Cosmic Pi Hardware Manual

Version 1.0

19/1/16

This document gives an explanation of the functional principles behind the hardware in the Cosmic Pi enclosure. It is divided into two parts, one for each of the circuit boards. It is presented at this stage in draft format and will be improved over the coming days and weeks! Additional details regarding the casing, assembly and disassembly and anything else we can think of that is relevant will be added in the near future. The accompanying design files (PDF schematics and EagleCad versions) can be found here.

Analogue Board

Note: This section of the document refers to the Cosmic Pi Analogue Board V2.3

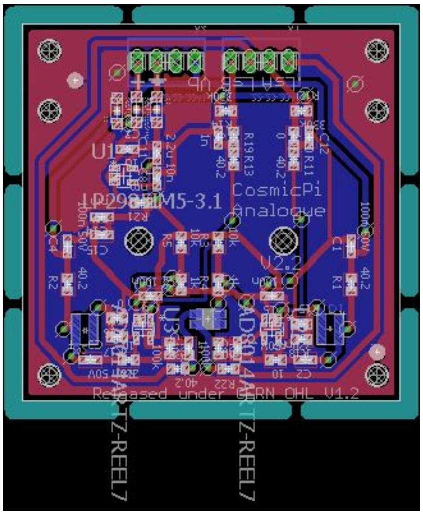


Figure 1: Analogue Board Version 2.2 (2.3 is the same just with 0806 LEDs)

The function of the analogue board is to accommodate two Silicon Photo-Multiplier (SiPM) sensors, which are close coupled to the scintillator material, and provide the necessary amplification and signal shaping to permit readout by the Analogue to Digital Converters located within the SAM3X microprocessor. The key design criteria driving the design for this circuit board are:

- Physical compatibility with mounting to the scintillator slab
- Modular structure, integrating all analogue parts so that the output signals are ready for digitisation
- Low noise, due to separation from other components.

At a functional level, the following functions are provided by the circuit board:

- Dedicated 4V supply rail derived from 5V input (to minimise noise)
- Ferrites to reduce noise transmitted from the Main Board.
- Two independent channels of amplification and signal shaping (one for each SiPM)
- LEDs to allow light injection into the scintillator at two wavelengths.

The PCB is two sided and measures 50 mm by 50 mm by 1.6 mm, to minimise production costs. On the underside of the board, the connector to the Main Board is mounted, together with the three optical components (Two SiPM's and one LED). The SiPM's are Advansid 3 mm x 3 mm Near Ultra-Violet arrays, with a height of 2 mm. The LEDs are 0806 packages with a heigh of less than 1.9 mm to prevent disruption to the SiPM/scintillator physical interface. The SiPM's are not bonded to the scintillator, but joined using a transparent optical grease. They could also be bonded using a transparent epoxy resin (Aryldite tm or equivalent), but we decided not to do this as it makes the attachment permanent. The Analogue Board can be tested as a unit and replaced with an alternative design in the future without impacting the rest of the Cosmic Pi design. Motivations for this choice include:

- Selection of larger or alternative scintillator materials
- Alternative physical configurations (instead of the PCB-Scintillator-PCB sandwich)
- Change of SiPM vendor
- Design of sensor based on alternative technology (APD, GM tubes, RPC, etc).

Connectors

The connector to the Main Board provides sufficient height clearance for the 10mm thick scintillator to be sandwiched and mechanically secured using cable ties. Additional nylon bolts are used to maintain the Analogue Board and scintillator in position. In the future we might review this attachment method to allow for a thicker scintillator.

The physical connectors circuit on the analogue board is shown in Figure 2, where the connection is made to the Main Board.

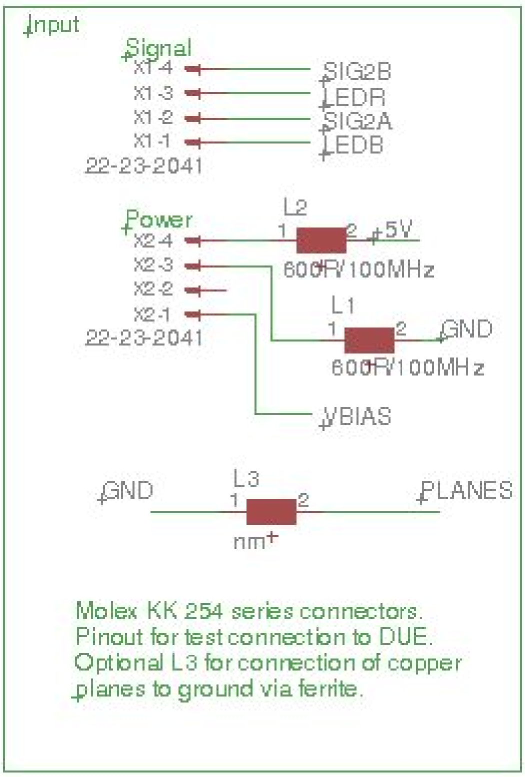


Figure 2: Input and Output connections from the Analogue Board

Two connectors are used to allow for the offset between the power and analogue input pins on the standard Arduino board (UNO and DUE). This allows the pins to be mounted in reverse (to the top side of the board) and direct insertion into an Arduino for testing or other experiential activities. Note that in this configuration the Vbias line (X2-1) should not be connected to Vin from the Arduino, as applied voltages in excess of 9V may cause damage. This configuration has been useful during development, however in future a single 7 or 8 pin connector may be more cost effective.

The X1 and X2 connectors use a standard 2.54mm pitch header, primarily for compatibility with Arduino and standard cables. Whilst the Molex KK 254 male pins include an additional mechanical support, the use of any 2.54mm pitch header pins should provide adequate performance, provided they are long enough to make a good connection with the Main Board.

Two ferrites are used on the 5V and GND connection lines to provide high impedance paths for high frequency signals either entering or leaving the Analogue Board. A third optional ferrite can be used to link the GND with the copper planes on both sides of the PCB. Again, the purpose of making this connection using a ferrite is to discourage high frequency noise being picked up by the plane and appearing on the signal lines.

SiPM Bias

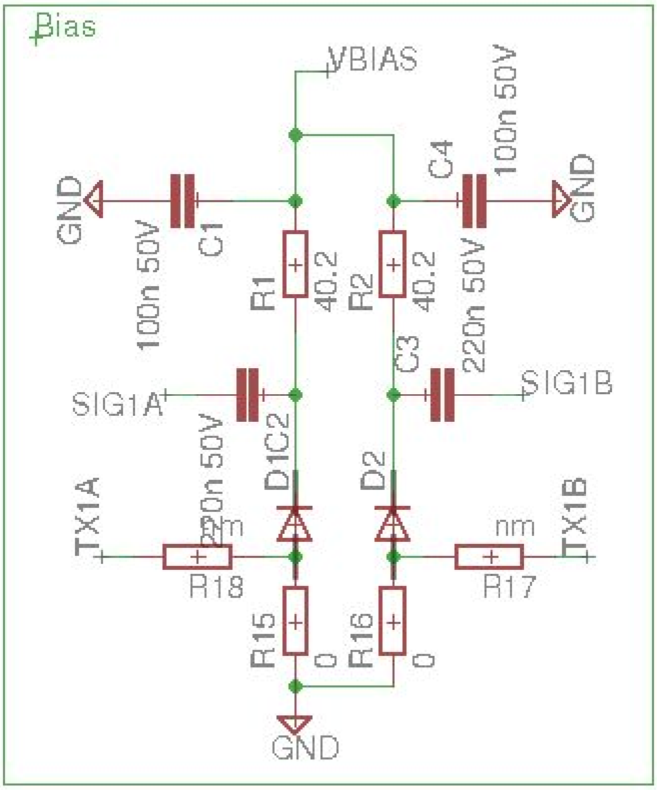


Figure 3: Bias configuration for SiPMs

The Vbias pin of the X2 connector supplies the bias voltage for both SiPM sensor devices. The common voltage is connected to an individual bias network for each SiPM to reduce cross talk. Capacitors C1 and C4 are inserted to prevent crosstalk by sourcing high frequency current during detection events. R1 and R2 provide current limiting, which may cause damage to the SiPMs if they are exposed to significant quantities of light (daylight or artificial) when under nominal voltage bias. The raw signal is decoupled and extracted via C2 and C3 two the two independent amplifier/shaper circuits. Resistors R15, R16, R17 and R18 are present to allow modification of the Analogue Board into a transimpedance configuration without changing the PCB layout. A transimpedance configuration may provide significant improvements in overall performance, however due to the adequate functioning of the circuit in voltage mode this has not yet been explored. We have some spare analogue boards from prototyping, if you would like to experiment with an unpopulated one please contact us.

