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BYU Wideband MIMO Channel Sounder Technical Reference Manual

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BYU Wideband MIMO Channel Sounder Technical Reference Manual

Version 1.0

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BYU Wireless Research Laboratory (YCOMM)

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Chapter 1: Introduction

This document serves as a technical reference manual for the wideband multiple-input multiple-output (MIMO) wireless channel sounder developed at the Wireless Research Laboratory at Brigham Young University. The development of this system is considered an “open hardware project,” which means that the details of the system may be freely used by others interested in designing and building similar systems. Also, it is hoped that the open hardware methodology will lead to fruitful cooperation in improving the system and sharing ideas.

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The organization of this document is as follows:

Chapter 2 presents an overview of the system architecture, explaining the overall design objectives and the main system components.

Chapter 3 provides details on the hardware modules and components, including schematic diagrams and parts lists of any custom-designed hardware.

Chapter 4 demonstrates calibration and use of the system for actual channel measurement campaigns.

Chapter 5 provides a reference of the most important MATLAB/C functions.

Chapter 2: Architectural Overview

This chapter outlines the basic design goals and assumptions of the system development. High-level operating principles of the system are presented, and specific details on the hardware and software are deferred to later chapters.

1 Design Goals

The wideband MIMO channel sounder developed at the BYU Wireless Research Laboratory was designed to allow wideband channel measurement in a number of important environments with fairly modest development time and cost. The main goals for this system were as follows:

Fast Development As much as possible, instruments and conventional off-the-shelf (COTS) components should be used to reduce the development time of the system.

Low Cost The system design assumes an equipment budget of about \$50,000.

Antenna Arrays The system should support up to 8 transmitters and receivers.

Modularity The components in the system should be flexible and modular, allowing easy reconfiguration for different measurement scenarios.

Frequency Range A frequency range of 2-8 GHz was deemed sufficient to cover current wireless bands of interest.

Bandwidth The system should support an instantaneous bandwidth of 100 MHz, allowing study of realistic communications signaling.

Mobility The system should support the measurement of mobile (time-varying) channels.

2 High-level System

The architecture which resulted from these basic design goals is depicted in Figure 2.1. The key operating principle of this system is the “switched array” technique, where the different antenna elements are connected to the transmitter and receiver via high speed microwave switches. Although “true array” architectures exist that measure the multiple transmit/receive channels simultaneously, such systems tend to be expensive, require longer development, and complicate maintenance and calibration. Since conventional high-speed microwave switches are available with switching times on the order of $1 \mu\text{s}$, the non-ideal response induced by a switched measurement is small.

The operation of the system is fairly straightforward. At the transmitter, an arbitrary waveform generator (AWG) creates a wideband probing signal, which is up-converted to the microwave band of interest by mixing with the local oscillator (LO). This signal is power amplified and fed to the single-pole eight-throw (SP8T) microwave switch, which routes the signal to one of eight transmit antennas. At the receiver, the signals on the different receive array elements are routed via another SP8T switch to a single radio-frequency (RF)

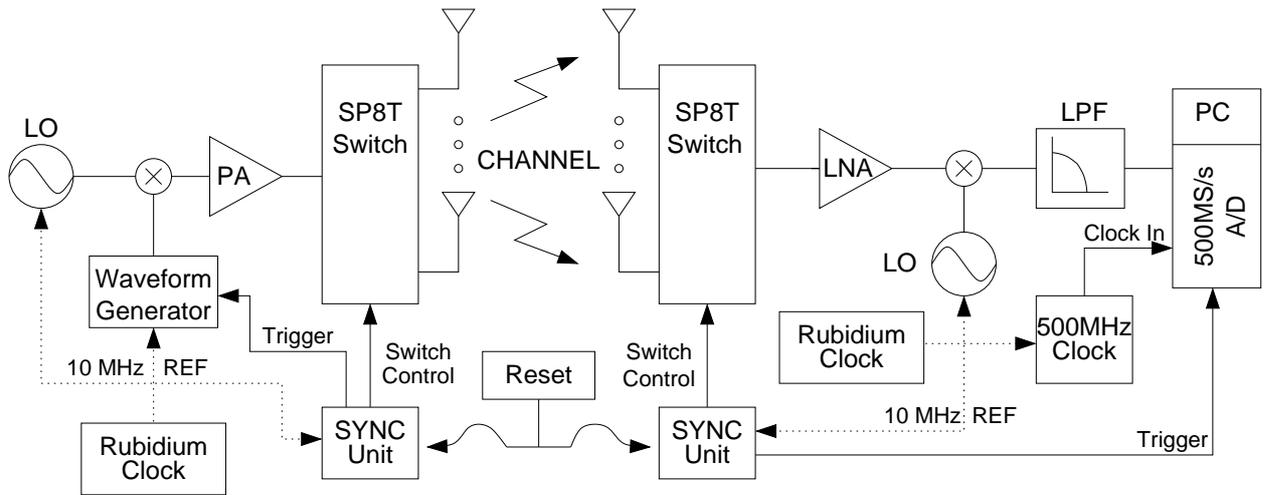


Figure 2.1: High level diagram of the BYU wideband MIMO channel sounder

receiver, consisting of low-noise amplification, single-stage down-conversion to an intermediate frequency (IF), low-pass filtering (LPF), automatic gain control (AGC), and sampling and storage with a PC-based A/D card.

Coordinated switching of the transmit and receive arrays is accomplished by a custom-designed synchronization (SYNC) unit, ensuring that all combinations of transmit and receive antennas are probed. All timing in the system is referenced to highly stable 10 MHz rubidium time/frequency references, ensuring proper timing and phase coherence throughout the system. Initially, the SYNC counters at transmit and receive must be reset manually with a simple trigger switch.

Chapter 3: Hardware Components

This chapter describes the hardware components in detail, allowing troubleshooting and maintenance of existing systems or building of new copies of the system. Sections 1 and 2 provide information on the transmit and receive subsystems, respectively, and Section 3 provides some information on antenna arrays that have been used with the system.

1 Transmitter Subsystem

Figure 3.1 depicts a block-diagram of the transmit subsystem. The following subsections describe these components and connections in detail. The basic operation of the transmitter is as follows. A single-channel baseband probing signal is generated on the AWG. The RF module mixes this signal with the LO to up-convert to the microwave center frequency and feeds this signal via a microwave switch to one of eight microwave outputs. The output signals (after optional power amplification) are delivered to the transmit antenna array. The synchronization unit controls timing of antenna switching and AWG bursts. Figure 3.2 depicts the transmit subsystem mounted on a cart.

1.1 Instruments

A highly stable Rubidium reference provides a 10 MHz clock to all time-sensitive components in the transmit subsystem. The 10 MHz signal is connected via a 3-way “Tee” to the high-impedance SYNC module input. Since instruments generally terminate the reference clock input, either an In/Out cabling procedure should be followed (as shown in the diagram) or a 10 MHz distribution buffer should be used for the remaining instruments.

