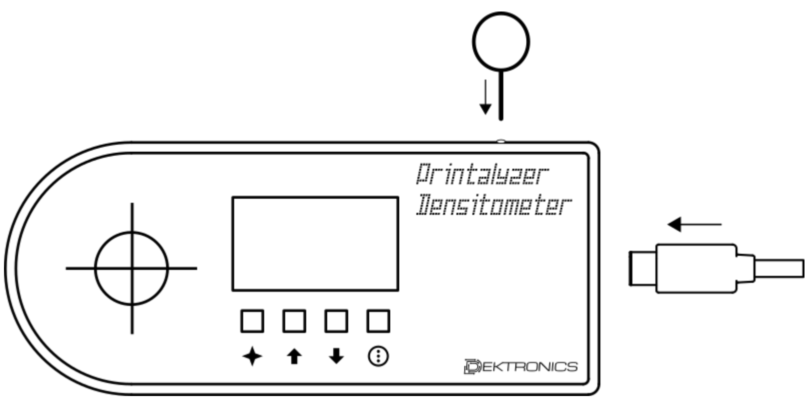

Fig. 6.4: Updating the bootloader

The bootloader update procedure is as follows:

- Make sure the USB cable is plugged into your computer, but not the device.
- Insert the pin into the tiny hole on the back side of the device. Inside the hole there is a tiny button, which you should press with the pin. It may be hard to feel, so be gentile.
- While using the pin to hold the internal button down, plug the USB cable into the device.
- The device should now start, but the display will remain blank. On Windows, you may notice the computer detecting a new USB device. On macOS or Linux, you are unlikely to notice anything unless you are looking at USB utilities or log files.
- You may now let go of the device.
- If you run the command `dfu-util -l`, you should now see several entries returned with the ID of `[0483:df11]`

To install the bootloader, run the following command:

```
dfu-util -a 0 --dfuse-address 0x08000000 -D densitometer-bootloader.dfu
```

(Note: Newer versions of dfu-util may no longer require the address argument.)

Once the update procedure is complete, you will need to unplug the device and plug it back in to reset it. If the main firmware is valid, then it will be started. If the main firmware is corrupted, then the bootloader (as described above) will automatically start.

6.4 Troubleshooting

- **The device hinge feels too loose or too tight**

  The hinge mechanism is designed to allow for free up-and-down motion, aided by a set of springs, and to lock into place when taking measurements. This is necessary to allow for ease of operation, while ensuring repeatable alignment with the transmission light.

  Normally, a set of screws on either side of the hinge keep it generally stable, while groves near the middle provide some extra tension for stability when closing the device. However, due to manufacturing tolerances or wear, it is possible that this mechanism may need adjustment.

  To adjust the hinge, use a 2mm sized hex driver. Both sides should be tightened as equally as possible, right up until the point where the hinge ceases to open smoothly. Once getting to that point, carefully back out the screws no more than a quarter turn at a time until the hinge moves smoothly again.

  Note: These screws are not designed for repeated adjustment after initial device assembly, as doing so could strip or weaken the threads inside the device. As such, this process should be performed as sparingly as possible.

- **The device displays "Sensor initialization failed" on startup**

  This means that the device's processor was unable to communicate with the light sensor used for density measurements. Please contact Dektronics about sending the device back for service or replacement.

- **The device displays "Invalid calibration" when taking a measurement**

  It is possible that the device's calibration data has become corrupted. To fix, it is recommended that you attempt to perform the target *Calibration* process. If that still does not fix the issue, then use the desktop software to check device calibration numbers and re-run gain or slope calibration if necessary before trying target calibration again.

  Note: The Quick Start Guide included with the device should include a label on its last page with the factory calibration numbers for your device. This can be used, in combination with the desktop software, to restore the initial calibration of your device.

- **The device displays "Sensor read error" when taking a measurement**

  - Message is shown after all measurements

    It is possible that there is a problem with the sensor or device. Please use the desktop software to check device light and gain calibration numbers if possible. If those appear normal, then please contact Dektronics for advice.

  - Message is shown only on some measurements

    It is possible that there is either a problem with the device firmware, or with the light and gain calibration. Please use the desktop software to check device light and gain calibration numbers if possible. If those appear normal, then please contact Dektronics for advice. When contacting Dektronics, please provide as much detail as possible about what material(s) cause this error during measurement.

