# ARIEL SPECTROMETER

**Rev. 3.5, October 2021**

ARIEL is astigmatism corrected F3 spectrometer using 80 mm unfolded Czerny Turner optical designs. It is a rugged spectrometer with all elements set in fixed positions. High acquisition speed, sensitivity and high optical quality, coupled with Gigabit LAN/USB 2 connection, extensive communication options make it well suited for R&D, OEM and industrial applications.

| Model | Wavelength range | Detector | Grating |
|---|---|---|---|
| ArielVis2000 | 380-1000nm | S11639-01 CMOS/2048 pixels | 400 g/mm |
| ArielUVis2000 | 200-1000nm | S11639-01 CMOS/2048 pixels | 300 g/mm dual-blazed |

**Table 1. Ariel Spectrometer Models**

| | |
|---|---|
| Wavelength range, nm | 380-1000 nm (Vis), 200-1000nm (UVis) |
| Wavelength resolution (with 20µm slit) | < 1nm |
| Dynamic range | ~5000 (typical) - single acquisition at 10ms [(1)] |
| Minimum integration time | 10 µs |
| Onboard data conditioning | Averaging, boxcar, nonlinearity correction, dark signal correction, fixed pattern noise correction |
| Nonlinearity | Residual non-linearity <0.5% |
| Data acquisition rate | 400Hz (typical) /1.5 kHz(max) |
| | |
| Optical system | Unfolded Czerny-Turner, fixed |
| Optical bench | 80 mm |
| Astigmatism correction | Torroid mirror |
| Input fiber connector | SMA 905 |
| | |
| ADC | 16 bits, 10 MHz |
| Communication | Gigabit LAN, USB 2 |
| Auxiliary port | 4xGPIO, I2C, 2xSPI, 4xPWM, 4xDAC, trigger, strobe |
| Power | 24 VDC |

**Table 2. ARIEL spectrometer basic specification**

[(1)] Dynamic range (DR) is determined as DR= ADC_range/rms_noise (ADC range is $2^{16}$=65535, rms_noise is a dark current noise). Dark current noise can be reduced significantly by signal averaging and boxcar averaging. Some boxcar averaging can be done without reduction of wavelength resolution (at least, 2 pixels averaging in 2048 detector ).

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**Fig. 2 Ariel spectrometer Footprint: 144mm x 130mm, Height: 55mm**

## SALIENT FEATURES

1. **Rugged design - fixed position of all elements.**
   Optical bench design for specific wavelength range and is not reconfigurable. No wavelength re-calibration needed.

2. **Unfolded Czerny-Turner design.**

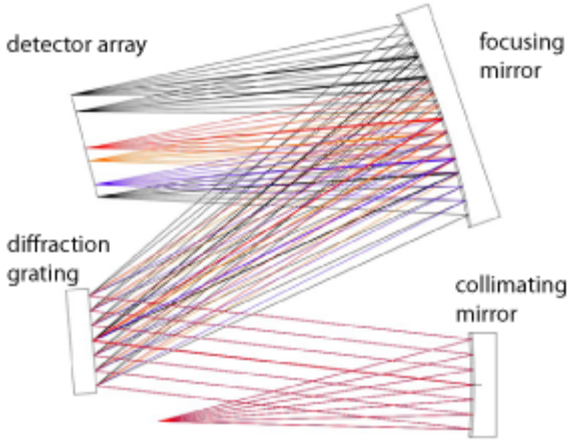


**Fig. 3 Optical design**

Unfolded design is used to reduce light scattering level by placing optical traps and buffers between the light paths. It is preferred for UV and Vis systems. Cross design, frequently used in commercial spectrometers, offer more compact mechanical packaging at the expense of some light scattering.

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### 3. Astigmatism corrected design using torroid mirror

Astigmatism is present in Czerny-Turner design due to oblique incidence of light on concave mirrors. Essentially, system has different focal lengths in saggital and tangential planes in case of oblique light incidence. Astigmatism means that a point at the entrance slit becomes a line at the image plane (on the detector). The end result is a loss of light because only part of the light reaches detector. Ariel uses torroid mirror to correct astigmatism. This approach does not introduce additional elements and has no adverse effect on light scattering, resolution or ruggedness of the spectrometer unlike other options (e.g. cylindrical lens). It also reduces other aberrations that effect resolution.

