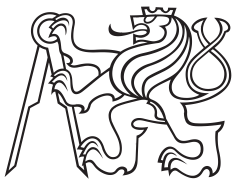
Master's thesis



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F3

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Fast multi-channel data acquisition system for radio-astronomy receiver

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http://petr.olsak.net/ctustyle.html
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Draft: 3. 5. 2014

Acknowledgement / Declaration

Prohlašuji, že jsem předloženou práci vypracoval samostatně a že jsem uvedl veškeré použité informační zdroje v souladu s Metodickým pokynem o dodržování etických principů při přípravě vysokoškolských závěrečných prací.

V Praze dne 12. 5. 2014

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Abstrakt / Abstract

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Klíčová slova:

Překlad titulu: Rychlý vícekanálový systém sběru dat pro radioastronomický přijímač

.

Keywords:

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Chapter 1
Introduction

1.1 Current radioastronomy problems

Nejprve z pohledu radioastronoma je podstatné, že jej v převážné většině zajímají signály přírodního charakteru, přicházející z okolního vesmíru. Tedy většinou ani nechce, aby měly nějakou spojitost s naší civilizací.

From radioastronomer point of wiev its important radioastronomy has interest in natural signals from surrounding universe. Radio astronomy do not have interest in terestrial civilisation made signals.

To je často velký problém, neboť na Zemi touto dobou existuje velké množství vysílačů, které pokrývají prakticky celé dostupné elektromagnetické spektrum a vytvářejí tak nepřebernou směs signálů, která se nejenom pro radioastronoma může stát nepřekonatelným problémem. Z tohoto důvodu byla již od počátků rádiového vysílání snaha udržet nad obsazením spektra určitou kontrolu a jedním z důsledků této snahy je například ¡a href=`http://www.ukaranet.org.uk/basics/frequency_allocation.htm`¿tabulka přidělených kmitočtů pro radioastronomii¡/a¿. Bohužel z mnoha důvodů nelze říci, že by tyto kmitočty byly dostatečně kvalitně čisté pro sériózní pozorování. Z toho vyplývá důležité zjištění, že v současné době nelze postupovat stejně jako v počátcích radioastronomie. A tedy i experimenty, vedoucí například k objevu reliktního záření nebo pulzarů, nelze v původní podobě zopakovat s uspokojivým výsledkem.

This is big problem because at this moment many terrestrial transmitters are active and all this transceivers made desnse signal mictrure which can cause troubles not only to radioastronomers. In consequence of this, there exist a tendence to control radiofrequency spectrum. As result of this controling the radiofrequency allocation table was created `http://www.ukaranet.org.uk/basics/frequency_allocation.htm` This table consist special bands allocated to radioastronomy use. But from many ... this bands are not clean enough for directly use in radioastronomy observations. As resul of this we cannot work by same way as radioastronomers in beginnig of radioastronomy. Many experiments namely, reliktive radiation detection and pulsar detection cant be realised in original form with satisfactive results.

Důkazem může být například projekt RadioJOVE, který přes svojí správnou ideu v dnešním civilizovaném světě jednoduše nefunguje. Důvodem jeho nefunkčnosti je právě přítomnost elektromagnetického smogu, který je řádově silnější, než Jupiter. A z praxe například i okolo světelného znečištění nelze očekávat nějakou radikální změnu k lepšímu.

This RadioJOVE project has good idea in creating publicly available cheap radioastronomy receiver. But in old fashioned construction which can work in centers of desert. But it simply cant work in modern civilisation as it is know in Europe. Origin of its disfuncion is presence of strong radiofrequency interferences. This interferences are orders of magnitude stronger than Jupeter decametric emmisions. From praqtice about light pollution we also know that there aro not much chance to improve this situation radicaly.

Nezbývá proto než hledat metody, jak se při radioastronomickém pozorování obejít bez úplně čistých pásem a prohlédnout skrze směs terestrického elektromagnetického rušení. Jednou z možností je využít zatím známých vlastností přírodních signálů, a to jejich relativně velké spektrální širokopásmovosti a zároveň velmi velkého plošného pokrytí vzhledem k pozemským vysílačům, protože pro přírodní objekty není problém vyzařovat v šířce pásma desítek MHz a přitom pokrýt plochu poloviny zeměkoule. Je ale ovšem jasné, že tyto parametry jsou na úkor dopadajícího výkonu a ten je tedy řádově miliardkrát menší, než výkon přijímaný z rozhlasového vysílače.

There are not other ways that searching for new methods in radioastronomy obserevations. New methods which allows us to work without completely clear radiofrequency bands asd alow us to see surroundind universe trough man made radiofrequency interference micture. One of sollutions is use of already known natural signals parameters. Natural signals usualy have different signal properties from local interference. Natural object do not have a problem with tansmission bandwith of tens megaherts in sub 100 MHz bands. This object also transmit the same signal for almost half of Earth without any difficulties. But it is also clear that signal parameters have drawbacks in reception power. The reception power of radioastronomy object is 1e9 smaller than signal power received from typical broadband radio transmitter.

Z těchto faktů je jasné, že nynější požadavky na radioastronomický přijímač jsou odlišné od těch v minulosti. Zejména jde o šířku přijímaného pásma. Tento parametr dříve dosahoval řádově jednotek až desítek kHz, což stačilo, neboť velká část pozorování se zpracovávala buď poslechem, a nebo pomocí zapisovače, který integroval signál přes definovanou oblast, a tím bylo možné zaznamenávat intenzitu a změny v přírodním kontinuu. Tou dobou ale neexistovaly žádné pozemské širokopásmové vysílače, snad kromě televizních, takže nebyl problém přijímač odladit do čisté oblasti. Dříve také nebylo nutné pozorovat paralelně z více míst planety, protože podmínky byly všude téměř totožné.