  - Message is shown only when taking a transmission measurement with no film under the sensor

    The most likely cause of this error is incorrect light calibration, possibly caused by a hinge alignment issue. If adjusting the hinge (see above) does not resolve it, then use the desktop software to run the gain calibration process. This will automatically calibrate both the measurement light and the sensor gain, as part of a combined sequence.

CHAPTER 7

Specifications

7.1 Device Specifications

- Features
  - Reflection and Transmission Density Measurement for B&W film and paper
  - Measurement reach sufficient to cover most test strips and material sizes up to 5x7"
  - Includes calibration reference materials for both reflection and transmission
  - USB interface for power, measurement logging, and desktop control
  - Firmware is user upgradable
- Measurement Specifications
  - Response spectrum approximating ISO 5-3:2009 Visual Density[1]
  - Reflection range: 0 - 2.5D
  - Transmission range: 0 - 4.0D
  - Measuring area: 3mm
  - Measurement accuracy: ±0.02D[2]
- Operating Specifications
  - Power source: 5VDC @ 150mA
  - Can be powered via a standard USB power adapter, or via the USB port of a computer (device connector is compatible with USB-C®[3])

[1] This claim is based on a combination of response curve of the sensor, properties of the UV-IR cut filter, and the emission spectrum of the light source. These are all off-the-shelf components, and are thus unable to exactly match the response spectrum in the ISO specification. However, they are fairly close, should meet the needs of most use cases involving B&W photographic materials.

[2] The goal for measurement accuracy is ±0.02D under most circumstances, and ±0.01D under freshly calibrated lab conditions. However, it is difficult to adequately test reflection density beyond 2.00D and transmission density beyond 4.00D due to availability of reference materials.

[3] USB-C® is a registered trademark of USB Implementers Forum.

- Temperature: 10°-30°C; 50°-86°F
- Dimensions: 11cm L x 4.5cm W x 3.5cm H
- Weight: 150g

7.2 Regulatory Information

7.2.1 Federal Communications Commission Notice

Note: This equipment has been tested and found to comply with the limits for a Class B digital device, pursuant to part 15 of the FCC Rules. These limits are designed to provide reasonable protection against harmful interference in a residential installation. This equipment generates, uses and can radiate radio frequency energy and, if not installed and used in accordance with the instructions, may cause harmful interference to radio communications. However, there is no guarantee that interference will not occur in a particular installation. If this equipment does cause harmful interference to radio or television reception, which can be determined by turning the equipment off and on, the user is encouraged to try to correct the interference by one or more of the following measures:

- Reorient or relocate the receiving antenna.
- Increase the separation between the equipment and receiver.
- Connect the equipment into an outlet on a circuit different from that to which the receiver is connected.
- Consult the dealer or an experienced radio/TV technician for help.

7.2.2 Industry Canada Compliance Statement

CAN ICES-003(B) / NMB-003(B)

7.2.3 CE Declaration

Hereby, Dektronics, Inc, declares that the Printalyzer Densitometer DPD-100 has been tested and is fully compliant with the EU EMC Directive 2014/30/EU.

7.2.4 UKCA Declaration

Hereby, Dektronics, Inc, declares that the Printalyzer Densitometer DPD-100 has been tested and is fully compliant with the UK EMC Regulations (2016).

7.2.5 Equipment Information

Instructions for disposal: Please dispose of Waste Electrical and Electronic Equipment (WEEE) at designated collection points for the recycling of such equipment.

CHAPTER 8

Theory of Operation

Density measurements for photography and graphic technology is officially based upon the following standards documents[1]:

- **ISO 5-1:2009** - Geometry and functional notation
- **ISO 5-2:2009** - Geometric conditions for transmittance density
- **ISO 5-3:2009** - Spectral conditions
- **ISO 5-4:2009** - Geometric conditions for reflection density

This section will eventually contain an in-depth description of the design and functionality of the device, as well as the various formulas used in the density calculations.

8.1 Basic Calculations

8.1.1 Reflection Density

Reflection density is typically defined by the following formula:

$D_R = -log_{10}R$

In this formula, "R" is defined as the reflectance factor. That means it is the ratio of light detected by the sensor as reflecting off of the target material, to light that would be detected if the target was a perfectly reflecting and perfectly diffusing material.