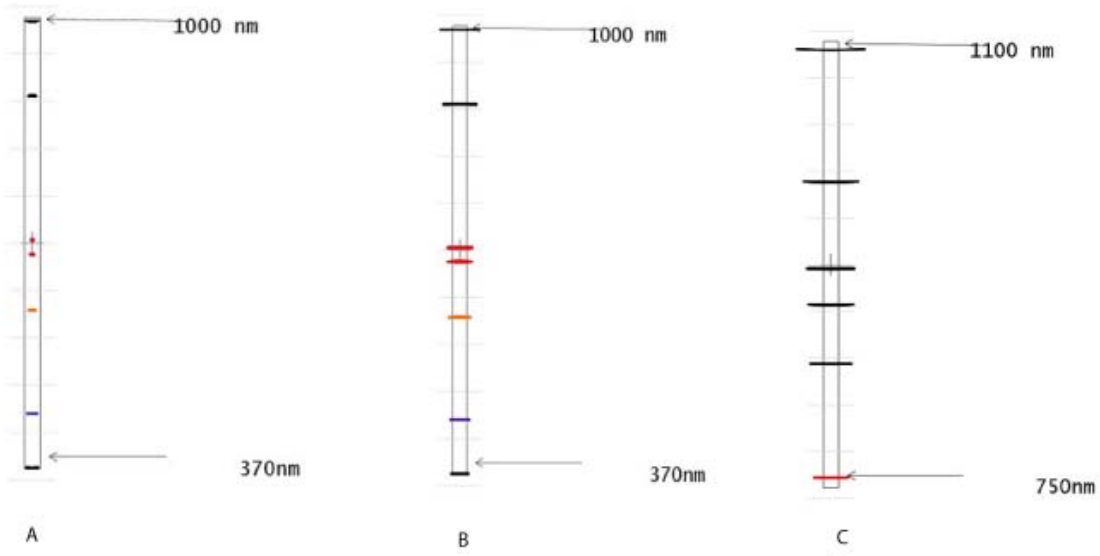


**Fig. 4 Image of entrance slit on detector plane**

**A.** Ariel spectrometer (astigmatism corrected), **B.** Same design without astigmatism correction. **C.** Design with 600 g/mm grating without astigmatism correction (equivalent of 40mm bench spectrometer with the same resolution)
Entrance slit 0.5mm height, image boundaries 0.5mm x 28.6mm (CMOS detector photosensitive area 0.2mm x28.6mm)

### 4. Gigabit LAN and USB 2 communication.

Well suited for industrial and desktop applications. LAN sustained measurement rate up to 1.5 kHz (with buffered spectra).

### 5. Aberration optimized design

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Optical design is optimized for low aberration and field flatness of all measured spectrum. The result is clean, symmetrical peaks in measured spectrum making spectrometer suitable for high quality spectroscopic measurements.