The typical performance parameters of the input stage are:

- SiPM Bias voltage 30-32 V
- Signal magnitude (1 photo electron) 34 mV

● Signal duration – rise time: 5 ns – fall time: 35 ns

Alternative SiPMs may be used, however the PCB footprint must be adapted to suit the manufacturer. Use of three terminal SiPM's with a 'fast output' pin has not been considered. If alternative SiPMs are to be used, the bias voltage and temperature coefficients required must be carefully considered. The Main Board is designed to source a maximum of 39 V, with limitation via a zener diode. Should SiPM's with a bias voltage requirement equal to or exceeding 39V the diode should be replaced or omitted and the Vbias power supply module on the main board may also require adjustment. The device firmware should also be adapted to take into account any changes in the temperature coefficient of new SiPMs.

4V Power Supply

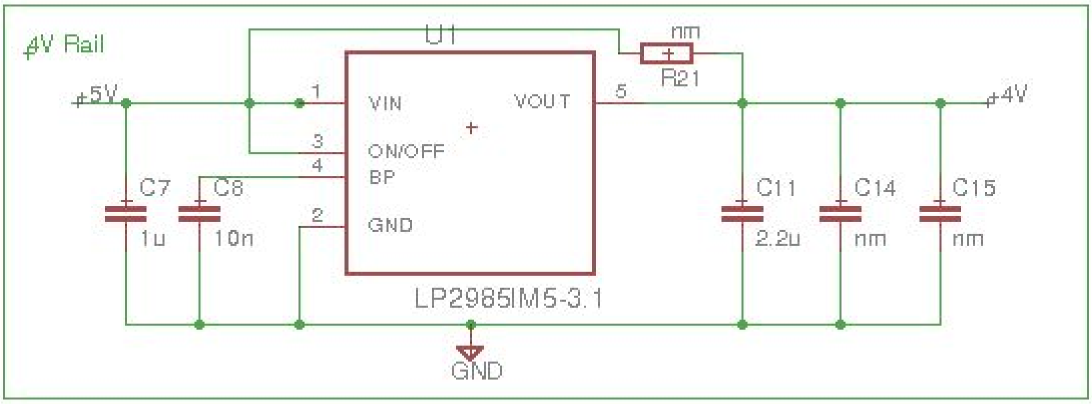


Figure 4: 4V power supply

A dedicated voltage rail is provided to supply the amplification stage. This is to minimise transmitted noise from the 5 V rail, which is drawn from the USB supply to the Arduino DUE. The advantages of having a dedicated supply are somewhat offset by the fact that the amplifiers (AD8014) require a minimum of 4.5 V to operate within their nominal parameters as listed on the data sheet. Based upon testing, the 0.5 V difference in supply voltage does not have a significant effect on the amplifier operation. A shunt resistor, R21, and two additional 0603 capacitor footprints, C14 and C15, are provided as an alternative to mounting the 4V low drop out regulator (LP2985).

Amplification and Shaping

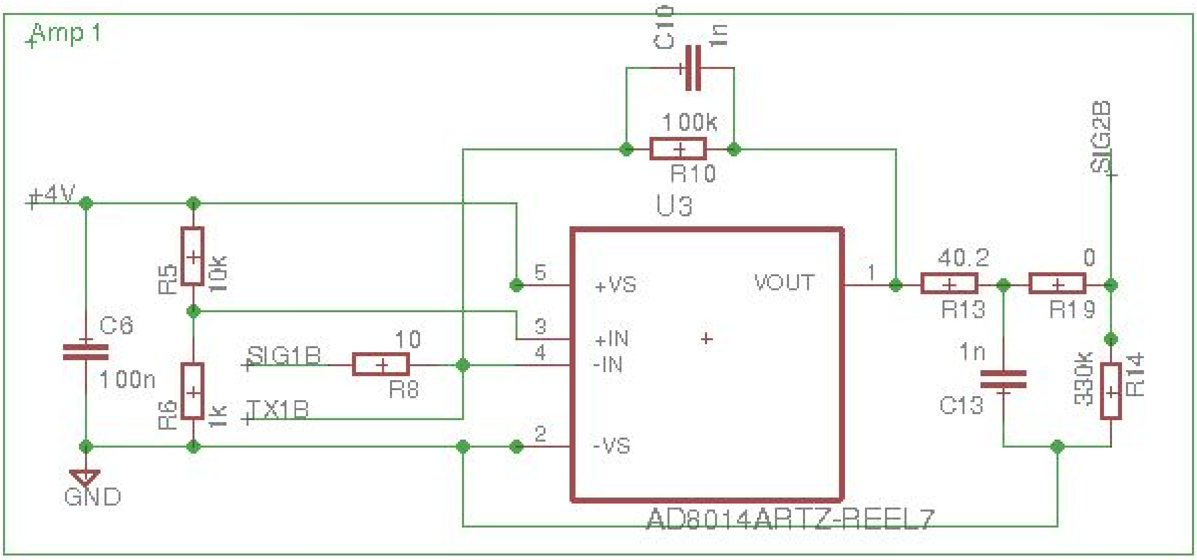


Figure 5: Amplification and shaping stage

Two single amplifier AD8014 SOT-23 footprint operational amplifiers are present on the top side of the Analogue Board. The circuit for the first amplification channel is shown in Figure 5 and includes the second input TX1B, used in a transimpedance configuration to avoid the need for a change of R8 to a 0 Ohm resistor. The AD8014 is supplied from the 4V rail and has a bias applied to the non-inverting input. An integrator is included in the amplifier feedback loop to stretch the signal from the SiPM, which is complemented with a zero pole in the output to prevent saturation.

FIGURE 6 – SPICE PERFORMANCE MODEL - to be added

The amplification stage has been modeled in LTSpice and observed performance is in good agreement with the predicted results. The LTSpice model is included in the open hardware distribution files for the Analogue Board.

Whilst the AD8014 amplifier exists in a dual package, individual amplifiers were selected to minimise cross-talk. There are a number of possible alternative amplifiers with an identical SOT-23 footprint, however the AD8014 was selected due to it’s high performance and a good price/performance trade off. The amplification stage for the second SiPM channel is identical to Figure 5.

LEDs for light injection

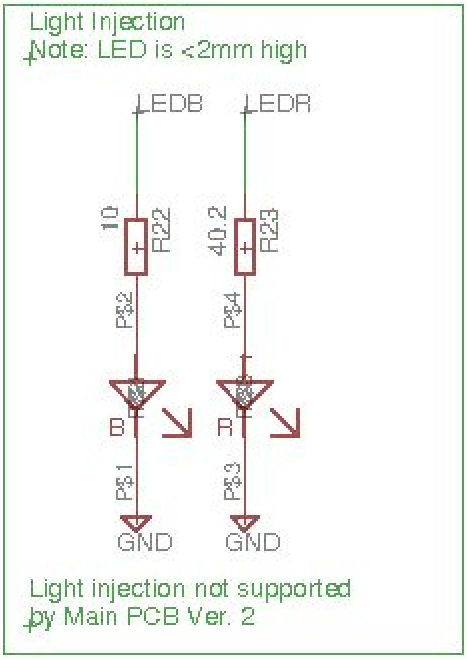


Figure 7: LEDs for Light Injection

After initial prototyping, it was decided to include an LED for light injection into the scintillator slab. Unfortunately the Main Board Version 2 alpha had already been manufactured at the time of this decision, so use of the LEDs will not be supported in the initial hardware. However, the LED selected for the initial production was too tall, hence the analogue board has been redeisgned to include 0806 footprints for two separate LEDs. These may be used during dedicated production testing of the Analogue Board, and provide an interesting opportunity for future revisions of the Main Board. The LEDs may be pulsed from the Arduino or production test sytem, with the light inside the scintillator measured directly by both of the SiPMs. This allows the light generated by cosmic rays to be easily simulated, which can be used to test both the optical coupling of each SiPM to the slab, overall operation of each SiPM and the associated amplification channel and the timing performance of the system, since the timing and duration of light injection can be precisely controlled. It is envisaged that the LEDs will be operated in digital mode, with modulation focused on pulse frequency and duration, rather than instantaneous intensity via modulation of the applied voltage using the Arduino DUE DAC channels.