In practice, the reflection calculations are based on using two reference measurements to draw a line in logarithmic space. The location of the target measurement along this line then determines its density.

The inputs to this calculation are:

- V_{target}: Sensor measurement of the target material

[1] The ISO standards for density were preceded by the following ANSI standards: PH 2.16, PH 2.17, PH 2.18, and PH 2.19. Older product specifications are likely to cite these instead.

- V_{hi}: Sensor measurement of the CAL-HI reference
- D_{hi}: Known density of the CAL-HI reference
- V_{lo}: Sensor measurement of the CAL-LO reference
- D_{lo}: Known density of the CAL-LO reference

First, all the input measurements are converted into logarithmic space:

$$L_{target} = log_{10}V_{target}$$
$$L_{hi} = log_{10}V_{hi}$$
$$L_{lo} = log_{10}V_{lo}$$

Then the slope of the line connecting CAL-HI and CAL-LO is determined:

$$m = \frac{D_{hi} - D_{lo}}{L_{hi} - L_{lo}}$$

Finally, the measured density is calculated:

$$D_{target} = (m * (L_{target} - L_{lo})) + D_{lo}$$

Note: An alternative approach would be to use the CAL-LO properties to determine what a perfect reflection reading would be, then use that value in the original density formula. In theory, this would yield the same answer. In practice however, due to the side effects of floating point calculations, the results would be slightly different.

8.1.2 Transmission Density

Transmission density is typically defined by the following formula:

$D_T = -log_{10}T$

In this formula, "T" is defined as the transmittance factor. That means it is the ratio of light detected by the sensor as passing through the target material, to light that would be detected if the path from the light source to the sensor was unobstructed.

In practice, the transmission calculations are based on using two reference measurements to compensate for any sensor error. One is the measurement of an unobstructed light path, while the other is the measurement of a high density reference material.

The inputs to this calculation are:

- V_{target}: Sensor measurement of the target material
- V_{hi}: Sensor measurement of the CAL-HI reference
- D_{hi}: Known density of the CAL-HI reference
- V_{zero}: Sensor measurement of an unobstructed light path

First, calculate the measured target and CAL-HI densities relative to the unobstructed light reading:

$$M_{hi} = -log_{10}\left(\frac{V_{hi}}{V_{zero}}\right)$$
$$M_d = -log_{10}\left(\frac{V_{target}}{V_{zero}}\right)$$

Then calculate the adjustment factor based on the known density of our CAL-HI reference:

$$F_{adj} = \frac{D_{hi}}{M_{hi}}$$

Finally, put these together to calculate the transmission density:

$$D_{target} = M_d * F_{adj}$$

8.2 Preparing Readings

Before any of the above calculations can be performed, the raw sensor readings must first be converted into a normalized form. This conversion takes into account a number of sensor properties, to arrive at a floating point value that is independent of the sensor's measurement settings and is corrected for any deviations in the sensor's response curve.

8.2.1 Gain Calibration

Because of the wide range of light values that need to be measured, the gain setting of the sensor cannot be kept constant across all measurements. Therefore, the current gain setting needs to be factored into any calculations that compare sensor readings.

The datasheet for the sensor does not provide exact values for these gain settings, but rather a range that can be expected.

Table 8.1: TSL2591 (CH0) Datasheet Sensor Gain Values

Setting	Min	Typical	Max
Low	-	1x	-
Medium	22x	24.5x	27x
High	360x	400x	440x
Maximum	8500x	9200x	9900x

To determine the actual values for these gain settings, or as close to them as we can get, a calibration process is required. This process is mostly automated, triggered by the desktop application. It works by leaving the device unattended with the sensor head held closed by a weight, while a series of independent raw measurements are performed.

For each adjacent pair of gain settings, raw measurements of the transmission light source are taken. For low/medium and medium/high, these are at full brightness. For high/maximum, a reduced brightness level is selected to avoid saturating the sensor.

By walking across these pairs of readings, the actual gain values for the sensor are determined and saved as part of the device's calibration data.

Table 8.2: Example Measured Sensor Gain Values

Setting	Device 1	Device 2	Device 3	Device 4
Low	1x	1x	1x	1x
Medium	24.072321	24.189157	23.832190	24.142603
High	411.821594	408.613861	409.936462	409.528290
Maximum	9475.822266	9454.925781	9370.299805	9434.156250

8.2.2 Converting to Basic Counts

Raw sensor readings cannot be compared directly, because there are a number of setting variables and device constants that need to be taken into consideration. The process of incorporating these into the result transforms that result from a raw reading into something referred to as "basic counts."