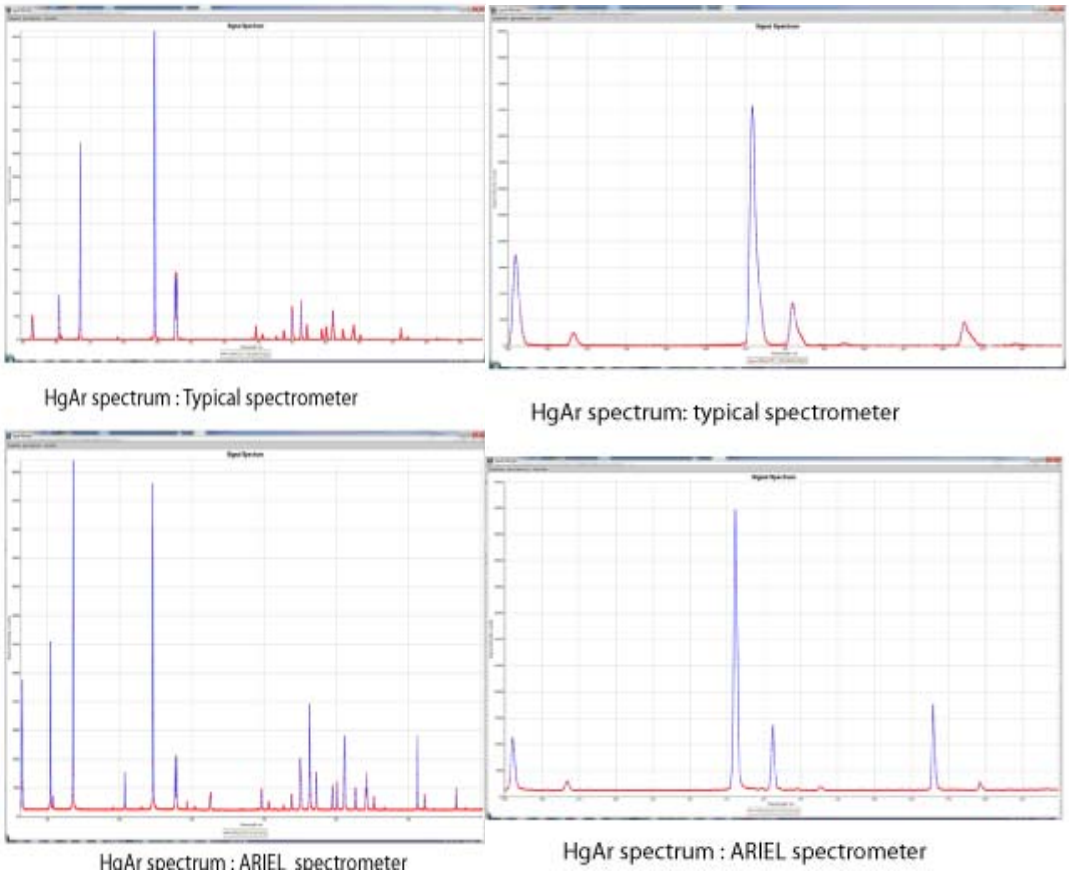


**Fig. 5 Comparison of HgAr spectrum measured with Ariel spectrometer and typical commercial spectrometer.** Ariel spectrometer shows more sensitivity at shorter and longer wavelengths making measured spectrum more uniform. Clean and symmetrical peaks as compared to distorted peaks of commercial spectrometer.

## 6. Onboard data conditioning

Data conditioning like averaging, boxcar, nonlinearity correction, dark signal correction, etc. are done in FPGA firmware. This means all spectrometer specific calibration data is stored in spectrometer flash memory and applied to signal correction.

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## INTERFACES FOR COMMAND AND CONTROL

**ARIEL** spectrometer has USB2 and LAN communication ports. Communication is working in request/ response (Modbus type) format. The same commands are used for USB and LAN communication.

### LAN/Ethernet port

By default, ARIEL spectrometer joins multicast group 239.239.239.238 , port 57356. Spectrometer will respond to discovery command sent to this address over UDP. This is used to find spectrometer on the network.

All control/communication commands should be sent over TCP, except discovery command that is send over UDP

The default IPv4 static settings are:

- IP Address: 192.168.1.88
- Subnet mask: 255.255.255.0
- Port: 7

Spectrometer can configured with DHCP client running. In this case, if DHCP server is available on the network, IPv4 address will be assigned automatically.
Configuration can be changed using either LAN or USB connection.

### USB

USB communication using FTDI FT2232 chip in FIFO-485 mode to achieve full USB 2 speed. Communication commands are the same as for LAN but they are sent in special package as described below

### POWER

ARIEL spectrometer is using 24VDC power. There are two power connectors: standard 2.1mm socket connector and TE 1586041-2 connector for OEM and industrial applications. These connectors can be used interchangeably.

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## AUXIALARY PORT

Ariel spectrometer has two auxiliary ports for communication with other devices: 34 pin main auxiliary port (AWHW 34A-0202-T connector) and 4 pin secondary port (Harting 14010413102000 connector). The secondary port is a wire terminal and it replicates PWM and GPIO signals of the main port for OEM convenience.