From this fact is clear one relust. Modern requirements on

1.2 Modern Radio astronomy receiver

In beginning of radioastronomy receivers were constructed as simple station with single antenna or multi antenna array with fixed phasing. This approach were used due to limits of previous electronics. Main challenges were noise number and sensitivity due to poor characteristic of active electronic components such transistors and vacuum tubes.

Řešením je pravděpodobně použít přijímač, který bude mít velkou šířku pásma, nejlépe řádu MHz, a vysokou vstupní odolnost. A pokud možno půjde sfázovat s nějakým dalším na jiném místě planety. Existuje několik zařízení, které tyto požadavky splňují. V naprosté většině jde o takzvané ¡a href=`link wikipedie`¿SDR¡/a¿ přijímače, jako například USRP, USRP2, SDR-IQ a SSRP. Tato zařízení ale mají většinou zásadní nevýhodu, že jejich pořizovací cena je více jak 1000 USD a jsou velmi univerzální. Takže se moc nehodí na nějaké kontinuální pozorování, kde nebudou využity všechny jejich draze zaplacené vlastnosti. Poslední z uvedených ¡a href=`link wikipedie`¿SSRP¡/a¿ je ale jednoduchá konstrukce 16bit AD převodníku připojeného k USB řadiči, který hrne všechna navzorkovaná data do PC. Je to velmi zajímavé zařízení s řádově nižší pořizovací cenou. Avšak v této podobě je omezené datovým tokem USB, které omezuje vzorkovací frekvenci na zhruba 30MSPS. Z čehož vyplývá, že v prvním Nyquistově pásmu není možné zpracovávat signály o frekvenci vyšší něž 15MHz. To je pro radioastronomické účely poměrně nízko. Řešením by byl přechod do vyšších Nyquistových

zón, kde ale začne vznikat problém s vhodnou konstrukcí antialiasign filtru a omezením sample-hold obvodu na vstupu ADC.

Many of today radioastronomy equipments were constructed in this manner. They were constructed usually shortly after WWII or during The Cold War as parts of military technology. These systems are slowly modernised and complete new systems are constructed. ALMA, SKA..

This new radio astronomy receivers have completely different approach to solve the problem of radioastronomy signal reception. They almost exclusive uses multi antenna arrays and mathematical algorithms for signal handling. Radio signal recorded by this metod can be used by many ways. Radio image can be computed (if sufficient cover of u/v plane is achieved), radiation intenzity can be measured, spectrum can be analysed for velocity measurement. etc.

1.2.1 Observation types

Today radioastronomy knows several observation types.

- Spectral observations
- Intensity observations
- Velocity observations

All of these observations ideally needs high frequency resolution and stability. Wide observation bandwidth in hundreds of MHz is usually desirable for easier discrimination of source types.

1.3 Required receiver parameters

This new approach of receiver construction has different requirement on receiver parameters. No signal to noise ratio on single antenna is improved. But other parameters are requested at now.

1.3.1 Sensitivity and noise number

These parameters are are tied together, but multi antenna and multi receiver arrays requires to keep price of receiver at minimal values. This implicates that sensitivity and noise number must be least as good to detect (signal /noise ¿ 1) observed object on majority of receivers connected to observation network.

1.3.2 Dynamic range

Dynamic range is huge problem of current radioastronomy receivers. This parameter is enforced by anywhere present humans made EMI radiation on RF frequencies. The modern radio astronomy receiver must not be saturated by this high levels of signals.

1.3.3 Bandwidth

From requirements mentioned above

The system requires proper handling of huge amount of data.

Professional radioostoronomers uses uses proprietary digitalisation units `http://arxiv.org/abs/1305.3550` or by multichannel sound cadrd on amateur levels `http://fringes.org/`

Chapter 2
Trial design

The whole design of radioastronomy receiver digitalization unit is constructed to be used in a wide range of applications and tasks related to digitalisation of signal from radioastronomy receivers. A good illustrating problem for its use is a signal digitalisation from multiple antenna arrays. This design will eventually become a part of MLAB Advanced Radio Astronomy System.

2.1 Required parameters

Wide dynamical range and high 3 intercept points are desired. The receiver must accept wide dynamic signals because a typical radioastronomy signal has a form of a weak signal covered by a strong man-made noise signal.

- Dynamical range better than 80 dB
- Phase stability between channels
- Noise (all types)
- Sampling jitter better than 100 metres

2.2 Sampling frequency

Sampling frequency is limited by the technical constrains in the trial design. This parameter is especially limited by the sampling frequencies of analog-to-digital conversion chips available on the market. Combination of the required parameters – dynamic range which needs at least 16bit and a minimum sampling frequency of 1 MSPS, leads to high end ADC chips which does not support such low sampling frequencies at all. Their minimum sampling frequency is 5 MSPS.

2.3 System scalability

For analogue channels scalability, special parameters of ADC modules are required. Ideally, there should be a separate output for each I/Q channel in ADC module. ADC module must also have separate inputs for sampling and data output clocks. These parameters allow for conduction at relatively low digital data rates. Then the digital signal can be conducted even through long wires.

Clock signal will be handled distinctively in our scalable design. Selected ADC chip are guaranteed to have defined clock skew between sampling and data output clock. This allows taking data and frame clocks from the first ADC module only. The rest of the data and frame clocks from other ADC modules can be measured for diagnostic purposes. (Failure detection, jitter measurement etc.)

This system concept allows for scalability, that is technically limited by a number of differential signals on host side and its computational power. There is another advantage of scalable data acquisition system – economic one. Observatories or end users can

make a choice of how much money are they willing to spent on radioastronomy receiver system. This freedom of choice is especially useful for science sites without previous experience in radioastronomy observations.