The inputs to this conversion are as follows:

- V_{raw}: Raw 16-bit integer representing the output of the sensor's analog-to-digital converter (ADC)
- A_{time}: Sensor integration time, in milliseconds[2]
- A_{gain}: Sensor gain value, for the active gain setting
- GA: Glass attenuation factor, which represents the effect of the enclosure the sensor is placed within[3]
- DF: Device factor, which is a constant specific to the sensor

The conversion itself is then as follows:

$$CPL = \frac{A_{time} * A_{gain}}{GA * DF}$$

$$V_{basic} = \frac{V_{raw}}{CPL}$$

8.2.3 Slope Calibration

Slope calibration is a special correction step that is typically performed on a basic count value, before that value is used to perform actual density calculations. Its purpose is to ensure the linearity of the device's density readings, across its measurement range.

There are two major parts to this process. The first part involves determining the calibration coefficients, which is typically performed with the help of the desktop software. The second part involves applying the calibration coefficients to a basic count value, which is performed on-device.

To determine the calibration coefficients, we first begin with a calibrated step wedge. Basic count readings are then taken from an empty light path, all the way through every patch of that step wedge. For each patch, the calibrated step wedge values are then used to calculate the expected basic count readings.

The inputs to this calculation are:

- D_{step}: The calibrated step wedge value for the current patch
- V_{zero}: The basic count reading for the unobstructed reading, otherwise known as step zero

To get the expected reading for a given row:

$$V_{expected} = \frac{V_{zero}}{10^{D_{step}}}$$

[2] To avoid the need to calibrate the integration time, all readings are taken with the same value for this setting.

[3] The "GA" and "DF" constants are only relevant for lux calculations. For the purposes of our device, they are not important as long as they do not change.

Table 8.3: Example Slope Calibration Readings

Step	Density	Basic Reading	Expected Reading
0	0.00	272.233765	272.233765
1	0.05	234.992798	242.628598
2	0.25	146.573486	153.088296
…	…	…	…
19	3.49	0.061933	0.088093
20	3.63	0.045201	0.063818
21	3.83	0.028095	0.040266

The next step is to prepare a table that shows the relationship between the basic and expected readings, when interpreting both on a logarithmic scale. This table takes each reading value from above, and takes the log_{10} of that reading.

Table 8.4: Logarithmic Relationship Table

Step	x (actual)	y (expected)
0	2.434942	2.434942
1	2.371055	2.384942
2	2.166055	2.184942
…	…	…
19	-1.208078	-1.055059
20	-1.344852	-1.195057
21	-1.551371	-1.395062

Finally, a least squares approximation method[4] is used to find a second-order polynomial that best represents the relationship between the “x” and “y” columns.

The result of this is the coefficients “B0”, “B1”, and “B2”, which are then saved in the device’s calibration data. While the input values may vary wildly from device to device, the resulting coefficients do not vary dramatically. Therefore, while this calibration may be performed on a per-device basis, it may also be performed on a per-batch basis.

Table 8.5: Coefficients from Slope Example

Coeff	Value
B0	0.125822
B1	0.970680
B2	-0.008126

To give an example of why this correction is necessary, Fig. 8.1 shows the difference between the actual and expected sensor readings in logarithmic space. It also shows how closely the above coefficients can model this difference. It should also be noted that the most likely cause of the jaggedness of the raw data is the expected errors in the calibration values on the reference step wedge.

[4] The method itself is described here (https://en.wikipedia.org/wiki/Least_squares), whereas the actual code used is based on this (https://www.bragitoff.com/2018/06/polynomial-fitting-c-program/) implementation.