| PIN | ASSIGNEMENT | Purpose |
|---|---|---|
| 1 | VCC | 3.3 V |
| 2 | VCC | 3.3 V |
| 3 | GRD | Common ground |
| 4 | GRD | Common ground |
| 5 | Single Strobe | Output strobe synchronized with acquisition |
| 6 | Trigger | External TTL trigger |
| 7 | GPIO-1 | |
| 8 | GPIO-2 | |
| 9 | GPIO-3 | |
| 10 | GPIO-4 | |
| 11 | PWM(1) | |
| 12 | PWM(2) | |
| 13 | PWM(3) | |
| 14 | PWM(4) | |
| 15 | MOSI (SPI_0) | Two SPI channels |
| 16 | MISO (SPI_0) | |
| 17 | CLK (SPI_0) | |
| 18 | CS (SPI_0) | |
| 19 | MOSI (SPI_1) | |
| 20 | MISO (SPI_1) | |
| 21 | CLK (SPI_1) | |
| 22 | CS(SPI_1) | |
| 23 | SDA | I2C |
| 24 | SCL | I2C |
| 25 | DAC-CLC | 4 SPI output channels |
| 26 | DAC-DIN | Can be used with optional |
| 27 | DAC-OUT | DAC board for |
| 28 | DAC-CS1 | Analog output of the |
| 29 | DAC-CS2 | Measurement results |
| 30 | DAC-CS3 | |
| 31 | DAC-CS4 | |
| 32 | GRD | |
| 33 | GRD | |
| 34 | VAUX | 3.3/5V depending on the jumper setting |

**Table 3. AUX PORT pins assignment** (AWHW 34A-0202-T connector)

| PIN | ASSIGNEMENT | Purpose |
|---|---|---|
| 1 | PWM | PWM(1) pin 11 AUX |
| 2 | GND | |
| 3 | GPIO | GPIO-1 pin 7 AUX |
| 4 | GND | |

**Table 4. AUX 2 PORT pins assignment (**Harting 14010413102000 connector**)**

## COMMUNICATION COMMANDS

Following commands can be used for communication via TCP IP or USB connection.
Conventions:
a) All request commands are started with the "/"
b). Big endian convention
c). Responses are not terminated
d). Request commands have standard termination \r\n
There are two types of the requests and two types of the responses: WriteRequest and ReadRequest, WriteResponse and ReadResponse
The purpose of the Write Request is to write the data to the firmware, the matching WriteResponse is send back to confirm success of failure of the operation.
The purpose of the ReadRequest is to read the data from the firmware/spectrometer, matching ReadResponse sends back requested data or error code in case of the failure.
The general structure of :
Response to ReadRequest: /Operation code[1 byte]number_of_bytes_in_message[2 bytes]message
Response to WriteRequest: /Operation code[1 byte]Success-Error_code[1byte]
Response to ReadRequest: /Operation code[1 byte]num_bytes[2byte] data
WriteRequest: /OperationCode[1 byte] {num_bytes}data
ReadRequest / OperationCode[1 byte] Instructions

WriteResponse return 0 if success, 1 or error code (<0) if failed.

| Operation code | Purpose | Request (terminated \r\n) | Details | Response |
|---|---|---|---|---|
| 0 | Read Firmware version | /0 | | /0[num_bytes] [message]<br>Message example: Rev.1.0,09/01/2013 |
| 1 | Write parameters to flash (basic info) | /1num_bytes [2 bytes] index[1 byte] data | Index- is always 0 for basic information. Other data see function id= 97 | /10 – success<br>/11 – failure |
| 2. | Read parameters from flash (basic info) | /2 index [1 byte] num_bytes_read [2 bytes] | index always 0,<br>num_bytes_ read (unsigned short) – number of byte to read<br>Other data see function id= 98 | /2 num_bytes[2 byte] data<br>/2E<br>E-error code (<0) |
| 3. | Write integration time | /3 value[4 byte (long)] | Integration time in µs | /30 – success<br>/31 - failed |
| 4. | Read Integration time | /4 | | /4value(4 bytes)<br>/4[-1000] |
| 5 | Write dark current correction | /50 – no correction<br>/51 – enable correction | | /50 – success |
| 6 | Read dark current correction status | /6 | | /60 – no correction<br>/61 enabled |
| 7 | Write boxcar averaging | /75 – enable 5 pixels smoothing<br>/70 – disable smoothing<br>1 byte | | /70 success<br>/71 failure. |
| 8. | Read boxcar averaging | /8 | | /8[num_pixels]<br>/85 – 5 pixels averaging |