2.3.1 Differential signalling

The concept of scalable design requires relatively long circuit traces between ADC and digital unit which captures the data and performs the computations. The long distance between the digital processing unit and the analog-to-digital conversion unit has an advantage in noise retention typically produced by digital circuits. Those digital circuits, such as FPGA or other flip-flops block and circuit traces, usually work at high frequencies and emit wide-band noise with relatively low power. In such case any increase in a distance between the noise source and analog signal source increase S/N significantly. However, at the same time a long distance brings problems with the digital signal transmission between ADC and computational unit. This obstacle should be resolved more easily in free-space than on board routing. The high-quality differential signalling shielded cables should be used. This technology have two advantages over PCB signal routing. First, it can use twisted pair of wires for leak inductance suppression in signal path. Moreover, the twisted pair may additionally be shielded by uninterrupted metal foil.

2.3.2 Phase matching

For multiple antenna radioastronomy projects, system phase stability is mandatory. It allows precise high resolution imaging of objects.

High phase stability in our scalable design is achieved by centralised frequency generation and distribution with multi-output LVPECL hubs, that have equiphased outputs for multiple devices.

This design ensures that all devices have access to defined phase and known frequency.

2.4 System description

In this section testing system will be described.

2.4.1 Frequency synthesis

We have used centralised topology as a basis for frequency synthesis. One precise high-frequency and low-jitter digital oscillator has been used while other working frequencies have been derived by its division. This central oscillator has a software defined GPS disciplined control loop for frequency stabilisation.[1]) Frequency monitoring compensation method has been used in order to meet modern requirements on radioastronomy equipment which needs precise frequency and phase stability on wide area for effective radioastronomy imaging.

Every ADC module will be directly connected to CLKHUB02A module which takes sampling clock delivered by FPGA from main local oscillator. This signal should use high quality differential signalling cable – SATA cable should be used for this purpose.

[1]) `http://wiki.mlab.cz/doku.php?id=en:gpsdo` SDGPSDO design has been developed in parallel to this diploma thesis as a related project, but it is not explicitly required by specification.

2.4.2 Signal cable connectors

Several widely used and commercially easily accessible differential connectors were considered.

- HDMI
- SATA
- DisplayPort
- SAS/miniSAS

MiniSAS connector was chosen as the best to be used in connecting multiple ADC modules. The miniSAS connector is compatible with existing SATA cabling system and aggregates multiple SATA cables to a single connector this cable type is shown on image 2.1. Translation between SATA and miniSAS is achieved by SAS to SATA adapter cable which is used in servers to connecting SAS controller to multiple SATA hard disc in RAID systems thus is commercially available. One drawback is that miniSAS PCB connectors are manufactured in SMT versions only. But outer metal housing of connector is standard trough hole type. This mechanical design should degrade durability of this connector type.

[img-miniSAS-cable]

Figure 2.1. A type of miniSAS cable similar to used.

2.4.3 Signal integrity requirements

Used ADC modules has DATA clock frequency eight times higher than sampling frequency in single line output mode. This implicates 40 MHz output bit rate.

2.4.4 Design of ADC modules

This modules have MLAB standard construction with four mounting holes in corner aligned in defined raster.

Data serial data output of ADC module should be connected directly to FPGA for basic primary signal processing. Used ADC chip has selectable bit width of data output bus thus output SATA connectors has signals arranged to contain a single bit from every ADC channel. This signal concept enables selection of proper bus bit-width according to sampling rate. (Higher bus bit-width downgrades signalling speed and vice versa.)

For connection of this signalling layout, miniSAS to multiple SATA cable should be used.

For PCB layout KiCAD design suite was used. Used version has the CERN Push & Shove routing capability integrated but was slightly unstable and sometimes falls on exception during routing. Design must be often saved due to this stability issues. But Open-source KiCAD works well compared to commercial solutions as MentorGraphics PADS or Cadence Orcad. And much better than widely used Eagle software.

New PCB footprints have been designed for FMC, SATA a and miniSAS connectors. These new footprints were committed to KiCAD github library repository. And they are now publicly accessible from official KiCAD repository at GitHub.

2.4.5 ADC selection

Several ADC signalling formats currently exist for communication with FPGA.

- DDR LVDS
- JEDEC 204B
- JESD204A
- Paralel LVDS
- Serdes
- serial LVDS

Serial LVDS has been selected because uses lowest number of differencial pairs. This parameter is mandatory for construction complexity and reliability. `http://www.ti.com/lit/pdf/snaa110`

An ultrasound AFE chips should be ideal for this purpose – this chips has front-end amplifiers and filters integrated. But theirs drawback is incapability of handling differential input signal and relatively low dynamic range (consists 12bit ADC). This IO has many ADC channels thus scaling are possible in factor of 4 receivers (8 analogue channels).

If we require separate output for every analogue channel and 16bit deph. Only several 2-Channel simultaneous sampling ADCs currently exists which meet these requirements. These ADCs parameters are summarised in table ??

ADC Type	LTC2271	LTC2190	LTC2191	LTC2192	LTC2193	LTC2194	LTC2195
SNR [dB]	84.1	77	77	77	76.8	76.8	76.8
SFDR [dB]	99	90	90	90	90	90	90
S/H Bandwidth [MHz]	200			550			
Sampling rate [MSPS]	20	25	40	65	80	105	125
Configuration				SPI			
Package	[ADC-types]	52-Lead	(7mm	■	8mm)	QFN	

Table 2.1. Summary of available ADC types and theirs parameters.

All parts in this category are compatible with one board layout. Main differences are in sampling frequency and signal to noise ratio. The slowest one has maximal sampling frequency 20 MHz. But all types have minimal sampling frequency 5 MSPS.

All types were configurable over serial interface (SPI). SPI seems to be a standard for high-end ADC chips from main manufacturers (Analog Devices, Linear technology, Texas instruments, Maxim integrated..).