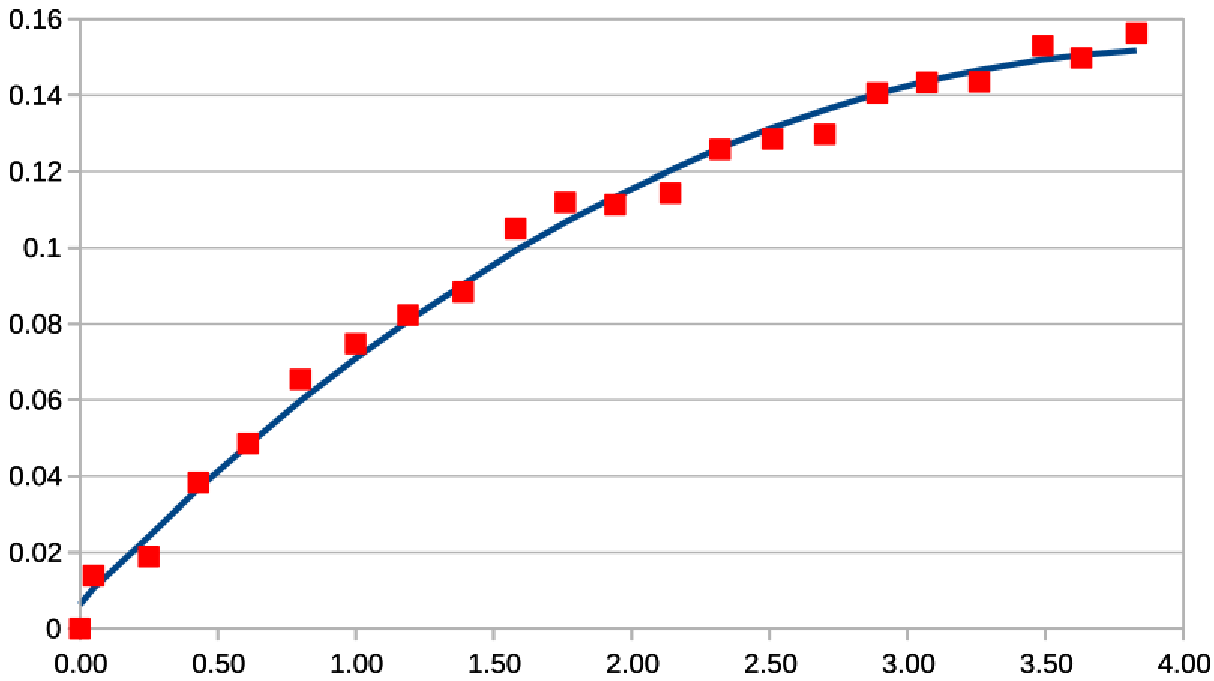

Fig. 8.1: Modeled Logarithmic Sensor Reading Error

8.2.4 Slope Correction

Applying the slope calibration coefficients to a basic count value is performed on-device, before that value is used as part of density calculations.

The process is fairly straightforward. It involves applying the polynomial calculated above to the value in a logarithmic space, then converting back to a linear space.

The inputs are as follows:

- B_0, B_1, B_2: Slope calibration coefficients
- V_{basic}: Sensor reading value, in basic counts

The correction itself is thus:

$$
\begin{aligned}
M_{reading} &= log_{10} V_{basic} \\
M_{expected} &= B_0 + (B_1 * M_{reading}) + (B_2 * {M_{reading}}^2) \\
V_{corrected} &= 10^{M_{expected}}
\end{aligned}
$$

8.3 Sensor Head Design

The sensor head is designed to support both reflection and transmission measurements from a single sensor element, using multiple light sources. It is articulated using a hinge mechanism that brings the two halves of the unit to a repeatable alignment and parallel position, when an object no thicker than a normal piece of photographic film or paper is placed in-between.

For reflection measurements, the light source consists of four light-emitting diodes (LEDs) arranged and directed so that they shine at a 45° angle to the target. This arrangement was chosen to ensure even illumination regardless of surface or alignment imperfections, and because it provides a converging cross-hair effect when positioning a material to be measured. The LEDs are driven with a constant current that is matched between all four of them to ensure even illumination.

For transmission measurements, the light source consists of a single LED positioned below a diffuser in the base of the unit. It is also driven with a constant current, and shines upwards directly towards the sensor.

The light path towards the sensor itself, within the sensor head, consists of a diffuse material followed by a UV-IR cut filter. These help even out the light from the measurement target, and reduce the impact of any residual infrared light on the sensor readings.