For the avoidance of doubt, the LEDs are not a necessary functional element of the Analogue Board, but merely serve to facilitate testing and performance evaluation.

They may be omitted (due to cost or availability constraints) with no detriment to the detector performance.

Mechanical and general assembly elements

Four fiducial points are provided on the Analogue Board PCB, two on the top side and two on the bottom side.

Six 2.8mm holes are provided at the edges of the PCB for mechanical attachment, 4 of which are positioned to be used when coupled to a 65 mm x 65 mm x 10 mm slab. Two additional 3.5 mm holes are provided to allow mechanical fixing direct to the slab in addition to adhesive attachment, however this are not used in Cosmic Pi production or prototype units.

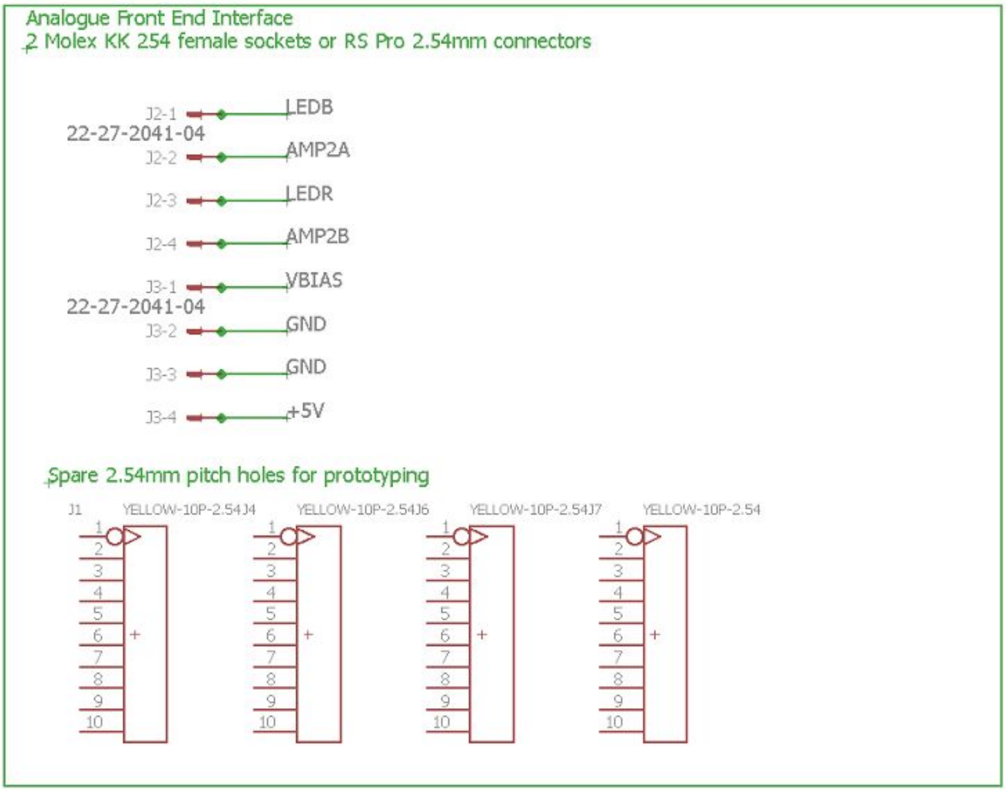
Future modifications currently being considered for the Analogue Board include:

- Additional connector holes for pre-mounted SiPMs to allow hand-soldering of all components.
- Direct integration of all components onto the Main Board to allow the scintillator to be mated directly.
- Designs using SiPMs from different vendors (Sensl or Hammamatsu).
- Single channel operation to reduce costs.
- Connection to significantly larger scintillator slabs for testing and calibration purposes.
- Possible edge connection to scintillator slabs.

Main Board

This part of the guide covers the technical design of the Main Board for the Cosmic Pi. This guide is based on Main Board versions 2 Alpha and schematics/PCB layout for version 2.1. These boards are found in Cosmic Pi units in the Version 1 batch produced for the 2016 CERN Beamlines for Schools Competition.