The AWG creates the baseband waveform required for sounding the channel. Although a multitone signal is used in the BYU wideband channel sounder, other signals (frequency sweep, pseudonoise sequence, etc.) could also be employed. A description of multitone signal construction is provided in Section 1 of Chapter 4.

The LO provides the single microwave tone required by the RF module, necessary for up-conversion of the signals.

The specific instruments used in the BYU sounder are listed in Table 3.1, along with notes on specific operational parameters.

1.2 SYNC Module

System synchronization at transmit and receive is accomplished with a SYNC module, consisting of counters operating at a rate of 10 MHz. The unit provides antenna selection signals and event outputs required for antenna switching and AWG and A/D triggering. Figure 3.3 shows a schematic diagram of the synchronization module, which is available as a gEDA schematic under `./design/schem/sync_gate.sch`. VHDL code that simulates the operation of this circuit may be found under `./design/vhdl/sync_unit`.

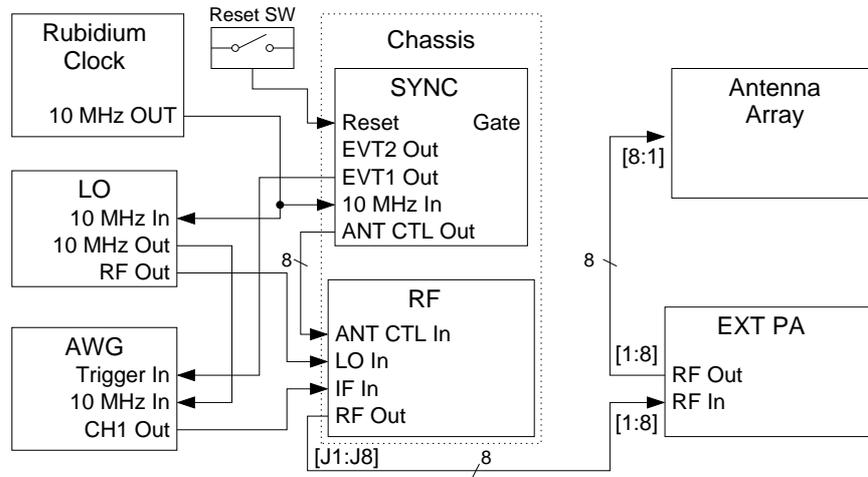
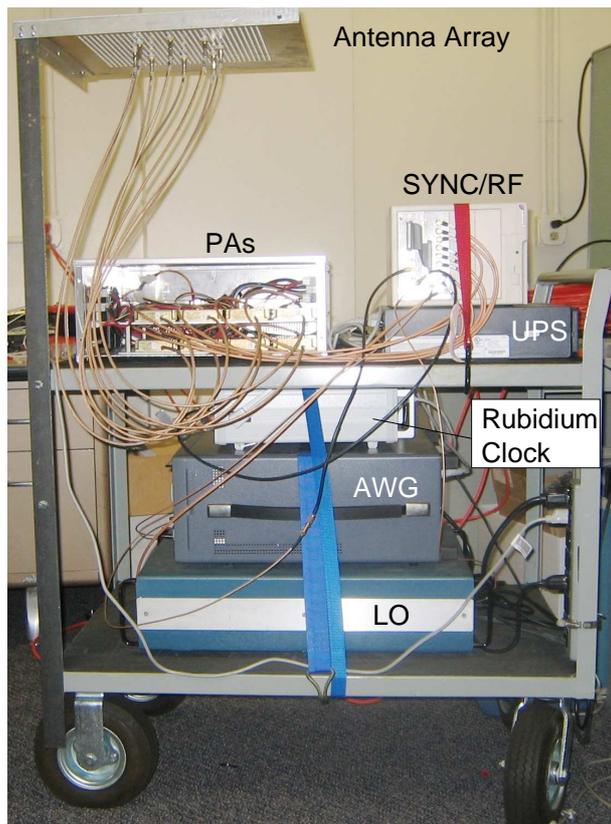


Figure 3.1: Block diagram and connections of the transmit subsystem



(a) Side View



(b) Front View

Figure 3.2: Photos of the (a) side and (b) front of the transmit system, showing the major instruments and modules

Component	Instrument Used	Notes/Operating Parameters
Rubidium Clock	Symmetricon RubiSource T&M	These rubidium time-frequency references are factory-configured to provide 500mV RMS sine wave output on the front panel at 1, 5, and 10 MHz. The 10 MHz sine output is used as the clock input to the components in the BYU system. Also provided are 5 and 10 MHz square wave signals. A nice feature of the RubiSource reference is the ability to connect the 10 MHz output of one source to the input of another for automatic frequency calibration. Other similar sources often require programming via an RS-232 interface to accomplish fine frequency tuning. List price is about \$6000 per unit.
LO	Gigatronics 905	This is an older but dependable synthesized microwave source providing the local oscillator signal in the range from 10 MHz to 26 GHz. The 10 MHz In and Out ports are on the back panel, labeled as EXT CLK IN and INT CLK OUT, respectively. A single SMA connector on the front panel provides RF output from low levels up to 7 dBm. This unit was acquired used on another project for about \$6000.
AWG	Lecroy LW410	This arbitrary waveform generator features 8-bit resolution and 400 MS/s output rate, accommodating an analog bandwidth of up to 100 MHz. Waveforms are loaded via MATLAB ASCII files stored on a 3.5" floppy disk. Details on constructing waveforms for this unit may be found in Section 1 of Chapter 4. Although the instrument has 10 MHz input and output ports on the back panel, the 10 MHz output should not be used, since it is not locked to the input reference. The trigger mode for the device should be set to "single," so that a single burst of the probing waveform is output for each EVT1 clock from the SYNC unit.

Table 3.1: Specific instruments and operating parameters of the transmit subsystem used in the BYU wideband channel sounder