2.4.6 ADC modules interface

All two ADCdual01A modules was connected to FPGA ML605 board trough FMC2DIFF01A adapter board. Construction of this adapter module suppose FMC LPC connector. And this board is not MLAB compatible design. But this board is designed to meet VITA 57 standard specification for boards which uses zone 1 and zone 3. This specification guarantee compatibility with others FPGA board which has FMC LPC connector for Mezzanine Card. Schematic diagram of this adapter board is included in appendix.

Primary purpose of this PCB is to enable connection of ADC modules from space excluded from PC case. (In PC box analog circuits cannot be realised without using of massive RFI mitigation techniques). Differential signaling connectors should be used for conducting digital signal over relatively long cable. Signalintegrity sensitive links (clocks) are equiped by output driver and translator to LVPECL logic for better signal transmission quality.

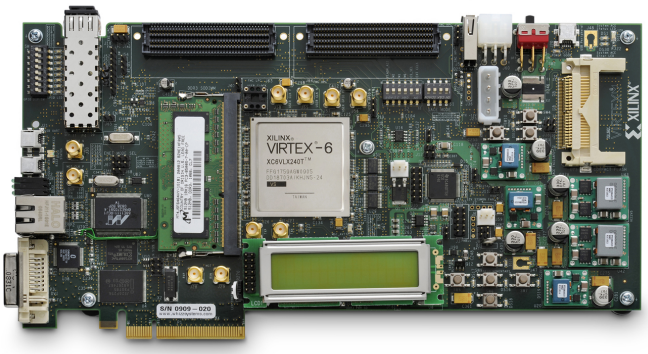


Figure 2.2. Used FPGA ML605 development board.

Several SATA connectors and two miniSAS connectors are populated on this board. This set of connectors allows connection of any number of ADC modules in range of 1 to 8. ADC data outputs should be connected to the miniSAS connectors. Other supporting signal should be routed directly to SATA connectors on adapter.

Signal configuration used in testing construction is described in tables.

2.4.7 Output data format

		160bit packet							
Data name	FRAME	ADC1 CH1		ADC1 CH2		ADC2 CH1		ADC2 CH2	
Data type	uint32	int16	int16	int16	int16	int16	int16	int16	int16
Content	saw signal	$t1$	t_{1+1}	$t1$	t_{1+1}	$t1$	t_{1+1}	$t1$	t_{1+1}

Table 2.2. System device `/dev/xillybus_data2_r` data format

2.5 Achieved parameters

2.5.1 Data reading and recording

For reading data stream from ADC driver Gnuradio software was used. Gnuradio suite consist gnuradio-companion which is a graphical tool for creating signal flow graphs and generating flow-graph source code. This tool was used to create basic RAW data grabber to record and interactive wiev data stream output from ADC modules.

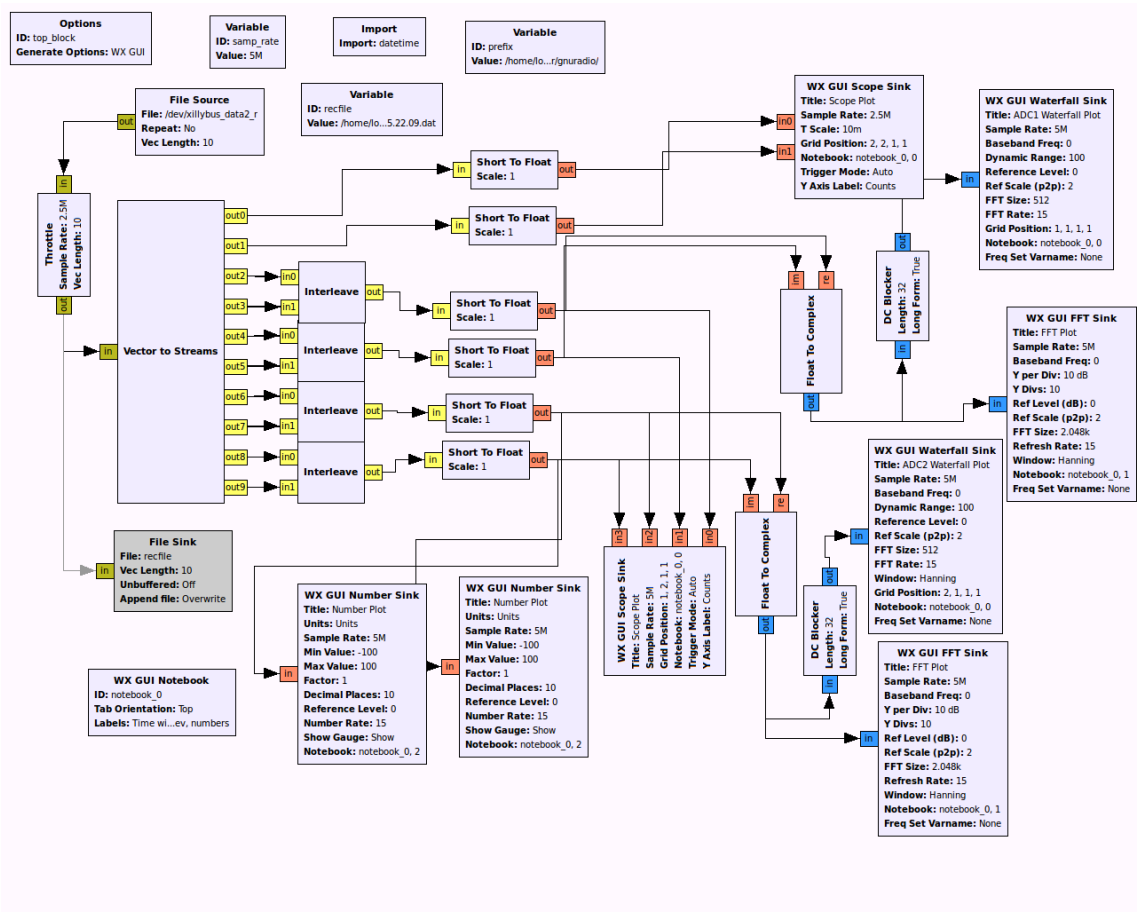


Figure 2.3. ADC recorder flow graph created in gnuradio-companion.