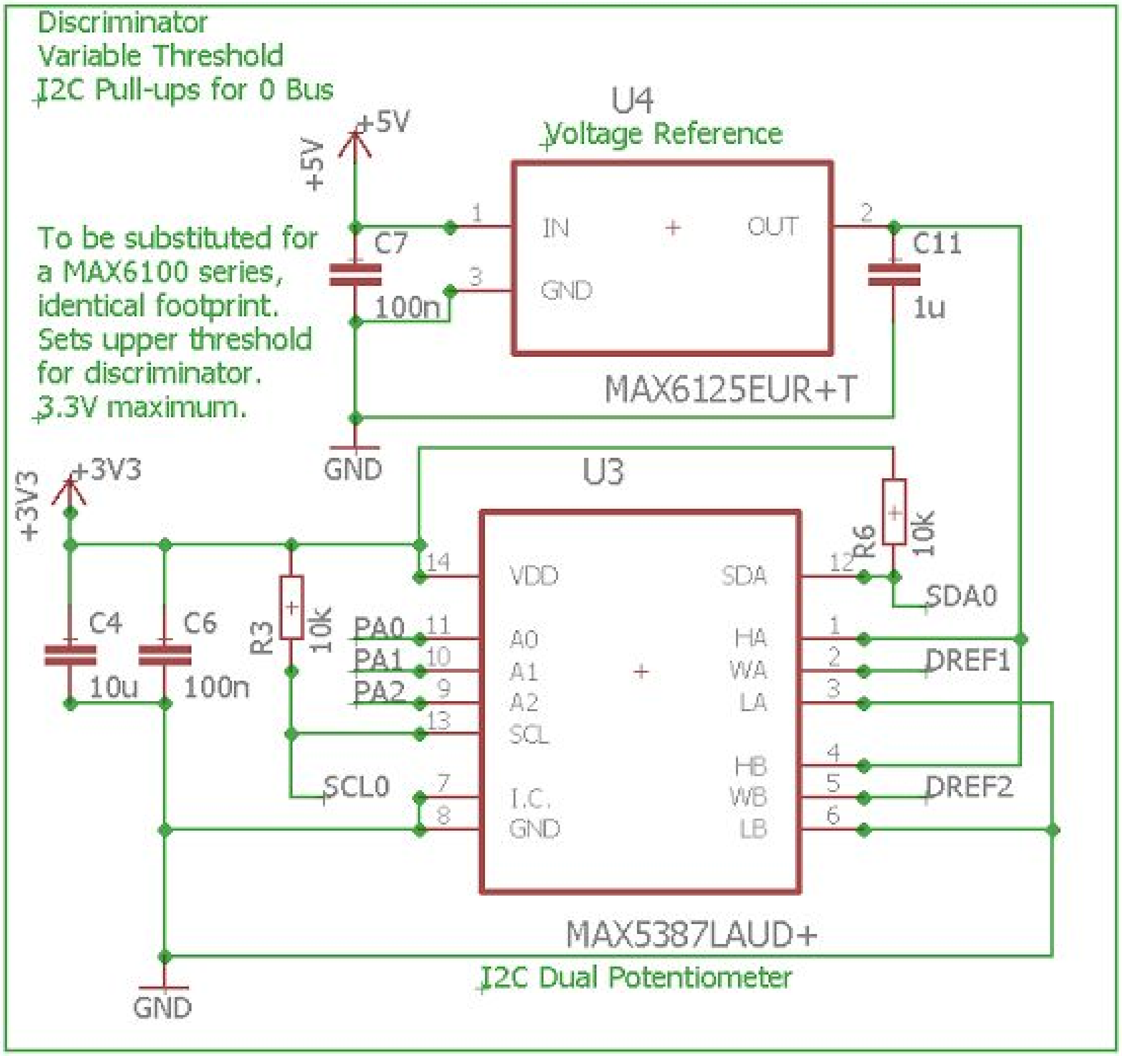
Connections



Two four pin headers are provided for connection to the Analogue Board. In version 2 alpha main boards, only 5 signals are connected to these headers (AMP2A, AMP2B, VBIAS, GND and +5V). Version 2.1 adds two additional signals LEDB and LEDR, to permit light injection testing if a suitable LED is installed on the analogue board. The headers are standard 2.54mm type and are fixed on the upper face of the PCB to allow the analogue board and scintillator module to be stacked on top.

Also in the connector frame are 4 rows of 10 x 2.54mm header holes, these are located at the far edge of the main board PCB and are intended for hardware modification or prototyping. They are not connected to anything on the board.

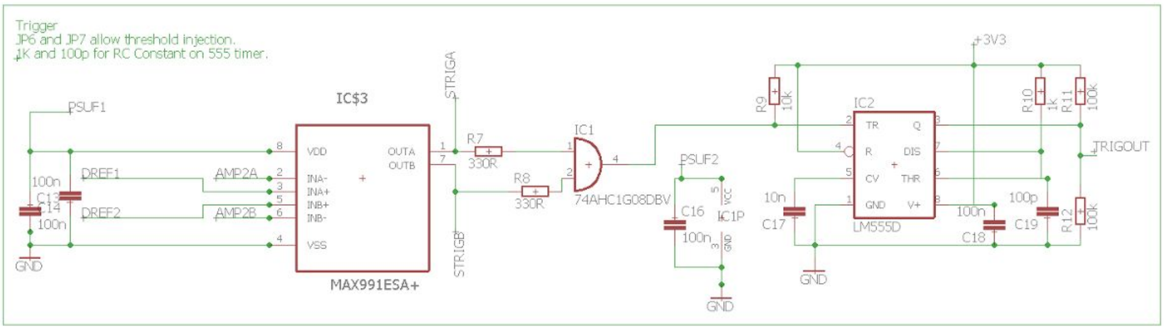
Discriminator



Discrimination is the general term used to describe the process of separating the signal (in this case cosmic radiation) from the noise (background, present in the electronics, and signals from other radiation). In order to filter the signal from the analogue board, a high speed comparator is used. The comparator is supplied with the two analogue signals directly and compares them to inputs generated in the discriminator block above. The discriminator has a 3.3V precision voltage reference taken from the MAX6100 family of SOT-23 footprint voltage references. For the beamlines for schools versions an ON Semiconductor pin compatiable part was selected, NCP51460SN33T1G. The accuracy of this part is +/-1%, providing a relatively high precision. The reference provides a high stability 3.3V source (separate from the 3.3V power rail generated by the Arduino DUE) and dedicated to the function of discrimination. The 3.3V reference is fed into an I2C dual potentiometer (MAX5387), which is effectively a digitally controlled variable resistor. It has two internal variable resistors that each have 256 position, ranging from 0 ohms to 100k ohms. The The two resistors are configured as potential divider circuits, which can be controlled independently from the I2C0 bus on the Arduino DUE. By changing the resistor value on each of the potential dividers, the voltage output from the discriminator can be changed in 256 steps from 0 to 3.3V (12.5mV per step). This value is then used as the threshold, with any signals of a higher voltage detected from the analogue board causing the trigger to activate.

The MAX5387 has additional input pins which allow the I2C address to be configured at power on. These are set to 0 when the Arduino firmware initiates in order to have a stable address. The default settings of the two variable resistors are 50% (i.e. 1.65 V).

Trigger



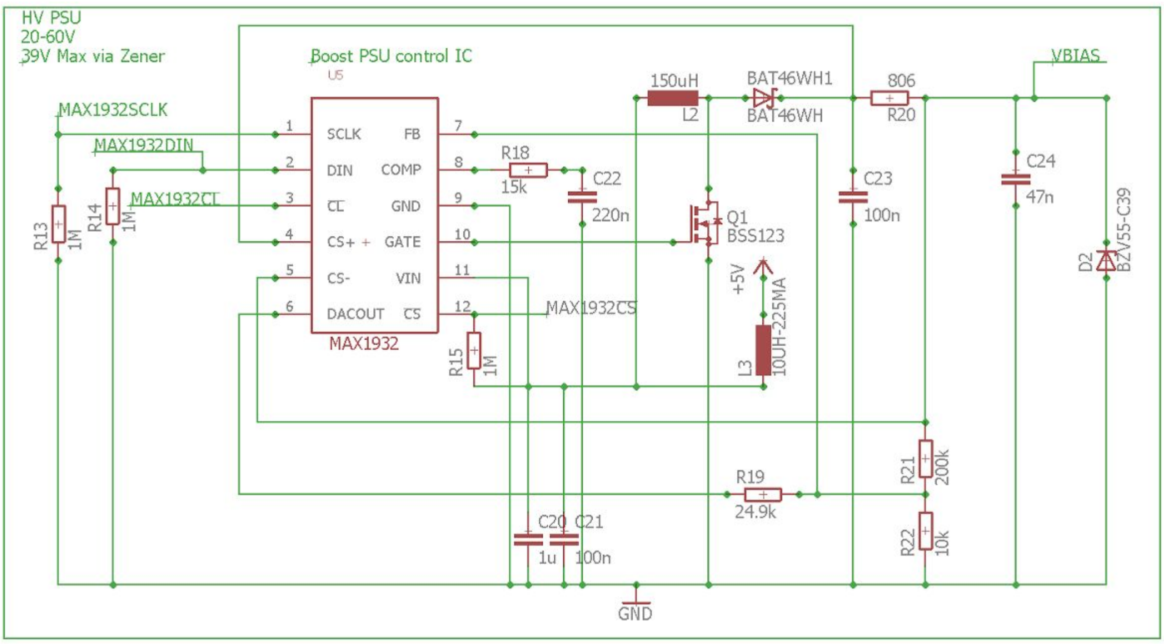
The trigger circuit provides a very fast electronic indicator for the detection of simultaneous above threshold voltages on the two analogue input lines from the analogue board. The first component is a fast comparator, which simultaneously compares two pairs of input voltages. In each case, there is an inverting and non-inverting input. The output of the comparator channel is positive if the non-inverting input voltage is higher than the inverting input. The output of the comparator channel is negative if the inverting input is higher than the non-inverting input. The comparator used is a MAX991ESA+, which has a 3.3 V rail supply which is filtered using a ferrite block to prevent noise contamination affecting this sensitive component. The propagation delay of the device is 120ns.

The output of the comparator is fed into a simple AND gate in an SOT-23 package. Two resistors are used to limit the current draw on the MAX991, thereby maintaining the datasheet performance; without these resistors there will be an increased current draw from the AND gate, which will reduce the slew rate (change in output voltage) of the comparator, and thereby increase the overlap required between the AMP2A and AMP2B input signals.

The final element of the trigger block is the venerable 555 timer. The LM555D module is used in a SOIC-8 package. The particular version which has been employed for Cosmic Pi has a wide range of acceptable supply voltages from 1.5 V up to 15 V. If assembling your own PCB, be sure to select a 555 which can operate at 3.3 V. A spice file to simulate the operation of the 555 is included in the main board .zip file available from the open hardware repository. The timer is required to ensure that the trigger signal lasts longer than a full clock-cycle of the Arduino DUE (83 MHz). Since there is a significant temperature coefficient, a wide design margin has been included and the typical output pulse from the trigger exceeds 100 nS. During the design testing process the AND gate replaced a NAND gate which failed to give the correct behaviour – we couldn't quite figure out why, since the 555 has an inverting input, however the circuit as shown on the schematic now performs as it should.