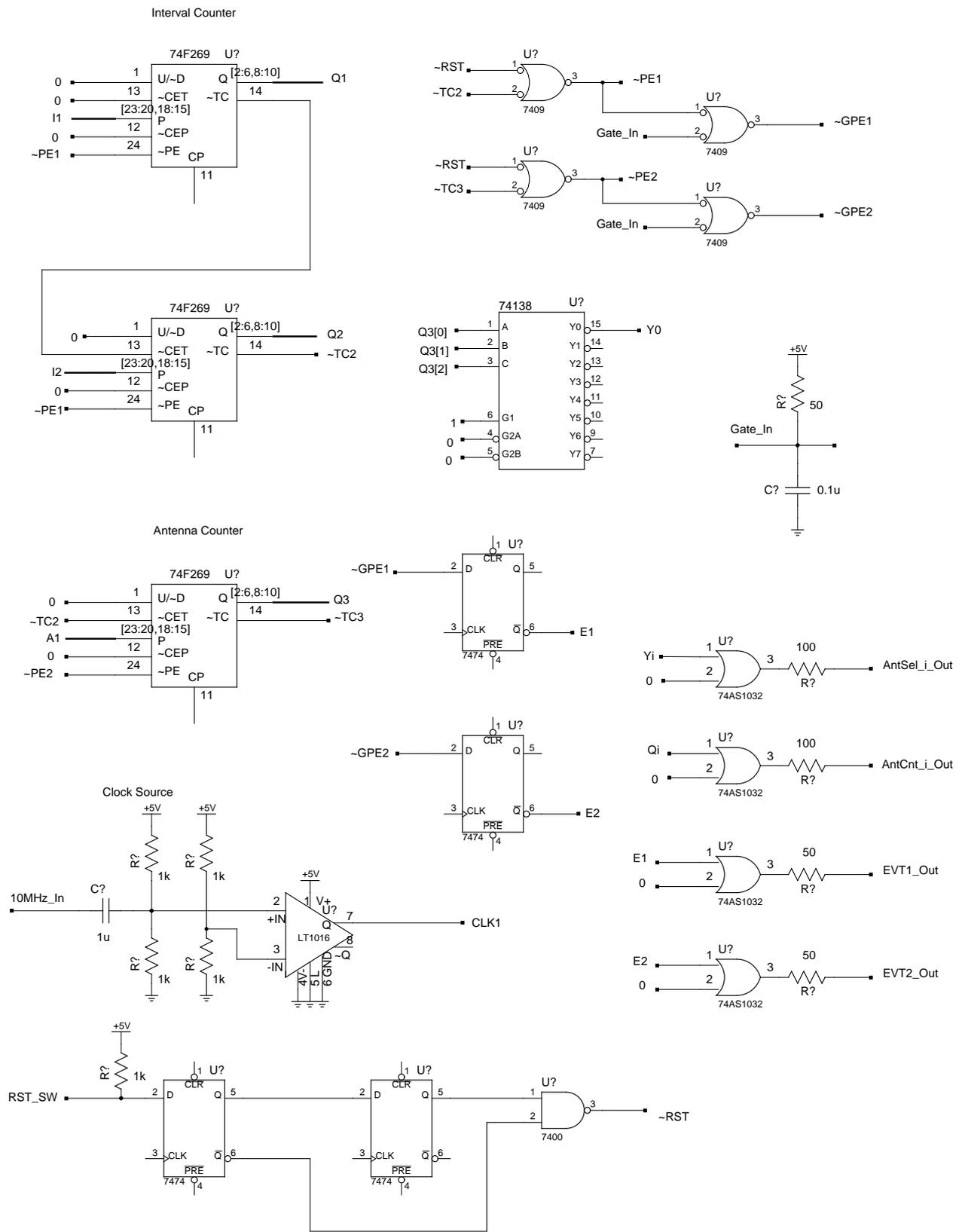


Figure 3.3: Schematic diagram of the synchronization (SYNC) unit

The timing on the SYNC board is driven by the single 10 MHz input. The board assumes that the input signal is a 10 MHz sine wave, and the “clock source” circuit converts this input to a 5 V TTL signal with a comparator. The inputs of the comparator are set to a quiescent level of 2.5 V with resistive voltage dividers. The positive comparator input is then capacitively coupled to the 10 MHz reference. Thus, positive and negative input levels correspond to 5 V and 0 V TTL outputs, respectively. Note that the 10MHz_In input is left unterminated, thus presenting a high impedance and allowing another reference input to be connected in tandem.

As depicted, the SYNC board consists of three 8-bit counters (74F269) operating at 10 MHz. The three counters are arranged into a 16-bit “interval counter” that controls the dwell time on each antenna and an 8-bit “antenna counter” that cycles through the antennas. Thus, dwell times from 100 ns to 6.5 ms and antenna counts from 1 to 256 are accommodated. The interval counter decrements on each clock cycle, and upon reaching the terminal count of zero performs a parallel reload of its starting value, enables the antenna counter to decrement, and asserts the \sim TC2 signal. When both the interval and antenna counters simultaneously reach their terminal count, the antenna counter is also reloaded and the \sim TC3 signal is asserted. The initial values of both counters are currently set by hexadecimal dials, which should be set to the desired interval *minus one*. The dials are single-throw switches, and the outputs must be pulled down with 1 k Ω resistors on the board.

The 8-bit antenna counter value is fed via high-speed line drivers with 100 Ω source termination to a ribbon cable connector. Since many commercial packaged PIN-diode switches have separate negative-logic enable lines for each port, a 74F138 device decodes the three least-significant bits and provides the negative-logic strobe signals for the switches via line drivers to the ribbon cable interface. In order to simplify triggering of AWG bursts and A/D conversion, event signals are also provided. The EVT1 signal is a synchronous and inverted version of the \sim TC2, thus asserting a pulse each time the interval counter resets. Likewise, the EVT2 signal is derived from the \sim TC3 signal, providing a pulse when the antenna counter resets. The event signals are delivered by 50 Ω source-terminated line drivers fed to SMA connectors.

Because the antenna counter counts in reverse order, the antenna outputs will be excited in descending order. For example, for a 4-antenna measurement, the port excitation order is J4, J3, J2, J1. The backwards order must be accounted for either by reversing the order of connection to the array (as in Figure 3.1) or by reversing the rows and columns of measured channel matrices during data processing.

An optional Gate_In signal allows the event signals to be gated by an external signal. This may be useful, for example, if two or more A/D cards must trigger simultaneously, and events need to be inhibited until both cards are set up and ready to be triggered. As depicted in Figure 3.4, a low signal on Gate_In will impede rising-edge triggering. Gate_In is pulled high with a 1 k Ω resistor, allowing normal un-gated operation when Gate_In is not connected.

The SYNC board is initially reset by an external reset switch connected to the RST_SW input. A temporary low signal on the RST_SW input creates a single reset pulse that causes the two counters to be loaded with their initial values. Figure 3.5

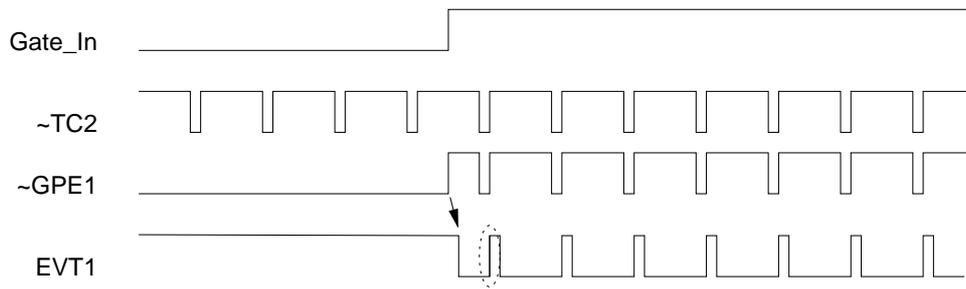


Figure 3.4: Timing of the gate signal, allowing rising-edge triggering to be externally inhibited



Figure 3.5: Trigger connected to two transmission lines, allowing simultaneous reset of two SYNC boards

depicts a reset switch used to trigger two SYNC boards simultaneously. This very simple unit consists of a momentary switch that simultaneously shorts the two SMA cables to ground when the button is pressed. When the two cables are connected to two SYNC boards, this action causes the boards to begin counting at the same time.