| | | | | |
|---|---|---|---|---|
| 9. | Write signal averaging | /9[num_ave] | Num_ave [1 byte] – number of averages<br>/90 – no averages<br>/910 – 10 averages | /90 – averaging set successfully<br>/91-error |
| 10. | Read current averaging status | /10 | | /100 – no averaging<br>/1010- 10 averages |
| 11. | Write Stop measurement | /11 | Stop the current measurement | /110 – measurement stopped |
| 12. | Read spectrum | /12[pix_start][num Pix] | Read spectrum data (numPix) from pix_start<br>/12203000<br>Read 3000 pixels starting with pixel 20 | /12[num_bytes][data]<br>Num_bytes – 2 bytes(the length of the message)<br>Each pixel 4 bytes fixed-point float<br>/[1 byte] [2 bytes][4n bytes] |
| 13 | Erase flash sector | /13 | Erase flash sector with properties data | /130 –success<br>/131 -failure |
| 14 | Write non-linearity correction | /14 [1 byte] | 1-enable correction;<br>0 –disable correction | /140 – success<br>/141 - failure |
| 15 | Read non-linearity correction status | /15 | | /150 –enabled<br>/151 -disabled |
| 16 reserved | | | | |
| 17 | Aux write Write I2C | /17[address][num bytes]<br>[2 bytes][2 bytes] | | /170 success<br>/171 failure |
| 18 | Aux I/O Read I2C | /18[address][num bytes]<br>[2 bytes][2 bytes] | address 2 bytes (support 7 bit and 10 bit address) | /18[num bytes][message]<br><br>/181 - failure |
| 19 | Aux I/O Write data via SPI | /19[num_bytes][1 byte address][value] | Address – SPI channel | /190 – success<br>/191 – failure |

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| | | | | |
|---|---|---|---|---|
| 20 | Aux I/O<br>Read data via SPI | /20[address][num_bytes]<br>/[1 byte][1 byte][1 byte] | Num_bytes – number of bytes to read | /20[num_bytes][data]<br>/[1 byte][1 byte][n bytes]<br>/20[1][1] |
| 21 | Aux I/O<br>Write PWM | /21[channel][freq][duty_c]<br>/21[1 byte][2 bytes][1b byte] | | /210- success<br>/211 - failed |
| 22 | Aux I/O<br>Read PWM | /22[channel] | | /22[freq][duty_c][status]<br>Status 1 – enabled<br>Status 0 - disabled |
| | | | | |
| 24 | Aux I/O<br>Set GPIO direction | /24[bitmask] | bit_mask – control GPIO channels<br>1 – means in<br>0 – means out | /240 –success<br>/241 - failed |
| 25 | Aux I/O<br><br>Write GPIO | /25[bit_mask:1 byte][ value 1 byte] | bit_mask – control 8 GPIO channels<br>byte: 10000000 – channel 1 on<br>01000000 – channel 2 on<br>Value: 0 –off, Value 1-on | /250 – success<br>/251- failed<br><br>If attempt to write value to IN grio 0 failure response |
| 26 | Aux I/O<br><br>Read GPIO | /26 | | /26 [bitmask_values][direction_bitmask] |

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| | | | | |
|---|---|---|---|---|
| 27. | Write trigger | /27[trigger_type][delay]<br>/27[1 byte][2 byte] | Trigger type:<br>0: Normal (free running),<br>1:Software,<br>2:External TTL<br>Delay – in µs (between trigger and detector integration)<br>2 bytes -short | /270-success<br>/271-failed |
| 28 | Read trigger | /28 | | /28[trigger type][delay]<br>/28E<br>E- error code <0 |
| 29,30 reserved | | | | |
| 31 | Write parameters | /31[2 byte][4 byte][1 byte][1 byte][1 byte] [1 byte]<br><br>[length][int time][boxcar][num avg][nl corr][ dark] | Convenience function combines: integration time, boxcar smoothing pix,averages, NL correction and dark correction in one call | /31 0 – success<br>/31 1- failed |
| 32 | Read parameters | /32 | Read integration time, averages, NL correction and dark correction in one call | /32 [2 byte][4 byte][1 byte][1 byte][1 byte] [1 byte]<br><br>[length][int time][boxcar avg][num avg][nl corr][ dark] |
| 40 | Aux I/O<br><br>Write SPI (for DAC output) | /40[num_bytes][address] [ value] | [ 1 byte1[1 byte][2 bytes]<br>Value - unsigned short, 2 bytes | /400 – success<br>/401 – failure |
| 50 | Change static IP | /50[ip_address][,][port][,][gateway] | /50[ 36 bytes] (empty space is | /500 –success<br>/501 – failure |