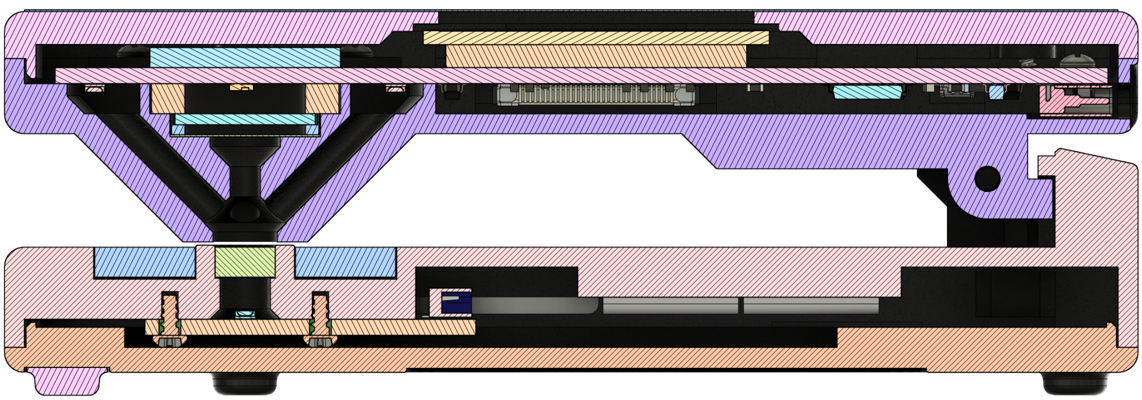

Fig. 8.2: Cross-section (side view)

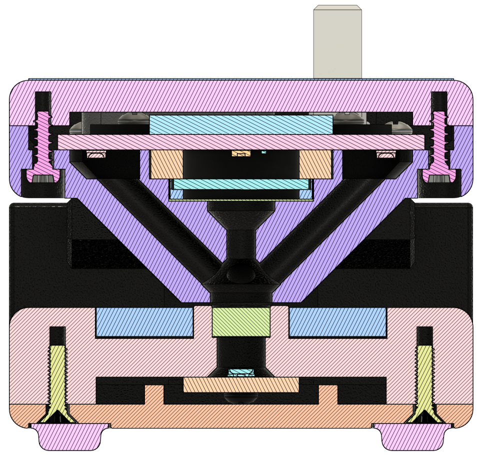

Fig. 8.3: Cross-section (sensor head)

8.4 Response Spectrum

The ISO specification for photographic density provides spectral conditions for each kind of density measurement. To reduce cost and increase ease of part sourcing, the sensor used in this device is an off-the-shelf component that was not designed with these conditions in mind. While it is close, it does not exactly match. That being said, when the response curve from the sensor's datasheet is combined with the transmission curve of the UV-IR cut filter, the combined sensitivity spectrum can be seen in Fig. 8.4.