Figure 3.6 depicts a layout of the SYNC board and Table 3.2 lists components that were used. Layout files are available under `./design/ads/sync_card_prj/networks/main_gate.dsn`. Note that each chip has a $1\ \mu\text{F}$ chip capacitor providing bypass at the VCC. In this circuit, faster logic families, such as 74F and 74AS have been used to minimize propagation time and ensure smooth operation at 10 MHz. Figures 3.7 and 3.8 show the top and front of the completed SYNC module, respectively. Here, the board has been mounted inside a 3.5" to 5.25" drive converter to allow the unit to be placed conveniently in a computer chassis. Also, note that the 5 V power is

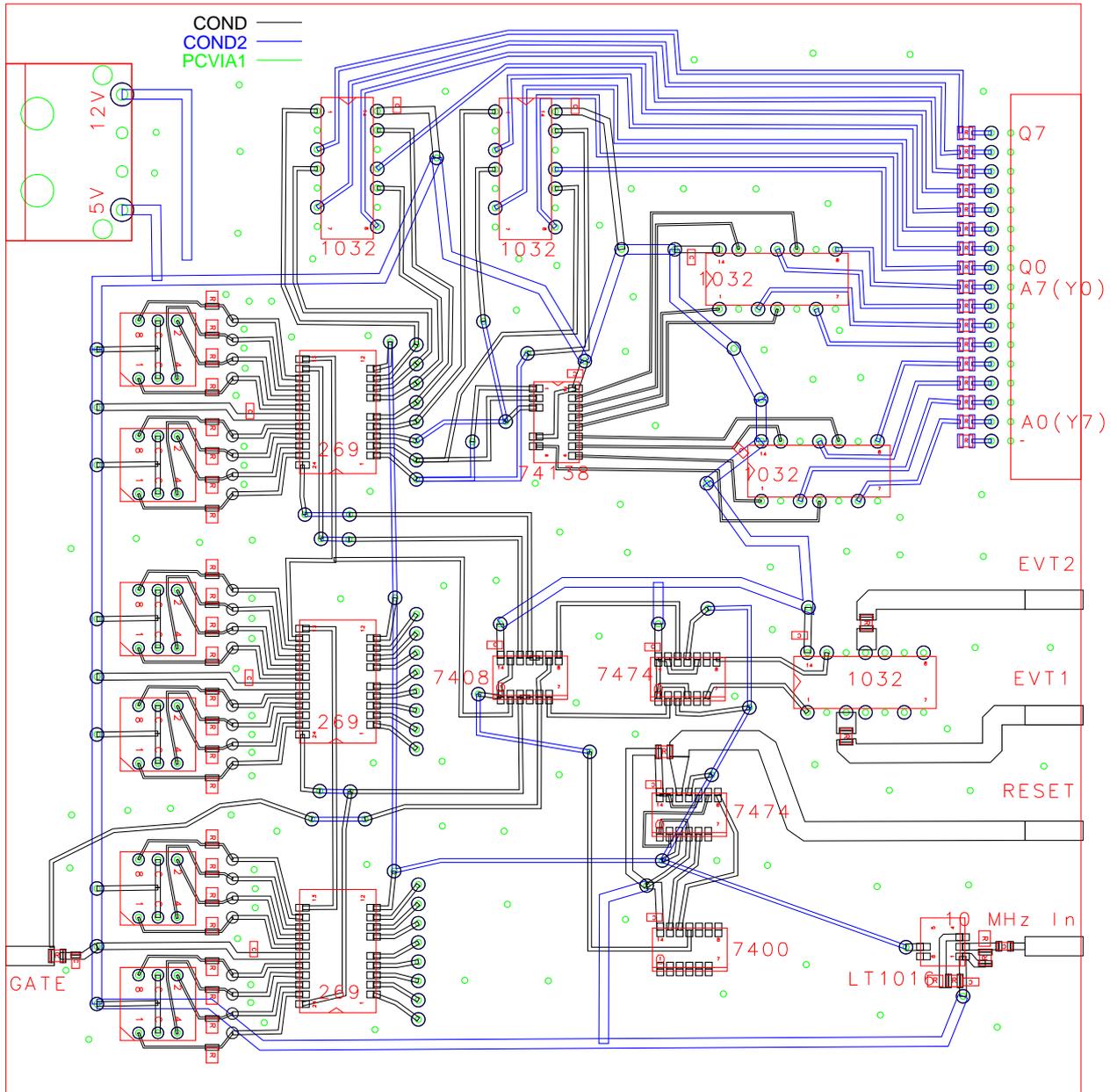


Figure 3.6: Layout showing top and bottom of the SYNC board

delivered via a standard disk drive power cable. The total cost of parts for the SYNC board is about \$200. A pinout of the control lines on the ribbon cable is shown in Figure 3.9.

1.3 RF Module

The RF module houses the microwave components required for up-conversion of the baseband probing signal to the microwave carrier and routing of the signal to the proper output antenna. A block diagram of the transmit RF module is shown in Figure 3.10. A top view of the completed RF module is shown in Figure 3.11 and a close up of the front connections of both the SYNC and RF modules is depicted in Figure 3.12. A list of the commercial components used in this module are listed in Table 3.3. Total cost of parts for the transmit RF module was about \$4000.

The transmitter RF module operates by mixing the external LO and IF signals to obtain the probing signal at the RF carrier. This signal is amplified by a power amplifier (PA) and fed to one of eight output ports (J1-J8) via a microwave switch. The switch is controlled by external TTL signals provided via a ribbon cable interface.

Two small interface cards were required in order to supply power and signals to the microwave switch. Figure 3.13 depicts a schematic, layout, and photo of the voltage regulation board. This board uses a simple DC-to-DC converter to convert the +12 V input signal to a -12 V output, required by the switch. The +5 V and +12 V signals are also passed through.

(pinout of ribbon cable)

The switch interface card accepts the antenna control signals via a ribbon cable header and directly connects these and external power to the sub-D connector required by the switch. A layout and photo of the interface card are shown in Figure 3.14. The blue wire was added between an unused pin on the 34-pin header and the +5 V supply to allow an external manual selection card to control the switch. A layout and photo of the selection card are depicted in Figure 3.15. On this card, the switch control inputs are normally pulled up via a 1 k Ω (connected to pads on the back of the board) resistor to +5 V. Turning ON a particular DIP switch connects the given control signal to ground, thus enabling that port on the switch. This card is useful for manual testing and calibration of the RF module.

A complete list of components required for the transmit RF module and switch selection card are listed in Table 3.4.