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| | | | | |
|---|---|---|---|---|
| | (writing new IP parameters to flash) | Example: /50192.168.1.10,7,192.168.1.10x2A….0x2A | padded with 0x2A)<br><br>Requires reboot | |
| 51 | Enable DHCP | /51[gateway_ip*]<br>Example: /5192.168.1.1000x2A0x2A | [15 byte] padded with 0x2A<br><br>Requires reboot | /510 –success<br>/511 – failure |
| 52 | DHCP status request | /52 | | /521 – enabled<br>/520 - disabled |
| | | | | |
| 60 | Set single strobe (Note 4) | /60[enable/disable][pulse width µs][delay µs][up/down][before/after] | /60[1 byte][2 bytes][2 bytes][1 byte][1 byte]<br>2 byte value shorts<br>0 – up, 1 – down, 0 – after, 1 – before acquisition start | /600 – success<br>/601- failed |
| 61 | Get single strobe | /61 | | /61[enable/disable][pulse width µs][delay µs][up/down][before_after]<br>Same as /60 request |
| 62 | Set measurement frequency | /62[ frequency Hz]<br>Sets continuous data acquisition with specified frequency<br>Frequency is int, no fractions. | /61[2 bytes]<br>2 byte is short<br>Frequency= 0 – means it is disabled. | /620 –success<br>/621 – failed<br>This command requires Software trigger ON (otherwise it is in a wait mode) |
| 63 | Get Measurement frequency | /63 | | /62[2 bytes]<br>2 bytes - frequency |
| 70 | Read Temperature | /70<br>Returns 4 byte: temperature of the detector and temperature of the body/heatsink | Note 5 | /70[2 byte][2 byte]<br>(/70[detector][body]) |
| 71 | Set sensitivity | /71 [1 byte] | | /710 –success |

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| | | | | |
|---|---|---|---|---|
| | (NIR detector) | 0 – HDR (high-dynamic range mode)<br>1-HS (high sensitivity mode) | | /711 – failed |
| 72 | Get sensitivity mode | /72 | | /720 – HDR mode<br>/721 –HS mode |
| 73 | Enable TEC (Note 5) | /73 [1 byte] | 1 –enable<br>0-disable | |
| 74 | Get TEC status | /74 | | /740 –disabled<br>/741 –enabled |
| 75 | Set Detector temperature | /75[1 byte] | | /750 –success<br>/751 - failed |
| 76 | Stop Measurement | /76 | Terminates signal acquisition process | /760 – success<br>/761 failure |
| | | Reserved | | |
| 80 | Set ADC range | /80 [1 byte] | 0 – default range (4V)<br>1 – short range (2V) | /80 0 success<br>/80 1 failed/ not supported |
| 81 | Get ADC range | /81 | | /80 0 – default range<br>/80 1 – 2V range<br>/80 E (E<0) – not supported |
| 82 | Set gain | /82 [4 byte] | 4 byte fixed point float (FF) | /82 0 – success<br>/82 1 failed |
| 83 | Get gain | /83 | | /83 [4 bytes] – FF value |
| 84 | Set offset | /84 [2 byte] | 2 bytes - short | /84 0 – success<br>/84 1 failed |
| 85 | Get offset | /85 | | /85 [2 bytes] – short |
| 90 | Write dark Calibration data | /90 length[2 bytes][n- bytes - floats] | | /900 success<br>/901 - failed |
| 91 | Read dark calibration data | /91 | | /91 length[2 bytes] data[] |
| 92 | Write structured noise correction(SNC) | /92 length[2 bytes][n- bytes - floats] | | /920 success<br>/921 - failed |
| 93 | Read SNC | /93 | | /93 length[2 bytes] data[] |
| 97 | Write calibration to flash | N/A | | **Only factory use .** |