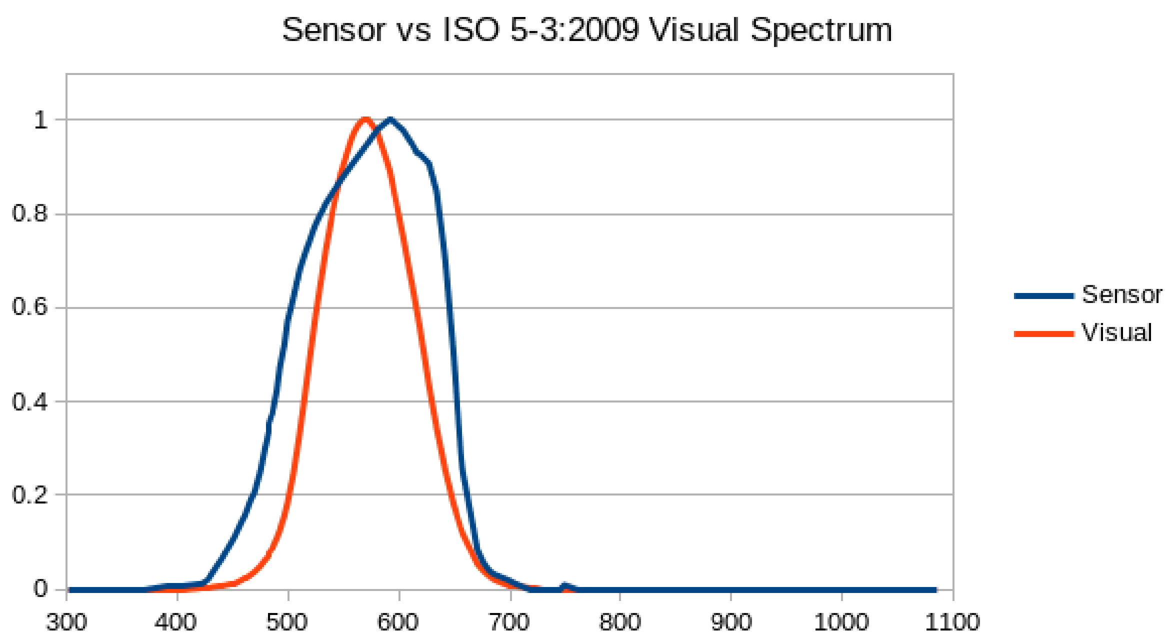

Fig. 8.4: Spectral response of the light sensor

It should be noted that because the sensor head's spectral response only approximates the ISO 5-3:2009 Visual Spectrum specification, and because modern LED-based light sources do not have the same full spectrum emissions as a tungsten lamp, the most consistent results will be achieved on normal black and white photographic materials. If the measurement target has a strong shift to the blue or red side of the light spectrum, results may no longer match up.

8.5 Temperature Performance

As part of pre-production device testing, the densitometer was subjected to a wide range of thermal conditions to determine their effect on density measurements. These tests consisted of a repeatable temperature ramp from 0°C through 45°C, and were conducted with a wide range of high and low density materials secured within the device's measurement target area. The readings were normalized around 25°C, and the measurement errors from the test can be seen in Fig. 8.5. The conclusion from these tests was that temperature has a very minimal effect across a reasonably large range.

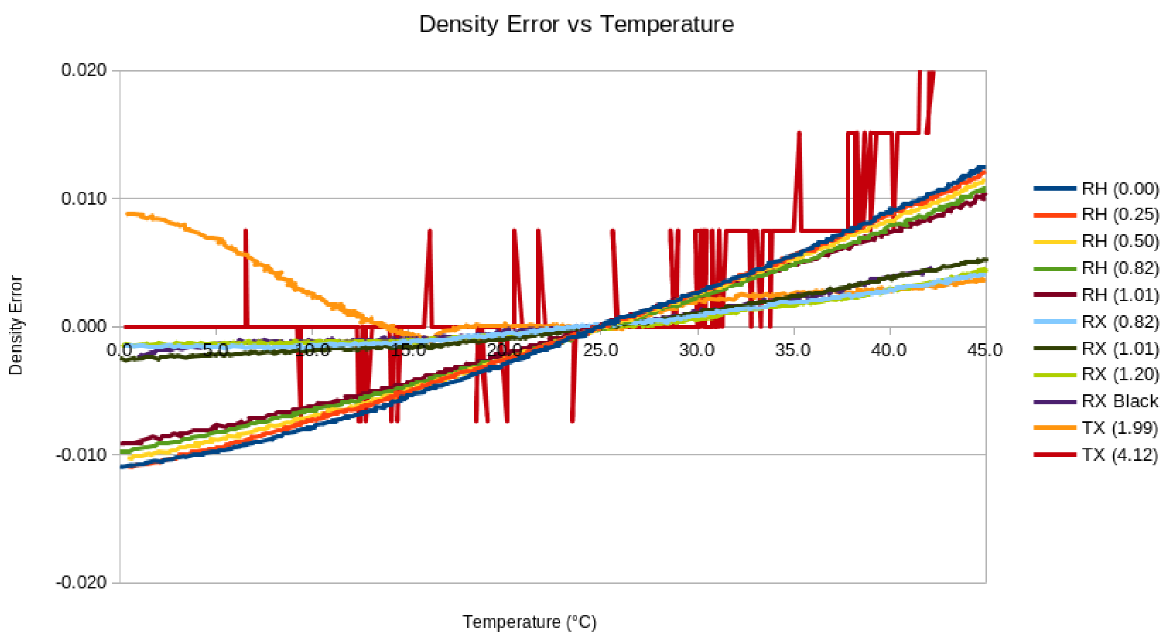

Fig. 8.5: Temperature sensitivity of density readings

It should be noted that the lines on this graph with the most jagged or inconsistent results were from high density transmission targets where the measurement resolution is relatively low. Due to the logarithmic nature of the scale, it would not be practical to increase the brightness of the light source by a large enough amount to compensate for this.