1.4 Output Power Amplifiers

Conventional PIN diode switches are often unable to handle high power levels, thus necessitating external power amplification for longer range measurements. Figure 3.16 depicts a chassis containing 5 W power amplifiers operating over the 2.3-2.5 GHz band.

The power amplifier chassis consists of 8 EmpowerRF MBM232579 amplifiers and two PC switching power supplies. Two power supplies were used to satisfy the 1.5 A

Item	Source	P/N	Qty.	Description
1	Digikey	GH1321-ND	6	Rotary Dip Switches
2	Arrow	74F269	3	8-bit counter
3	Arrow	74F74	2	Flip Flops
4	Arrow	74F00	1	NAND Gates
5	Arrow	74F08	1	AND Gates
6	Arrow	LT1016	1	High Speed Comparator
7	Digikey	DM74AS1032AN-ND	5	Quad Line Driver (or)
8	Digikey	296-14793-5-ND	1	3:8 Decoder (74AS138)
9	Digikey	A26295-ND	1	34-pos Header (RA)
10	Digikey	J658-ND	5	Edge Launch SMA Connectors
11	Digikey	P1.00KCCT-ND	29	1 kOhm Resistors
12	Digikey	P100CCT-ND	17	100 Ohm Resistors
13	Digikey	P50CCT-ND	3	50 Ohm Resistors
14	Digikey	PCC2287CT-ND	15	1 uF Capacitors
15	Digikey	PCC1788CT-ND	1	0.1 uF Capacitors
16	Jameco	P/N 117567	1	Disk Drive Connector
17	Rogers	RO4003C	1	Substrate
18	Tiger Direct		1	5.25" Disk Drive Adapter

Table 3.2: List of components for the SYNC board

Component	Model	Notes/Operating Parameters
Mixer	M/A-COM MY84	Double-balanced mixer operating with LO/RF from 1.8 to 10 GHz and IF from DC to 1000 MHz. Nominal LO drive is +9 dBm and LO/RF isolation is about 40 dB. This high isolation mixer was chosen to avoid the LO bleedthrough present with the simple direct up-conversion scheme.
Power Amplifier	Mini-Circuits ZVE-8G	Broadband power amplifier operating from 2-8 GHz with +30 dB gain and a 1 dB compression point of 30 dBm. The unit requires a single 12 V 1.2 A supply.
SP8T Switch	Herley F9180W	PIN diode switch operating from 1-18 GHz with terminated "OFF" ports (non-reflective). The switch operates linearly at about 100-200 mW, and can handle up to 1 W peak average input power. Isolation between output ports is 60 dB and insertion loss is about 3 dB. Switching time is 250 ns. Power and TTL control signals are supplied to the switch via a 15-pin female sub-D connector.

Table 3.3: Commercial components used in the transmit RF module

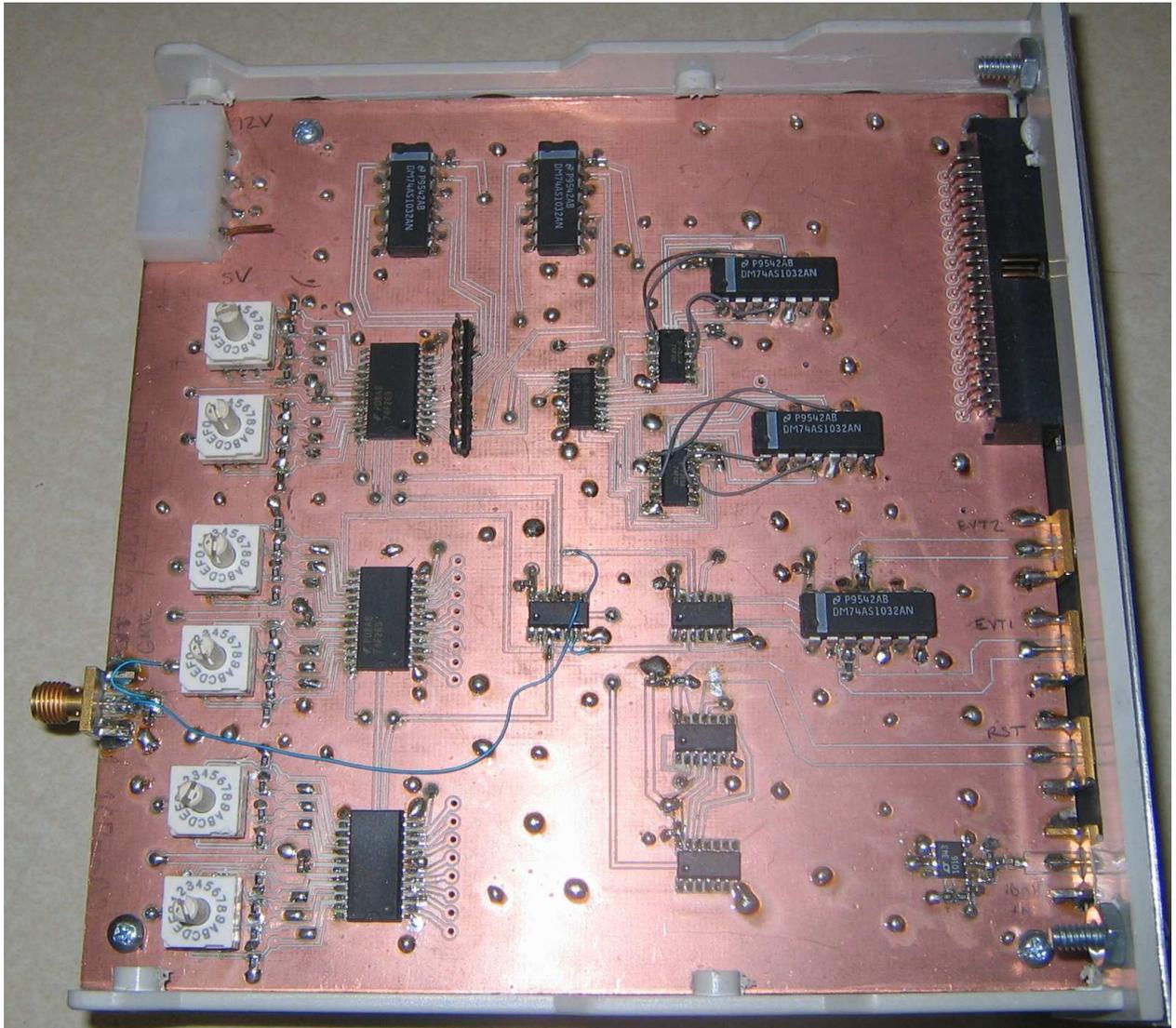
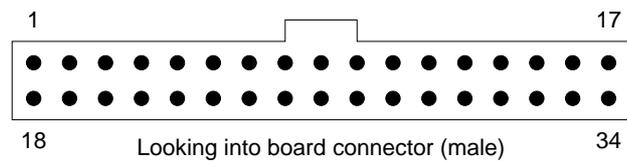


Figure 3.7: Photo showing top of the SYNC board. On this prototype, rework was necessary to invert the switch output logic and add the GATE input signal.