In order for the trigger to operate, both inputs must exceed their respective voltage threshold level for (Check MAX991 datasheet for the exact value). This will cause the output of the comparator to switch from 0 V to 3.3 V. The presence of 3.3 V at both inputs of the AND gate must overlap for at least 5ns in order to set its output high. Once a high logic state is detected by the 555 at its trigger input, the output of the trigger block will rise to 3.3 V for a minimum duration of 100 nS (to be verified with the LTSpice model). Should further trigger signals arrive at the input to the trigger block (up and including the input to the 555), they will have the effect of extending the output pulse by the difference between the time of the first triggering signal and the time of the second. The 555 also imposes a dead time after the output of the trigger block returns to 0. This dead time is Y nS, which is complemented by a further dead time, deliberately imposed in the Arduino software. Don't forget that the comparator introduces a 120ns propagation delay into the system.

HV PSU

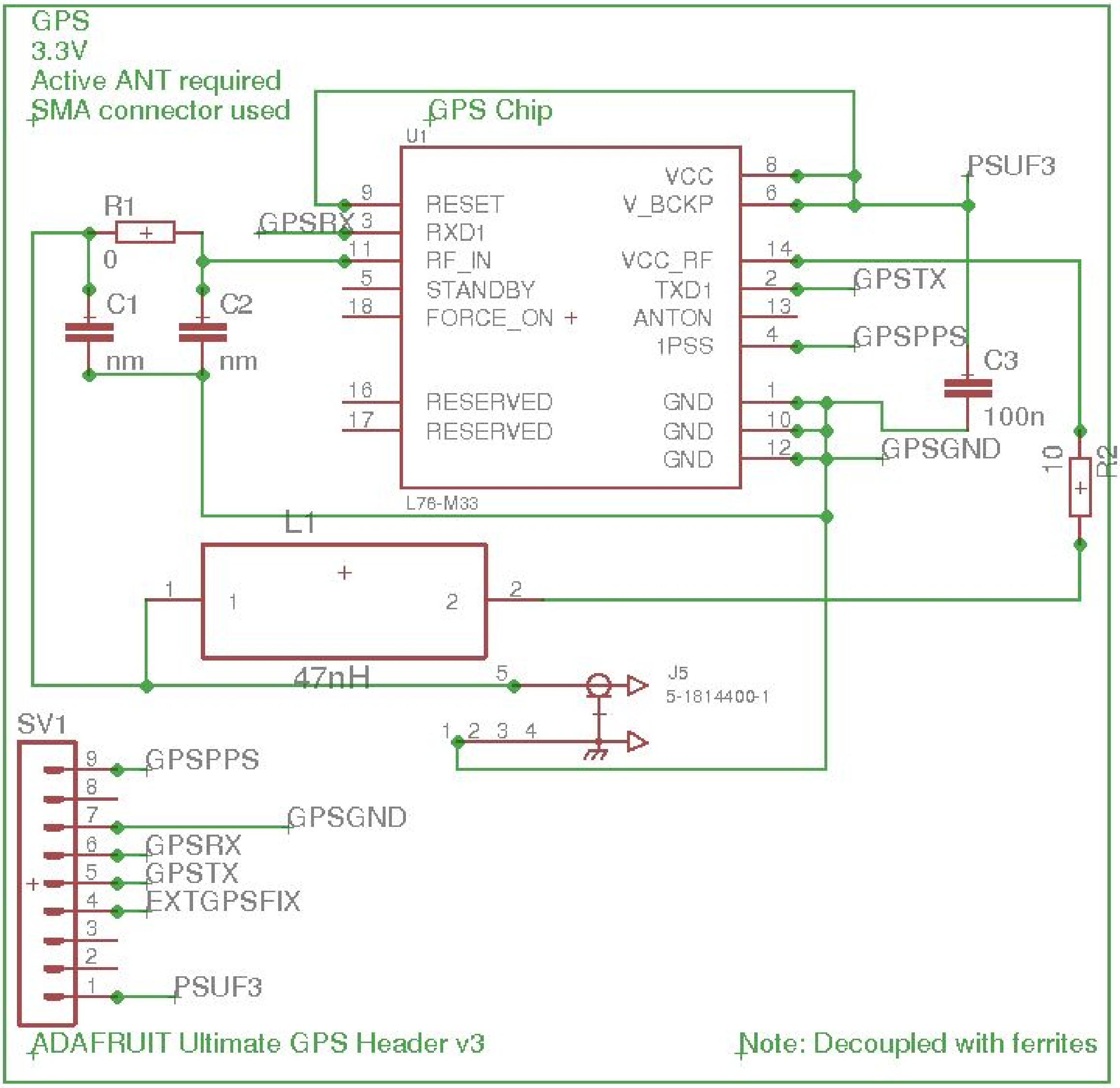


The HV PSU block generates the bias voltage applied to the Cathode of the SiPM sensors. The design is based on a Boost Converter Switch Mode Power Supply (SMPS), and employs the MAX1932 controller to provide a highly stable output voltage. The power supply is controlled via SPI bus, which is emulated in software on the Arduino DUE (Note: the Arduino DUE actually provides hardware SPI functionality, however the pins are located in an inconvenient place for the shield connection, therefore software emulation, which is very simple, was chosen as an alternative).

The MAX1932 implements a closed loop PWM controller with 127 output voltage steps. The device defaults to an output voltage of 5 V (the supply voltage) on power up. This voltage can be asserted by sending the output value of 0x00 over the SPI bus. The converter operates in the range 0xFF to 0x01, from minimum to maximum output voltage.

The input to the HV PSU block is filtered with an additional 10 uH inductor, to prevent high frequency leaking out onto the 5 V power supply line. Component D2 has also been added to the MAX1932 reference design (used as a basis for this block) to ensure that the output voltage does not exceed 39V.