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| | | | | |
|---|---|---|---|---|
| 98 | Read Calibration from flash | /98 num_data_bytes [2 bytes]<br>page[2 bytes] | | /98 num_data_bytes [2 bytes]<br>data[]<br><br>If failed:<br>/98 E<br>E-error code (<0) |
| 99 | Backup | N/A | Backup IP settings and basic settings to save area in flash | **Only factory use.**<br>This data is used for emergency reset when reset button on FPGA is pressed. |
| 100 | IP reset | /100<br>Reset IP to the default value | | /1000 – success<br>/1001 - failed |
| 101 | Multicast UDP | /101 | The message to find spectrometer | Response: /101[2 bytes length] SerialNumber<br>Note 1. |

**Table 4. Spectrometer commands.**

**NOTE 1.** Command 101 (0x65) is a UDP transmission send to group 239.239.239.238 and port 57356
Expected response is Serial Number of spectrometer ( IP address is embedded in the packet automatically)

**NOTE 2**
Fixed float notation.

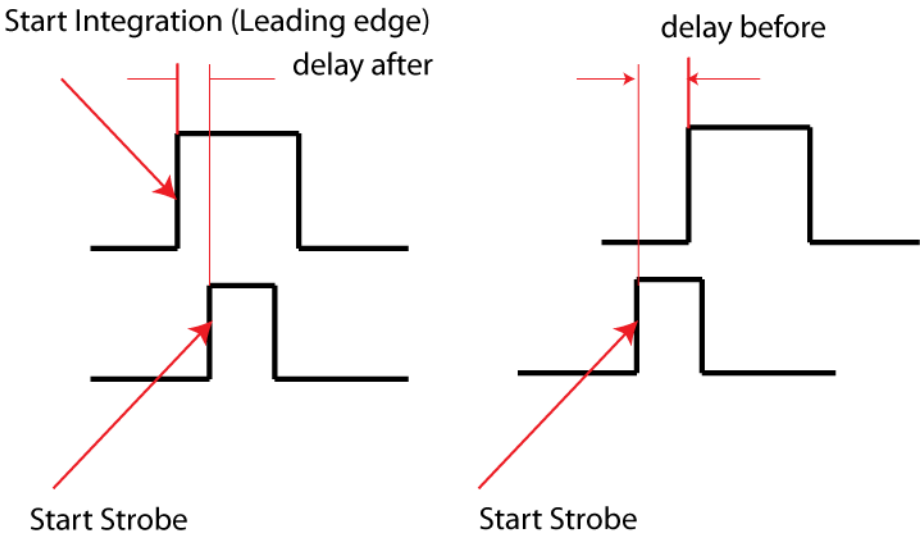
FF is 4 byte: 2 bytes (unsigned short) – before decimal point, 2 bytes (unsigned short) – after decimal point
X(.)Y is transmitted as 2 unsigned shorts: xy
where
x=X – 2 bytes . y=Y/2^16 – 2 bytes

**NOTE 3**
DHCP enable/disable

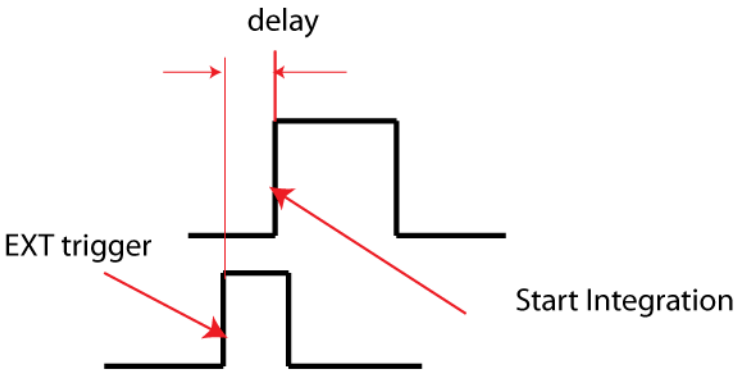
Sending command 50 (change static IP) automatically disables DHCP.
Sending command 51 (enable DHCP ) enables DHCP and sets DHCP server address (typically Gateway ip)

FPGA will need to be powered down and rebooted for changes to take effect after commands 50 and 51

**NOTE 4**




STROBE with software Trigger




EXTERNAL trigger

**Single strobe**

It is generated during each integration cycle and available on the AUX port pin. It is used to synchronize measurement with external device (like flash light, etc.). "Up" pulse means level normally low – pulse is raising 0->5V, down pulse means level normally high – pulse drops to 5V->0.
The strobe can be generated before or after the acquisition started.
This command is used together with **Software trigger.**
Normal sequence is to set Strobe, Set measurement frequency and use Sofware trigger to