Figure 3.8: Front panel of the SYNC module with inputs for 10 MHz clock and reset, and outputs for events and antenna control



Pin	Description
1	Connected to +5V on RF modules
2..9	Antenna selection ~Y7..~Y0
10..17	Antenna Index Q0..Q7
18..34	GND

Figure 3.9: Pinout of SYNC card cable

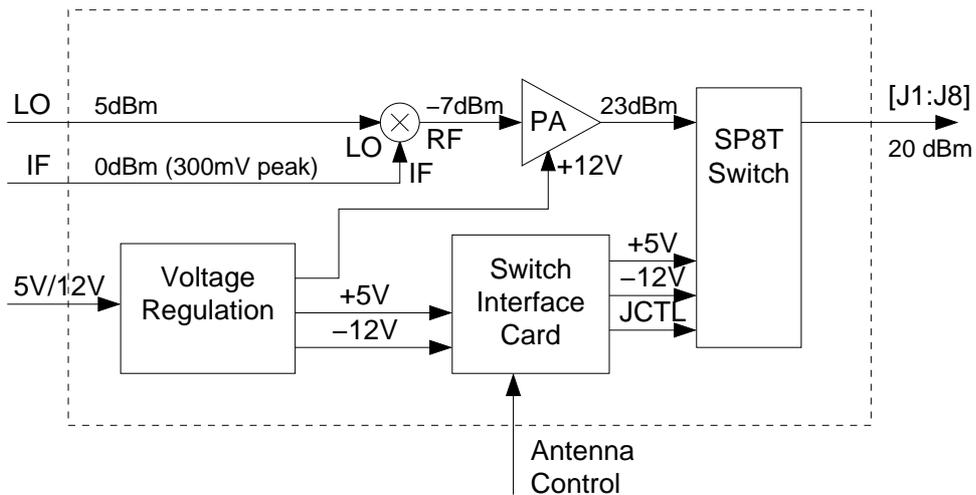


Figure 3.10: Block diagram of transmit RF module. Nominal RF power levels are also shown.