GPS module

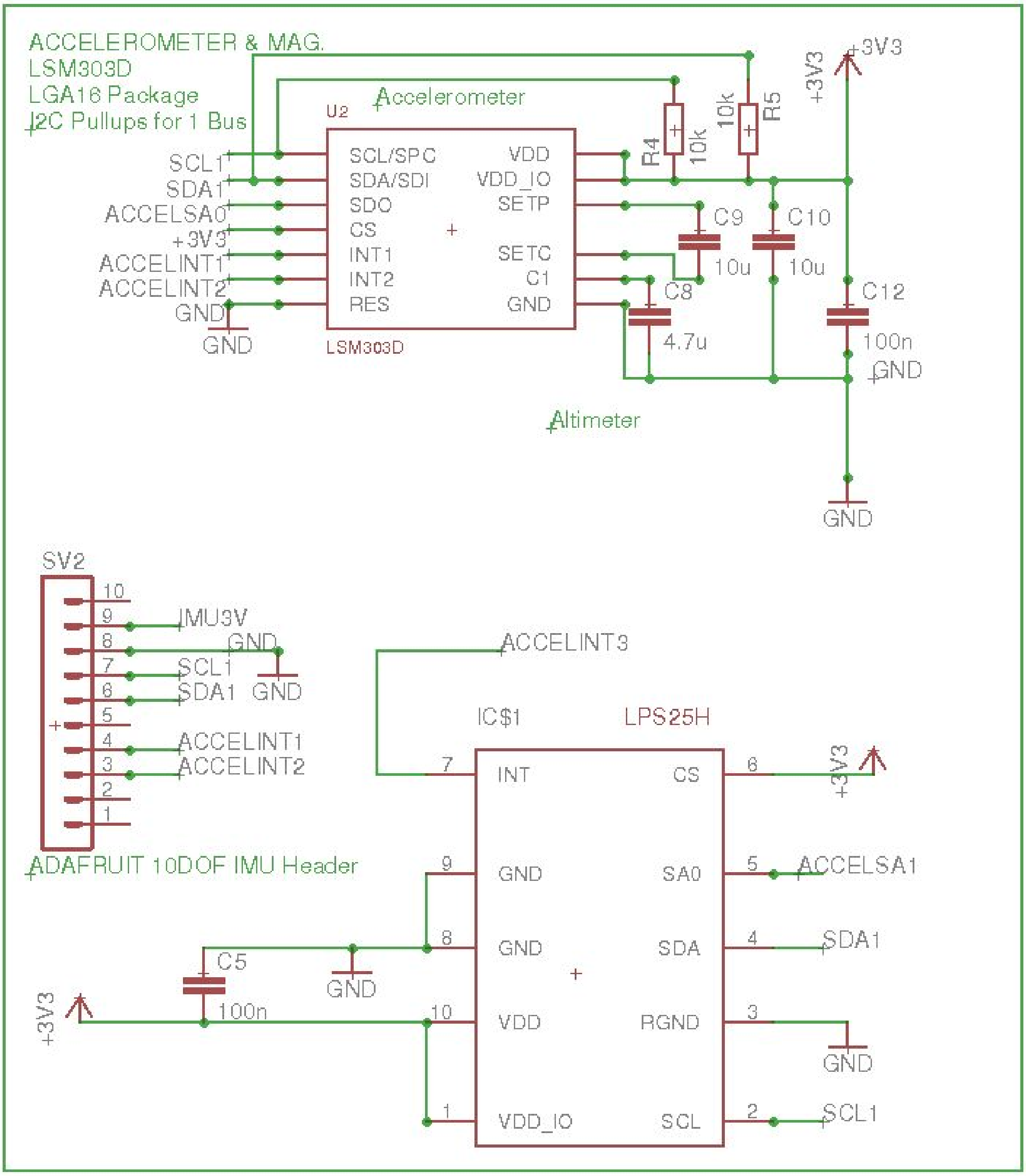


A Quectel L76-M33 GPS chip is used to provide position and precision timing information to the Cosmic Pi. The unit is powered from a ferrite filtered 3.3V source derived from the DUE power bus. GPS communication is via the UART connectors, which are wired to TX1 and RX1 on the DUE (note the inversion in the connection, such that TX → RX and RX → TX). The device operates by default at 9600 BPS. The Pulse Per Second (PPS) output is connected to Pin 2 on the DUE which has specialised timing functions.

The GPS module has an active antenna output, which is connected via the 47nH inductor. The external antenna is connected via a through hole MMCX connector, if buying your own antenna make sure to choose one with an active LNA onboard to maximise performance.

A 9 pin header is provided to allow self-assembly using an Adafruit Ultimate GPS module (version 3). If you are using the Adafruit module, we recommend an external antenna (you'll need one with a U.FL connector, or an adapter to MMCX).

Inertial Measurement Unit



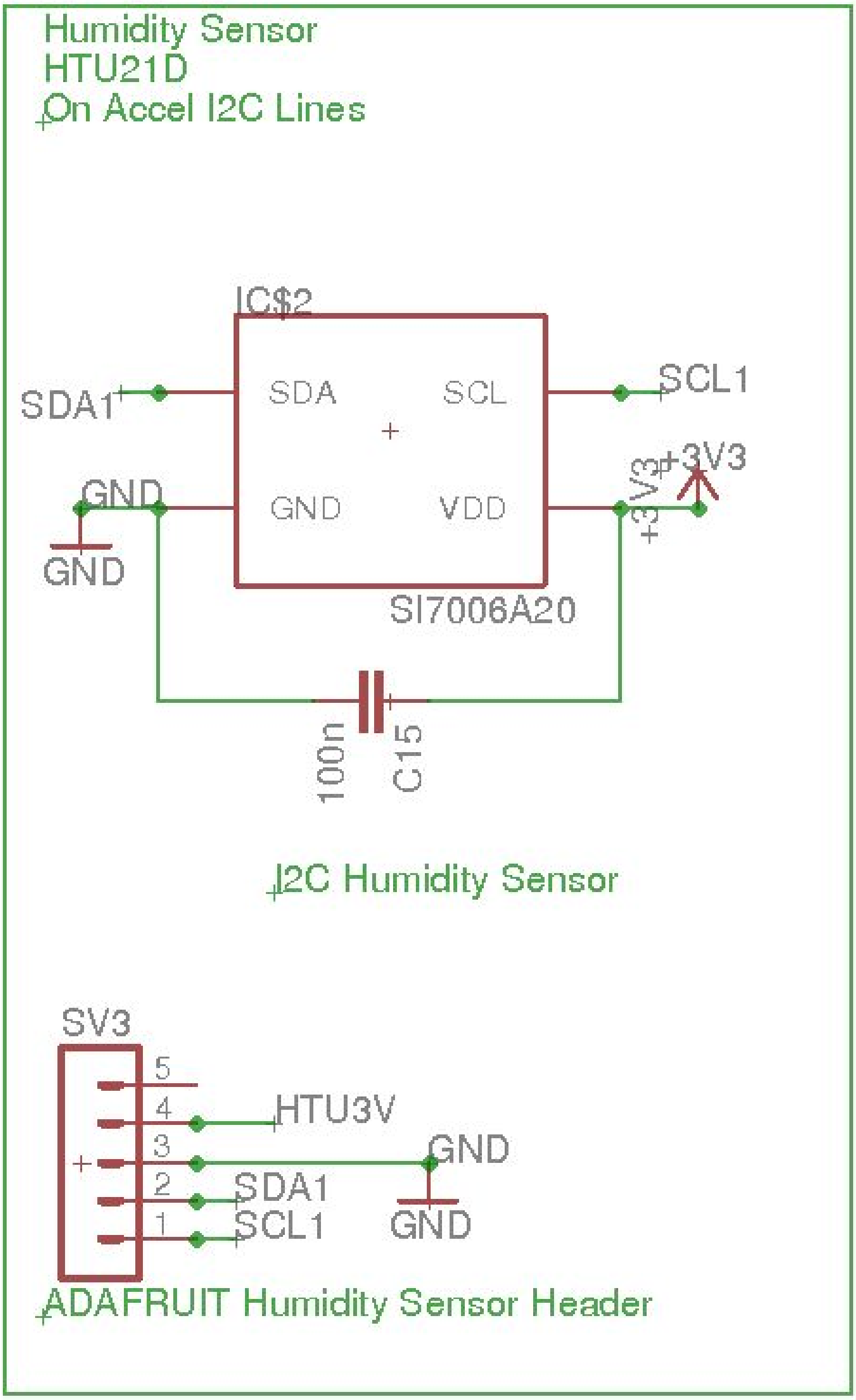
The Inertial Measurement Unit (IMU) is comprised of two discrete IC's which replicate the functioanlity of the Adafruit 10DOF IMU header. A 10 pin 2.54mm pitch header is provided for direct connection of the IMU breakout board if self assembling.

The LSM303D LGA16 package provides a 3 axis accelerometer and 3 axis magnetometer. It is connected to the I2C1 bus. It has a variable address line (ACCELSA0) which can be used to set the I2C address and avoid conflicts with other devices. By default this value should be set LOW.

Two user configurable interrupts are provided via ACCELINT1 and ACCELINT2 which can be used to signify high magnitude magnetic or acceleration events. This functionality allows for sudden changes in the local magnetic field (for example waving a magnet over the detector) or the acceleration (such as someone tapping on the unit or even an earthquake) to be rapidly flagged up to the DUE.

The second element of the IMU is a MEMS pressure sensor. The LPS25H sensor from STMicro has been chosen. It is also connected to the I2C1 bus and has one variable address line (ACCELSA1, set low by default). This is a different sensor to the one employed on the Adafruit breakout, which was chosen due to better availability.