Interactive graber wiewer user interface shows live osciloscope-like time-value display for all data channels and live time-frequency scrolling display (waterfall wiev) for displaying frequency components of grabbed signal.

2.5.2 ADC module parameters

Two pieces of ADC module design were realised and tested first piece denoted as ADC1 has LTC21190 ADC chip populated with LT660015 front-end operational apmlifier. This ADC1 module has 1kOhm resistors populated on inputs which gives to module internal attenuation of input signal. Value of this attenuation A is described by formula

$$A = \frac{1580 \times R_1}{R_1 + R_2}$$

ADC1 CH1 maximal input 705.7 mV
LTC2271 6600125 1k ADC2 CH1 maximal input 380 mV

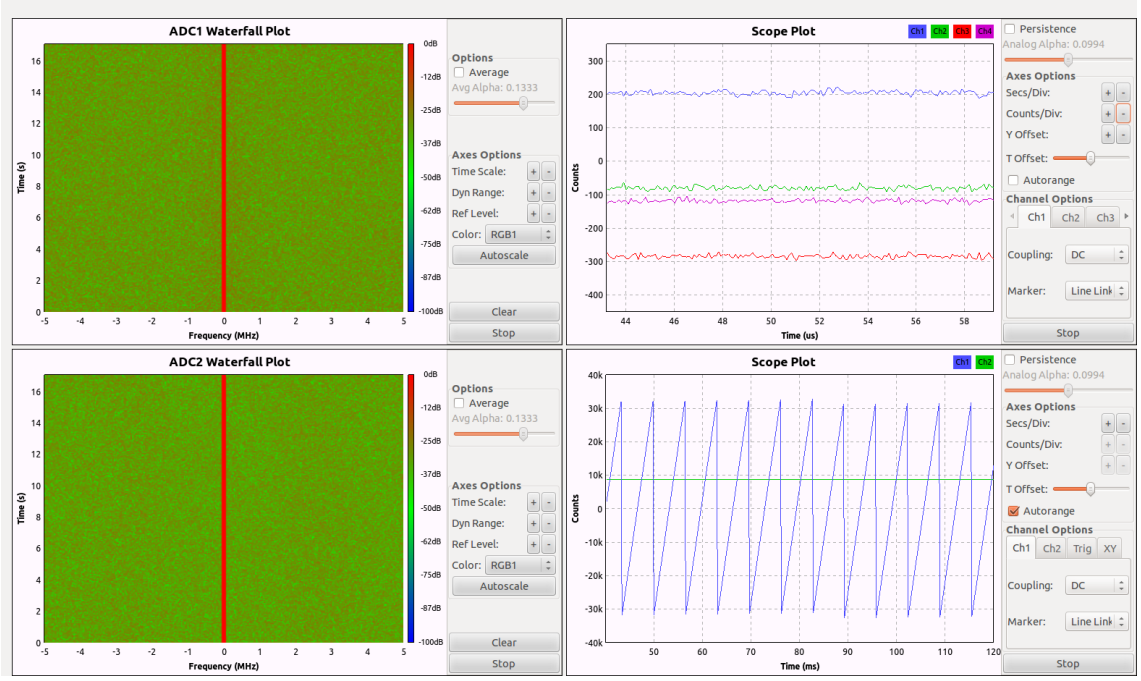


Figure 2.4. User interface window of running ADC grabber.

Figure 2.5. Sine signal from ADC1 module with LTC21190 and LT6600-5 devices.

Figure 2.6. Sine signal from ADC1 module with LTC21190 and LT6600-5 devices.

Chapter 3
Proposed final system

Construction of final system which should be used for real radioastronomy observations will be described. This chapter is mainly theoretical analysis of systems which should be used for data handling. Realisation of these ideas are planed for future development after full evaluation and testing of actual functional example design.

3.1 Custom design of FPGA board

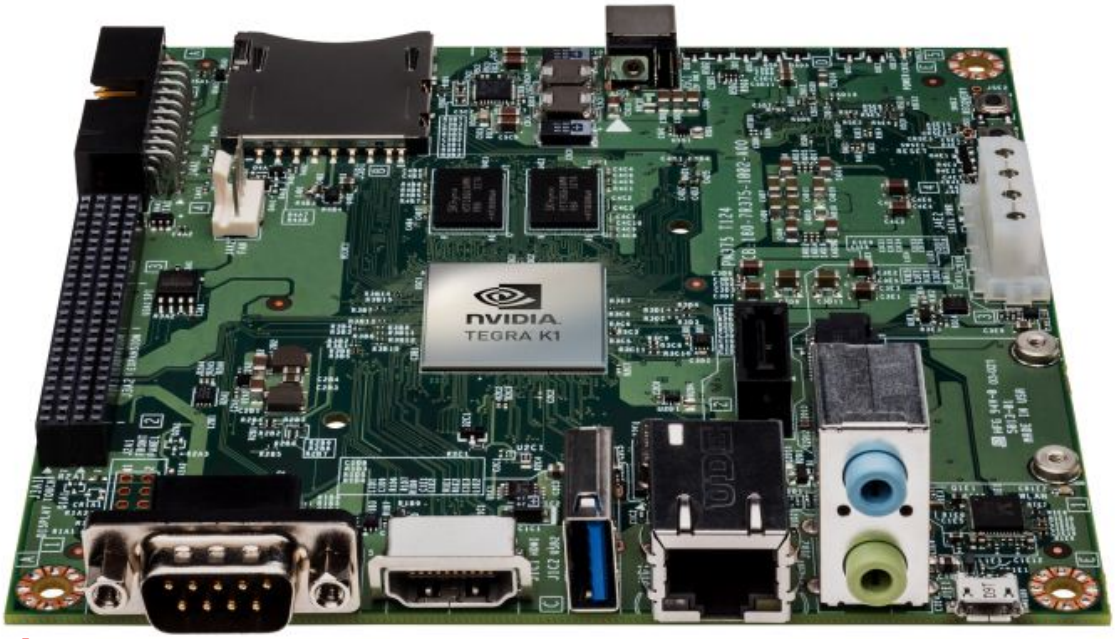
In beginning of the project coustom design of FPGA interface board was supposed. This FPGA board should include PCI express interface and should have lower price than functional example construction. This board should have MLAB compatible design which is backward compatible with existing or improved design of ADC modules. For connection of this board an another adapter board with PCIe host interface was supposed. Thunderbolt technology standard was supposed for use in this PC to PCIe -¿ FPGA module. Thunderbolt chips are currently available on the market for reasonable prices. But specification for these devices are accessible for licensed users only and Intel has mass market oriented licensing policy, which makes this technology inaccessible for low quantity product design. In consequence of this external PCI Express cabling and expansion slots should be better solution.