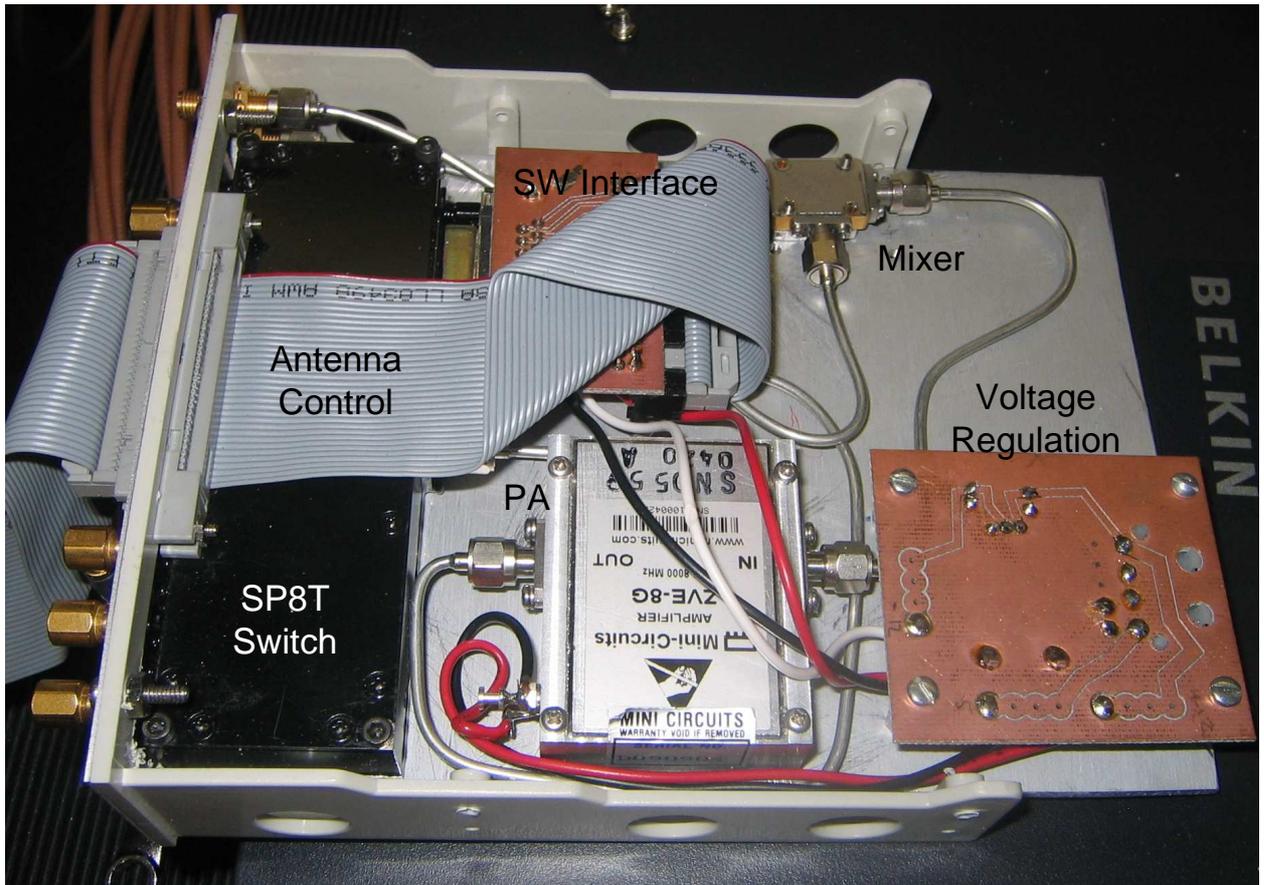


Figure 3.11: Top view of the completed RF module

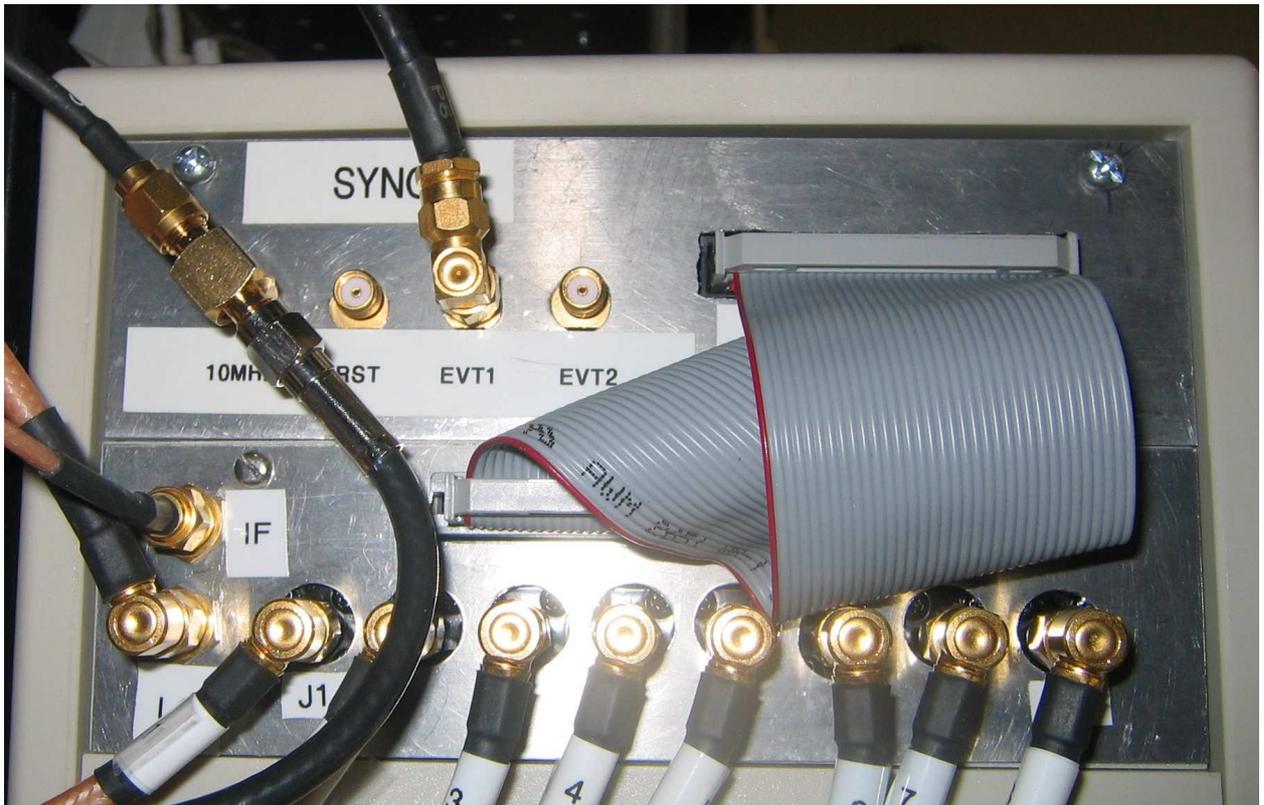


Figure 3.12: Front connections of the transmit SYNC and RF modules. These two modules are housed in a StarTech SCSI3CASE4 chassis.

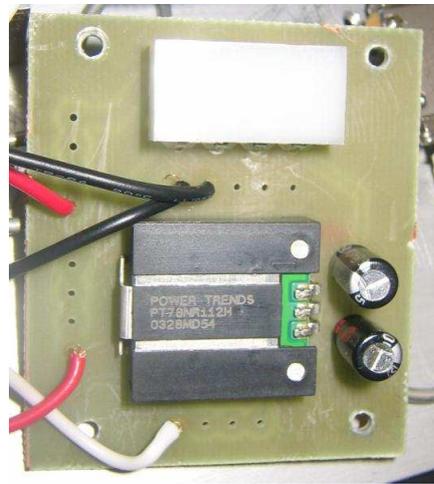
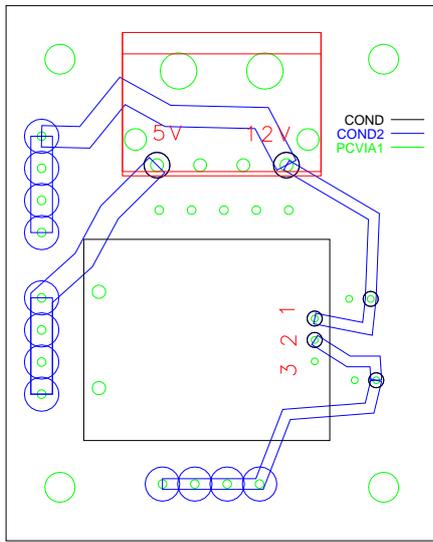
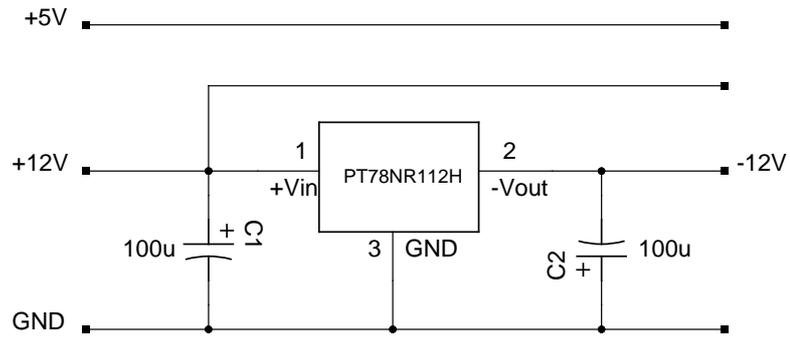


Figure 3.13: Voltage regulation board used on the transmit and receive RF modules

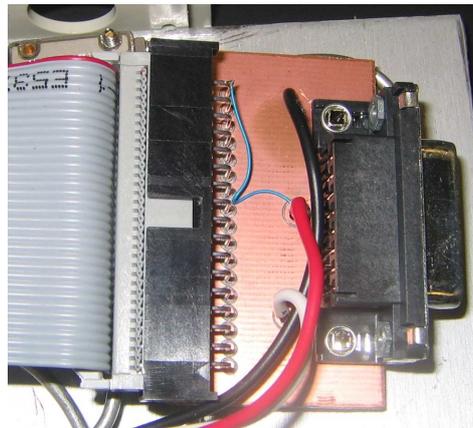
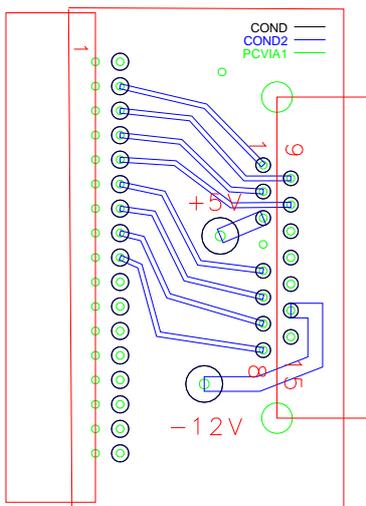


Figure 3.14: Switch interface card used to supply TTL switch control signals and power to the SP8T switch.