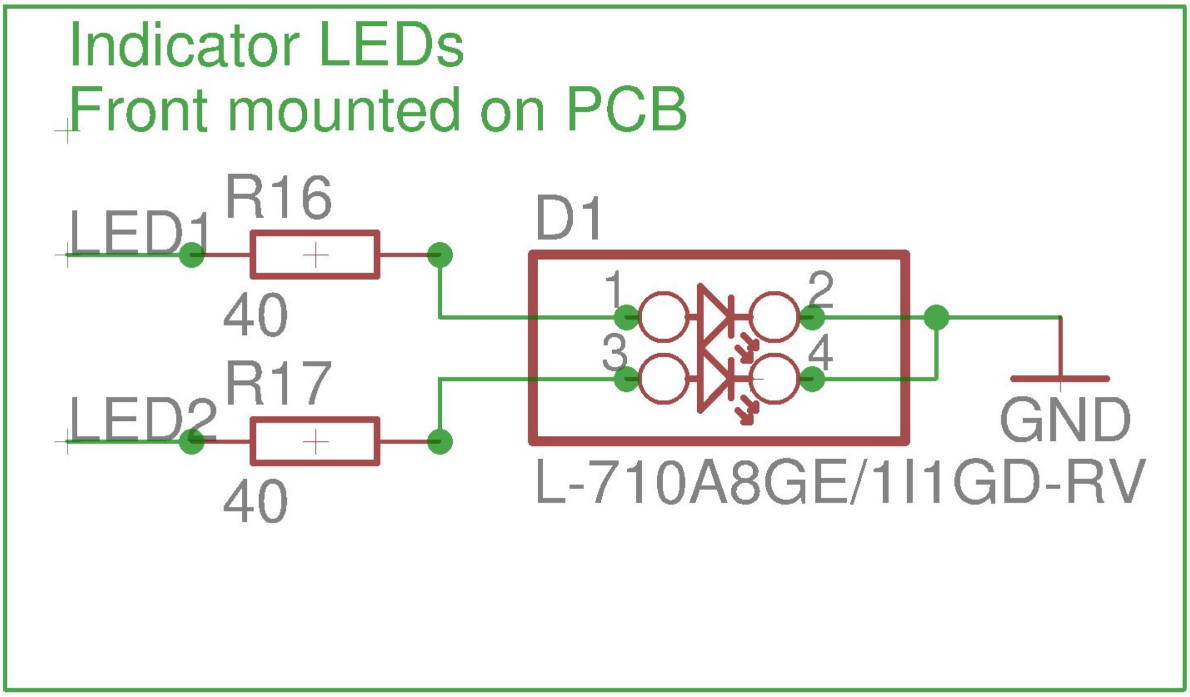
Humidity Sensor



A humidity sensor is provided to help track the ageing of the plastic scintillator. There are numerous papers which indicate that the presence of humidity has a negative effect on the lifetime performance of certain types of scintillator medium, therefore a sensor has been included to assist in checking the quality of the environment within the Cosmic Pi enclosure, and potentially assessing the state of the scintillator during the full life of the detector.

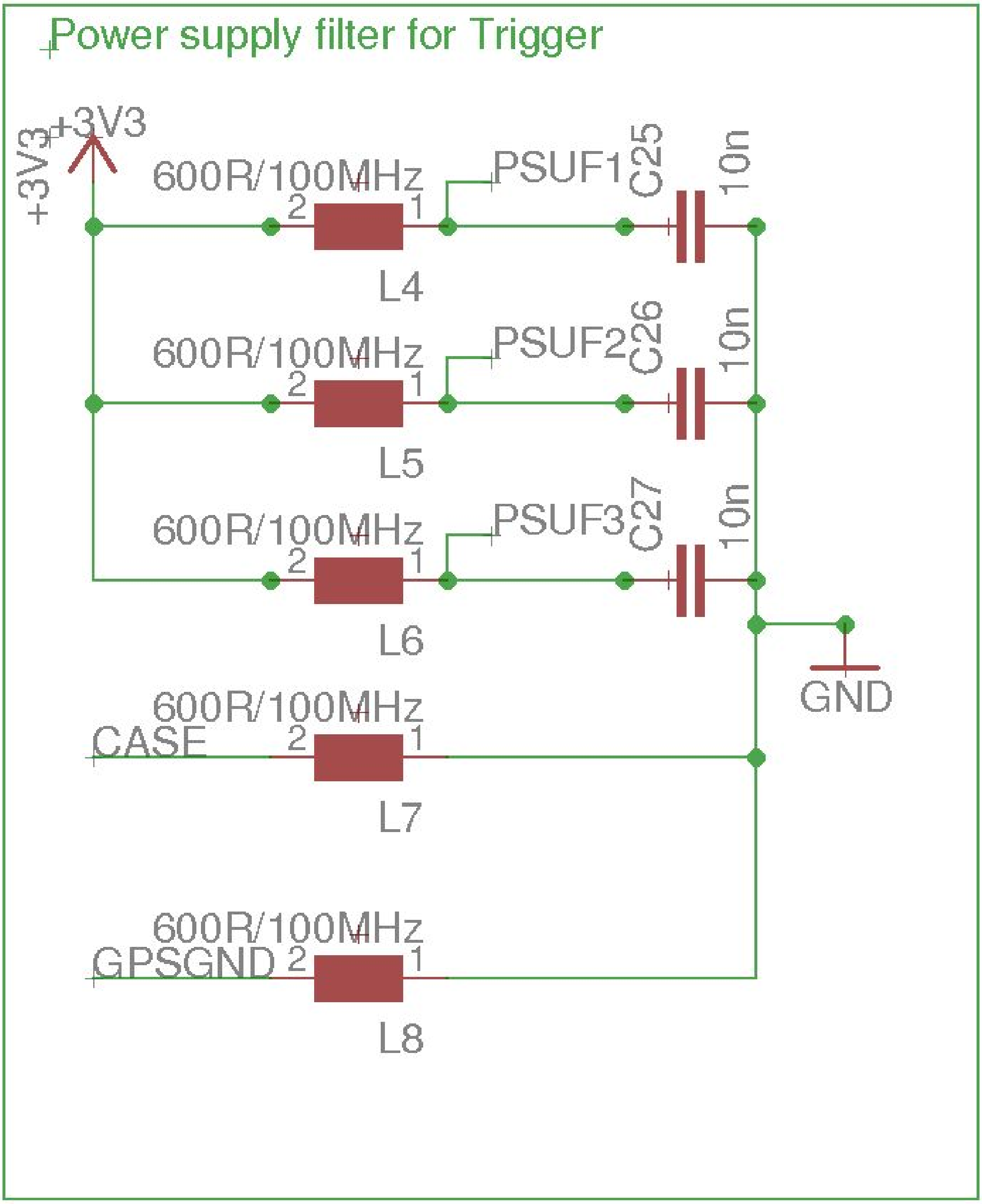
The Si7006 sensor has been selected since it’s easier to get hold of than the HTU21D used in the Adafruit Humidity Sensor breakout. A 5 pin 2.54mm pitch header is provided to allow self assembly with the Adafruit breakout. The sensor is connected to the I2C1 communications bus and has no hardware configurable elements.

Indicator LEDs



Two indicator LEDs are provided that show through the front panel of the Cosmic Pi enclosure. They are standard green LED’s with a 40 Ohm resistor to limit the illumination current. They are driven by the signals LED1 and LED2 respectively. LED1 is used to signal the power on status of the device and LED2 is flashed each time an event condition is detected. The LEDs are driven by the Arduino DUE, therefore neither will work unless the correct firmware has been loaded. The LED module is the L-710A8GE from Kingbright.