But this systems and cables are still very expensive. For example (http://www.opalkelly.com/products/x has price tag 995 USD at time of writing this thesis. Therefore better approach must be found.

3.2 Parralella board computer

3.3 GPU based computational system

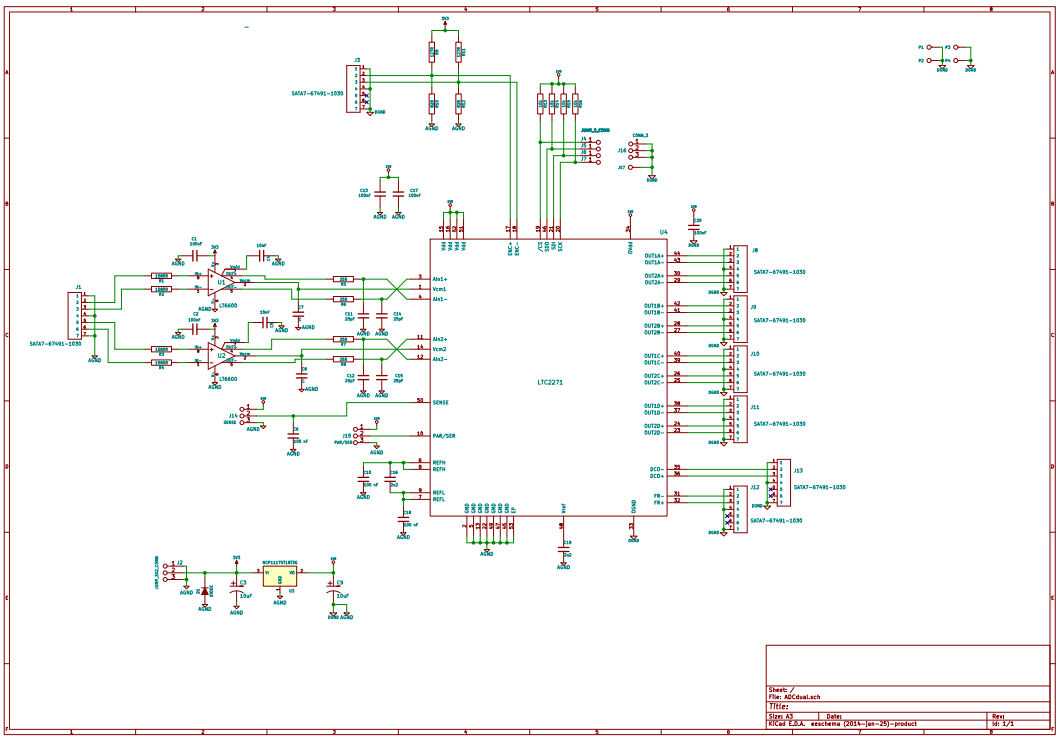
A new GPU development board NVIDIA K1 has been released in recent time it is shown on image 3.1. This board are intended for use in computer vision, robotics, medicine, security, and automotive. This board has ideal parameters for signal processing for this relatively low price 192 USD. But it is currently in pre-order release stage (in April 2014).



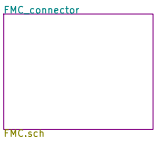
[img-NVIDIA-K1]

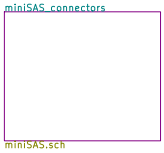
Figure 3.1. The NVIDIA Jetson TK1 Development Kit `https://developer.nvidia.com/jetson-tk1`.