Normal sequence is to set Strobe, Set measurement frequency and use Sofware trigger to enable/disable action.

| Command | Software Trigger | Single Strobe | Activate Strobe |
|---|---|---|---|
| Software Trigger | X | X | Yes |
| Single Strobe | -- | X | No |
| Single Strobe | X | - | No |

**Table 5.** Single Strobe logic (truth table)

**TRIGGER MODE.**
**Type 0** – default. Free running – no trigger. Signal integration and data readout is done continuously. Frequency is determined by the integration time+ readout time.

**Type 1** – software trigger. Acquisition stops and waiting for software request or "Set measurement frequency" activated.
a. Measurement frequency is set – acquisition proceeds with the specified frequency (internally generated). When measurement request arrived – fresh available measured spectrum is returned.
b. Measurement frequency is not set.
Measurement request – initialize one acquisition cycle and measured spectrum is returned. Acquisition is on hold until next request/

**Type 2** - data acquisition is on hold: waiting for the external trigger. After trigger arrives, one acquisition cycle is preformed. The cycle is triggered by the leading front of the pulse (0-5V rise).

**NOTE 5.**
For NIR detector, firmware should set following default value at startup:
TEC enabled, target temperature: – 5C

**NOTE 6.**

Temperature format. Temperature is returned as signed short (2 bytes). T – returned value, t- measured temperature deg. C. T=100*t;
If measured temperature t=5.23 deg. The returned value is 100*t= 523. (Client software will convert the value back to 5.23)

**USB communication.**

USB communication uses the commands as TCP but, in addition, communication is done using packets.

Encoding protocol isusing bulk transfer of the USB data. Current implementation is for FTDI synchronous FIFO mode. USB controller sends data in packets that are grouped in frames. Each data packet has a structure described in Tab. 1 This document describes encoding of the data field only.

Complete packet and additional required data fields are generated by the USB controller and do not require application program attention.

| Field | SYNC | PID | **DATA*** | CRC16 | EOP |
|---|---|---|---|---|---|
| #bits | 32 | 8 | **0-4096** | 16 | 3 |

* 4 bytes are reserved for FTDI status, etc., so only 508 bytes of the application data can be sent

**Table 6. Structure of USB transmission packet**

Maximum length of transmitted packet up to 508. The length should a multiple of 4. (non-complaint message should be padded with 0 to have the length multiple of 4).

| Name | Offset(bytes) | Length (bytes) | Comments |
|---|---|---|---|
| Start bytes | 0 | 2 | 0xA1 (offset 0).0xA0 (offset 1) |
| Protocol version | 2 | 1 | Current protocol =1 |
| Number of packets* | 3 | 1 | Number of packets in the transmission. |
| Function # | 4 | 1 | The command function number |
| Sequence # | 5 | 1 | Sequential Packet #, starts with 0 |
| Message length | 6 | 2 | The length of the following byte message. represented with short (2 bytes) |
| Payload | 8 | 500 | The message itself (same as TCP) |

**Table 7. Data field of the packet (see table 5) for USB communication**.

Payload is the command as determined by TCP command protocol, only broken in 500 byte chunks when needed.

- For example, measured data from 2048 pixels is 8192 bytes length (2048x 4)
  It requires 17 packets.
  Total payload: 8196 (2 bytes – the length of the data, 2 bytes to have a multiple of 4)
  16 packets – 500 bytes payload, 17$^{th}$ packet – 196 bytes payload).
  Total transmitted bytes (including headers): 508x16+(196+8) = 8332

**SOFTWARE INTEGRATION.**

There are several software integration options:

- Direct communication using commands in Table 4. This is especially easy in case of TCP communication - standard TCP socket communication can be used. There is no any drivers and operating system dependency. USB communication required the use of FTDI driver.
- SpectrometerClient software supplied with spectrometer and can be used to do basic function of data acquisition, data display and interface with AUX port. SpectrometerClient library has a public interface that can be used by external software as an SDK to communicate with spectrometer.
- TFCompanion software (available separately) can be used for Reflectance/ Transmittance and thickness, n&k measurement.