Power filters

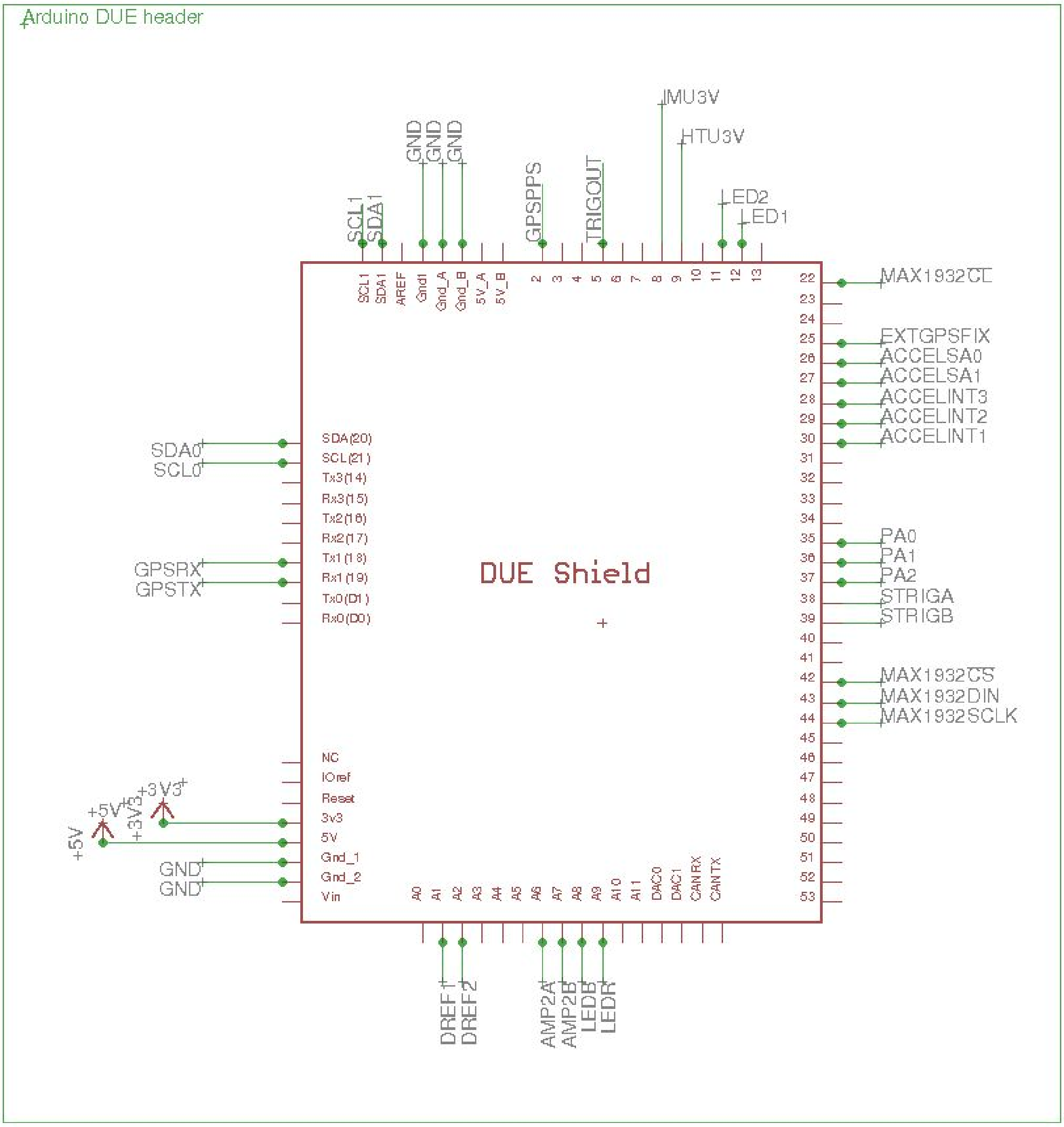


The power supply filter block uses ferrite beads (surface mount 600R/100MHz) to prevent high frequency noise transmission between the functional blocks.

Iron is used because it presents a low impedance at low frequency and a high impedance at high frequency. It is therefore ideal at preventing high frequency noise from contaminating a power supply line.

Three beads are used for 3.3V power supplies to the comparator (PSUF1), the AND gate (PSUF2) and the GPS (PSUF3). An additional ferrite is used to bridge the connection with the aluminium housing, aimed at preventing high frequency noise either exiting or entering the enclosure. A final bead is used to link the GPS ground to the system ground, again to prevent high frequency noise either entering or exiting the GPS block, which is particularly sensitive to noise.

Arduino DUE interface



The final element of the main board are the interface pins to the Arduino DUE PCB which is mounted underneath the main board. Starting from the top left, SCL1 and SDA1 are connected to the I2C1 bus which is used for the peripheral sensors (IMU and Humidity). The ground plane of the Arduino is connected with the ground plane of the main board. The GPSPPS signal arrives at Pin 2, which is connected to the hardware timing systems within the SAM3X processor on the DUE. TRIGOUT (the hardware event detection signal) is connected to Pin 5, which is also part of the hardware timing system in the SAM3X. Pin 8 is used to supply 3.3V to the IMU breakout board connection, which allows it to be power cycled without opening the enclosure. This was included as some issues were observed with instability on the Adafruit breakout board due to the use of dynamic level shifters. Pin 9 is connected to the Adafruit humidity breakout header to allow power cycling on the same basis as for the IMU breakout. Power cycling is not required for sensors which have been soldered on to the main board.

Pins 11 and 12 are used to control the indicator LEDs.

Pin 22 is connected to the overflow signal from the MAX1932, which indicates when the HV PSU block is overloaded. Normally this should not be the case.

Pin 25 is connected to the fix output from the external GPS header. If an onboard GPS is used it is not connected. It indicates the fix status of the Adafruit Ultimate GPS breakout, with 1 being a valid position fix and 0 being no position fix.

Pins 26 and 27 are used to set the least significant I2C address bits of the two sensors (accel/mag and pressure) that comprise the IMU. They should be set to 0 in the default configuration.

Pins 28 to 30 are used for interrupts from the IMU. In order to be used they must be declared as interrupts in the Arduino firmware. They are user configurable via the registers in the IMU sensor chips.

Pins 35 to 37 are used to set the I2C address of the MAX5387 variable potentiometer. They should be set to 0 by default.

Pins 42 to 44 are used to simulate the SPI bus headers with a software emulation routine. They are used to send the bias voltage value to the HV Power Supply unit.

Pins A8 and A9 (analogue) are used to drive the light injection LEDs on the analogue board module if equipped. Note that this feature isn’t enabled in the main board V2.1 Alpha version used in the beamline for schools editions. They should be driven in digital or PWM configuration if used, as an output rather than an input.

Pins A6 and A7 (analogue) are available to sample the reference voltage being sent to the MAX991 comparator. This feature isn’t used in the standard firmware but could be useful in the future.

Pins A1 and A2 are connected to the output from the Analogue Board and provide access to the raw signals from the amplifiers. They are sampled by the standard Arduino firmware after an event signal is detected.

The Ground, 5V and 3.3V rails of the Arduino are all connected to the main board.

GPSRX is connected to TX1 (pin 18) and GPSTX is connected to RX1 (Pin 19) for UART communication (hardware) between the Arduino and the GPS module.

SCL0 and SDA0 (comprising the I2C0 bus) are connected to pins SCL (21) and SDA (20) respectively. They provide access to the dedicated I2C hardware within the SAM3X used to communicate with the MAX5387 variable potentiometer.

General assembly information

The main board has deliberately exposed PCB tracks along both edges, top and bottom, to encourage a good electrical connection to the aluminium casing. These are electrically connected to the unit ground via a ferrite bead for noise suppression.

You may need to depress the main board gently in order to get the LED stack to mate correctly with the milled openings in the aluminium front plate. This should be done with care to avoid cracking the PCB.

The Analogue Board should be attached (with scintillator) prior to mating with the Arduino DUE as the nylon screws holding the Analogue Board cannot be easily installed with the DUE mated.

Please be careful if removing the Arduino DUE from the main board as the pins are easy to bend! When re-installing make sure that the face plate of the casing is correctly aligned as there are very small tolerances on the USB connectors.

The unit can operate without an external power supply (as total consumption in operation is 140mA), however performance is not guaranteed. We are working on a way to declare the Arduino DUE as a high power USB device, in the interim an external power adapter (supplied with the Beamlines for Schools units) is highly recommended, or a USB battery pack, which may be connected to the native micro USB port.