Appendix A
Circuit diagram of ADCdual01A module



Appendix B
Circuit diagram of FMC2DIFF module





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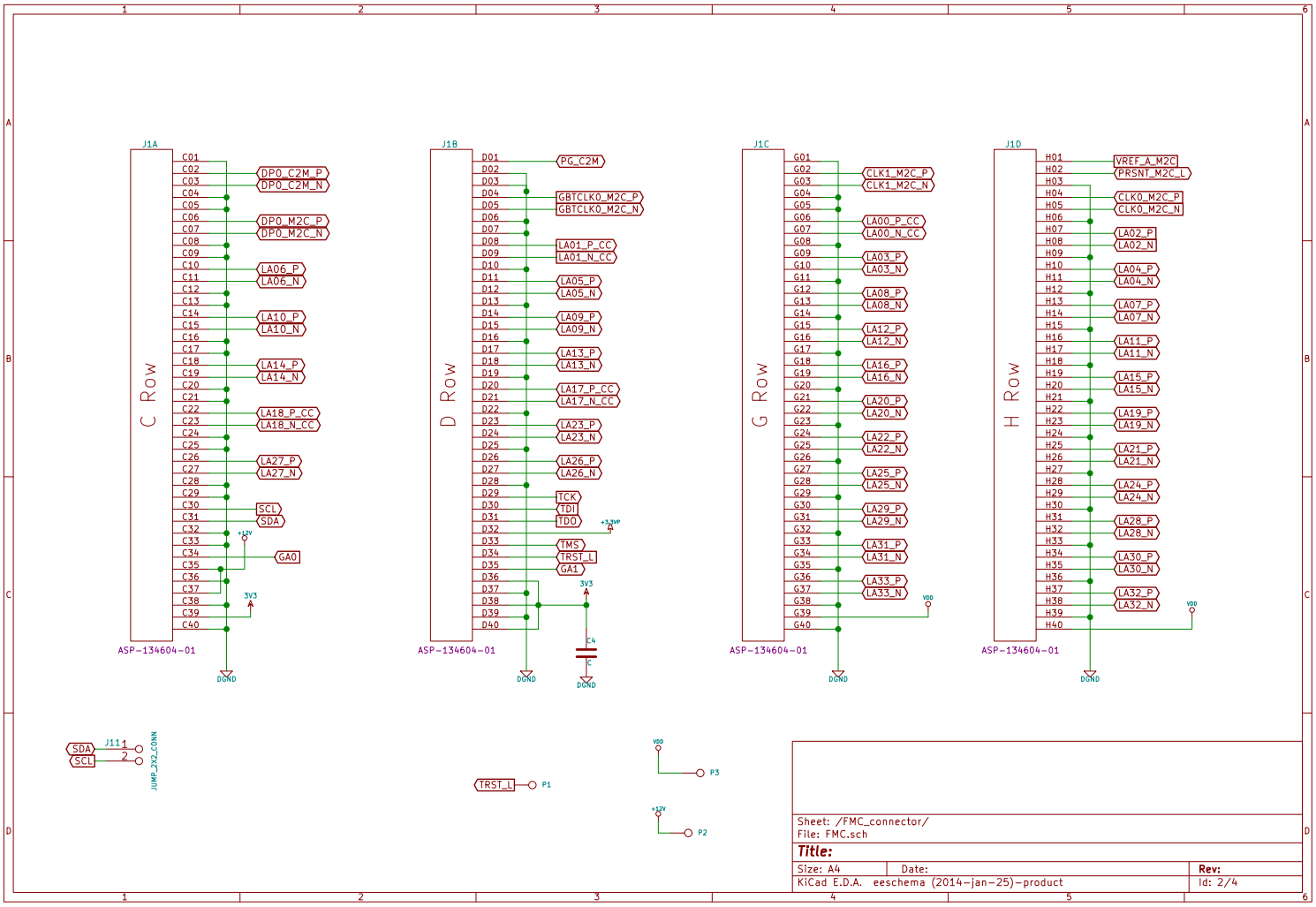
J1A
C Row
C01 C02 C03 C04 C05 C06 C07 C08 C09 C10 C11 C12 C13 C14 C15 C16 C17 C18 C19 C20 C21 C22 C23 C24 C25 C26 C27 C28 C29 C30 C31 C32 C33 C34 C35 C36 C37 C38 C39 C40
DP0_C2M_P
DP0_C2M_N
DP0_M2C_P
DP0_M2C_N
LA06_P
LA06_N
LA10_P
LA10_N
LA14_P
LA14_N
LA18_P_CC
LA18_N_CC
LA27_P
LA27_N
SCL
SDA
GA0
+12V
3V3
DGND
ASP-134604-01
J1B
D Row
D01 D02 D03 D04 D05 D06 D07 D08 D09 D10 D11 D12 D13 D14 D15 D16 D17 D18 D19 D20 D21 D22 D23 D24 D25 D26 D27 D28 D29 D30 D31 D32 D33 D34 D35 D36 D37 D38 D39 D40
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GBTCLK0_M2C_N
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LA01_N_CC
LA05_P
LA05_N
LA09_P
LA09_N
LA13_P
LA13_N
LA17_P_CC
LA17_N_CC
LA23_P
LA23_N
LA26_P
LA26_N
TCK
TDI
TDO
+3.3VP
TMS
TRST_L
GA1
3V3
C4
C
DGND
ASP-134604-01
J1C
G Row
G01 G02 G03 G04 G05 G06 G07 G08 G09 G10 G11 G12 G13 G14 G15 G16 G17 G18 G19 G20 G21 G22 G23 G24 G25 G26 G27 G28 G29 G30 G31 G32 G33 G34 G35 G36 G37 G38 G39 G40
CLK1_M2C_P
CLK1_M2C_N
LA00_P_CC
LA00_N_CC
LA03_P
LA03_N
LA08_P
LA08_N
LA12_P
LA12_N
LA16_P
LA16_N
LA20_P
LA20_N
LA22_P
LA22_N
LA25_P
LA25_N
LA29_P
LA29_N
LA31_P
LA31_N
LA33_P
LA33_N
VDD
DGND
ASP-134604-01
J1D
H Row
H01 H02 H03 H04 H05 H06 H07 H08 H09 H10 H11 H12 H13 H14 H15 H16 H17 H18 H19 H20 H21 H22 H23 H24 H25 H26 H27 H28 H29 H30 H31 H32 H33 H34 H35 H36 H37 H38 H39 H40
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PRSNT_M2C_L
CLK0_M2C_P
CLK0_M2C_N
LA02_P
LA02_N
LA04_P
LA04_N
LA07_P
LA07_N
LA11_P
LA11_N
LA15_P
LA15_N
LA19_P
LA19_N
LA21_P
LA21_N
LA24_P
LA24_N
LA28_P
LA28_N
LA30_P
LA30_N
LA32_P
LA32_N
VDD
DGND
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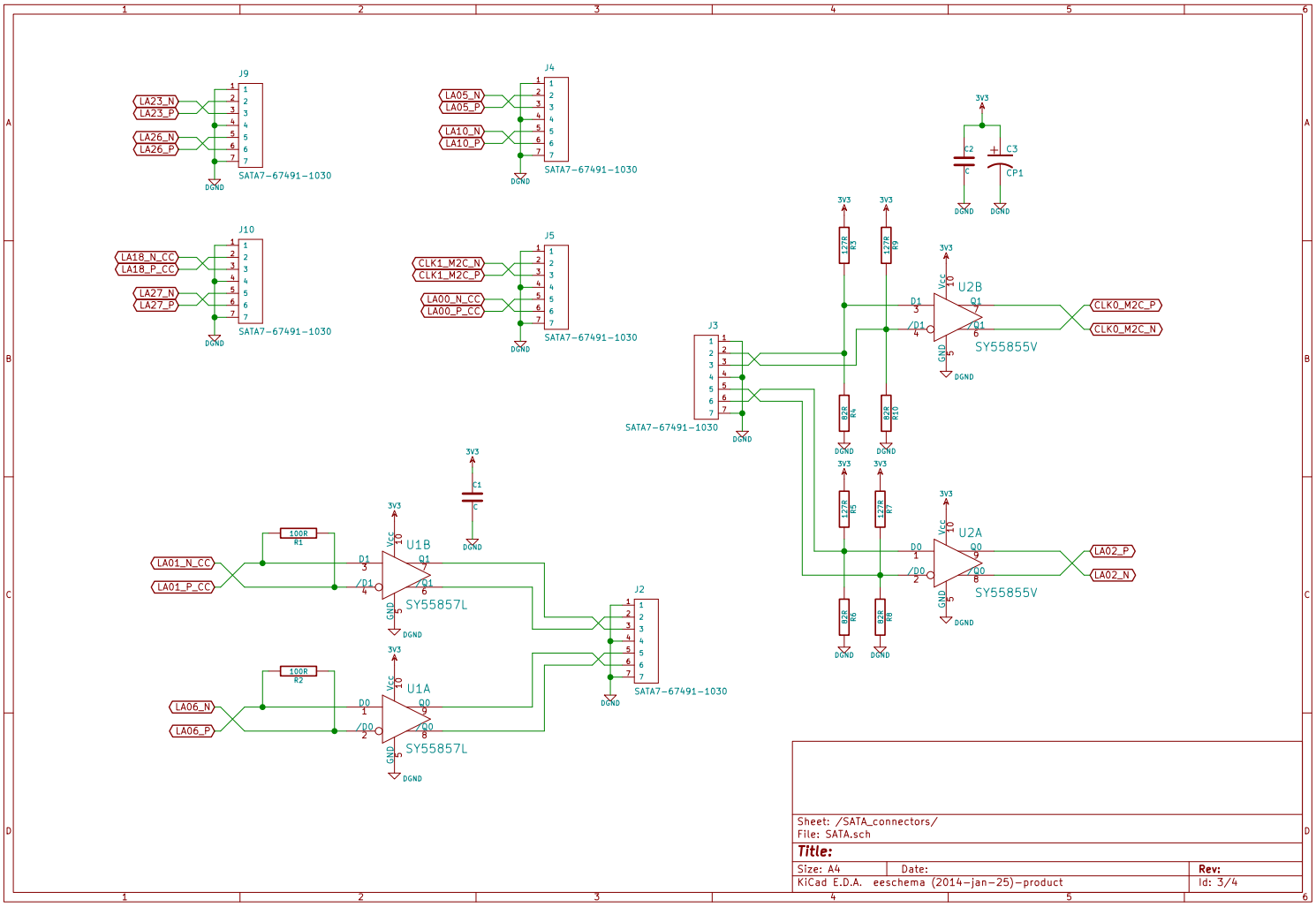
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3V3
C2
C3
CP1
DGND
J10
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LA18_P_CC
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R9
82R
R4
R10
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R6
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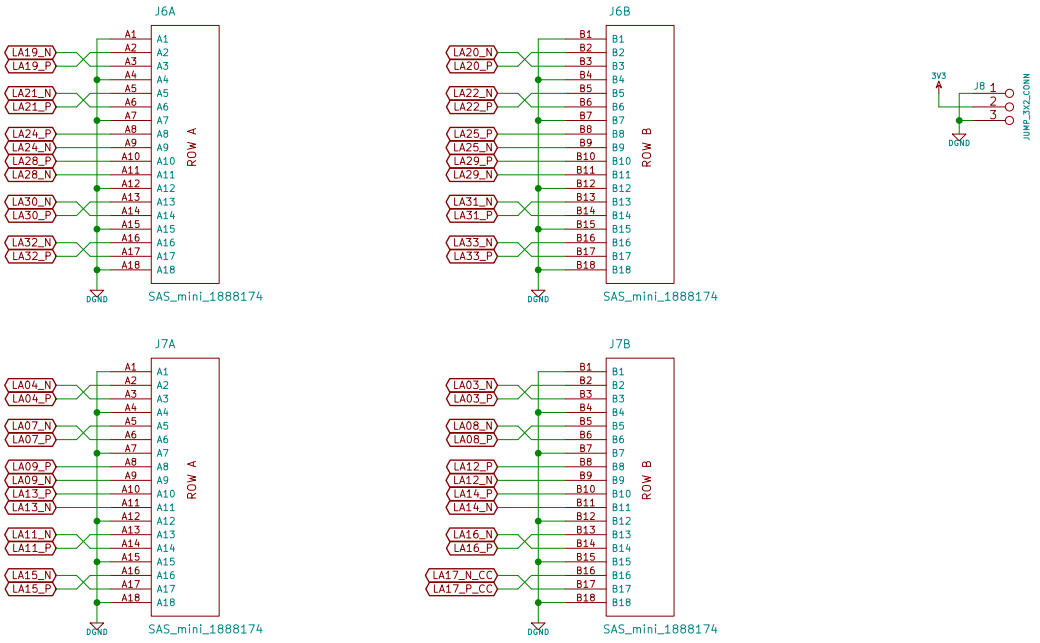

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