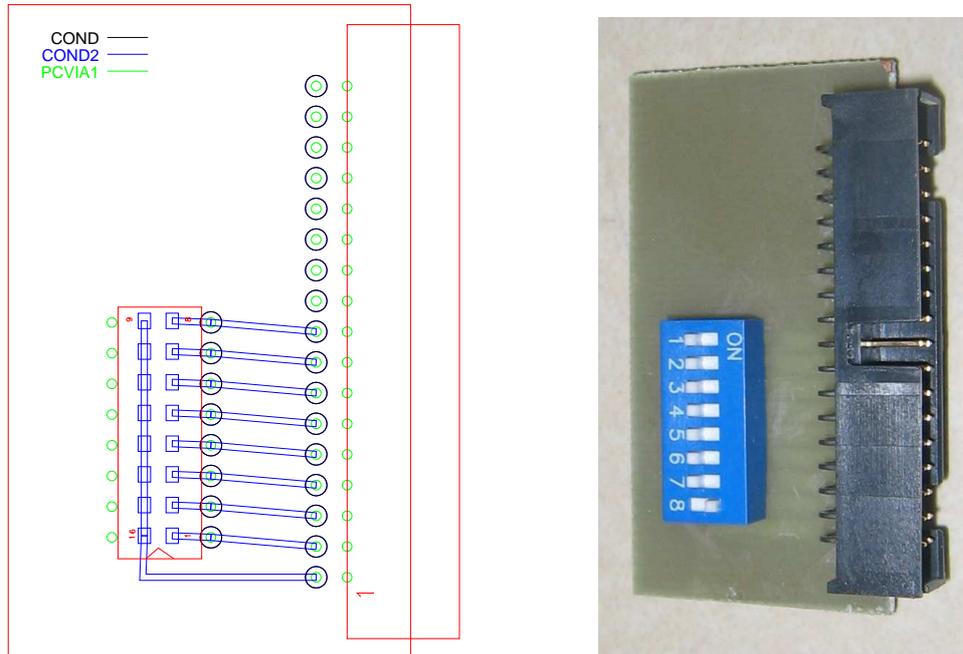


Figure 3.15: Selection card used to manually control SP8T switch

Item	Source	P/N	Qty.	Description
1	Mini-Circuits	ZVE-8G	1	1W 2-8 GHz power amplifier
2	Herley	F9180W	1	SP8T Switch
3	M/A-COM	MY84	1	2-8 GHz Mixer
4	Newark	97F922	2	Bulkhead connectors
5	Pasternack	PE-SR405AL		Semi-rigid cable
6	Digikey	MPL34K-ND	1	34-pos header (panel)
7	Digikey	J488-ND	8	Semi-rigid SMA connectors
8	Digikey	A2097-ND	1	Male D-sub connector (RA)
9	Digikey	A26295-ND	2	34-pos Header (RA)
10	Digikey	P1.00KCCT-ND	8	1 kOhm Resistors
11	Digikey	P5540-ND	2	100 uF electrolytic capacitors
12	Digikey	PT78NR112H-ND	1	voltage regulator
13	Digikey	MSC34A-ND	3	34-pos ribbon cable connector
14	Jameco	P/N 117567	1	Disk Drive Connector
15	Jameco	125794		20AWG Hookup wire
16	Jameco	38842	1	8-pos DIP switch
17	Jameco			34-cond ribbon cable
18	Tiger Direct		1	5 1/4" Disk Drive Adapter
19	Rogers	RO4003C	1	Substrate

Table 3.4: List of components for the transmit RF module

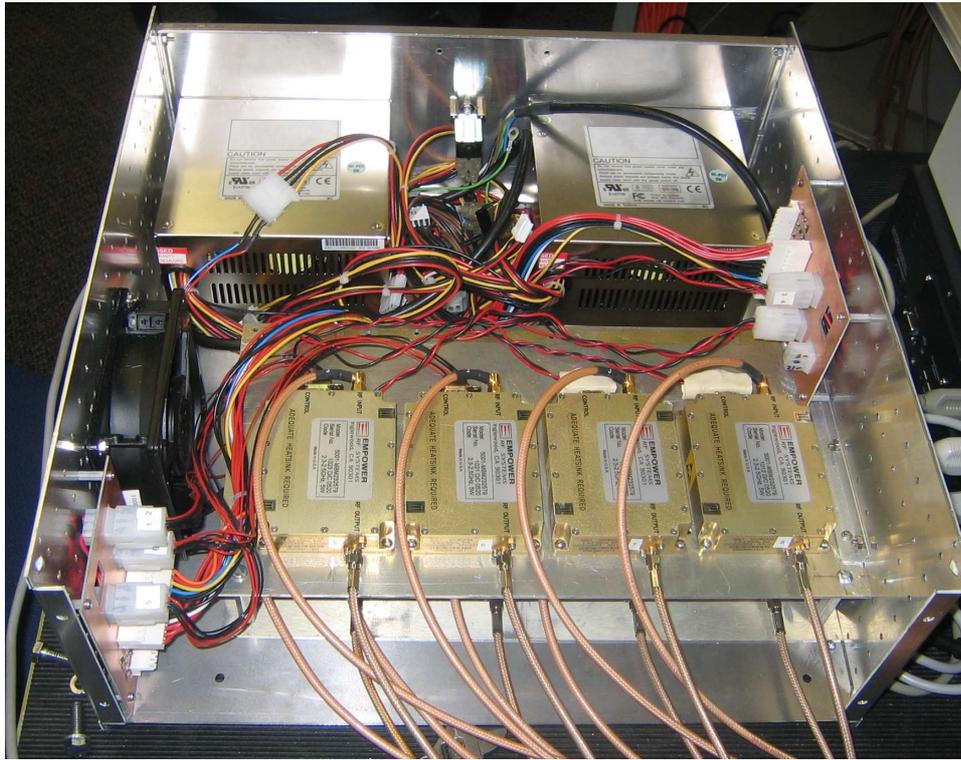


Figure 3.16: Chassis containing eight 5 W power amplifiers

power draw per amplifier. The amplifiers are arranged in two levels of four amplifiers and bolted to aluminum plates inside a BUD RM-14213 chassis. A large fan on one side of the chassis moves air across the plates, ensuring that the maximum amplifier case temperature of 70°C is not exceeded. The cost of the parts for the complete unit is about \$5000.

Figure 3.17 depicts the power distribution card which converts the PC power supply connector to multiple 6-pin Molex connectors carrying $\pm 5\text{ V}$ and $\pm 12\text{ V}$. The ADS layout for this card may be found under `./design/ads/at_to_molex/networks/card1.dsn`.

2 Receiver Subsystem

Figure 3.18 depicts a block-diagram of the receive subsystem. The following subsections describe these components and connections in detail. The basic operation of the receiver is as follows. The RF module employs a SP8T switch to route the signal from one of the receive antennas to a common RF receive chain consisting of a low noise amplifier (LNA), a mixer for single-stage downconversion to an intermediate frequency (IF), and a low-pass filter to remove the high-frequency image. The IF is controlled by the offset between the transmit and receive LOs. This signal is then amplified to a nominal average voltage level of 300 mV by the automatic gain control (AGC) unit. The resulting IF signal as well as the AGC gain level are sampled on a PC using A/D cards. Figure 3.19 depicts the receive subsystem mounted on a cart.



Figure 3.17: power card used to connect the power amplifiers

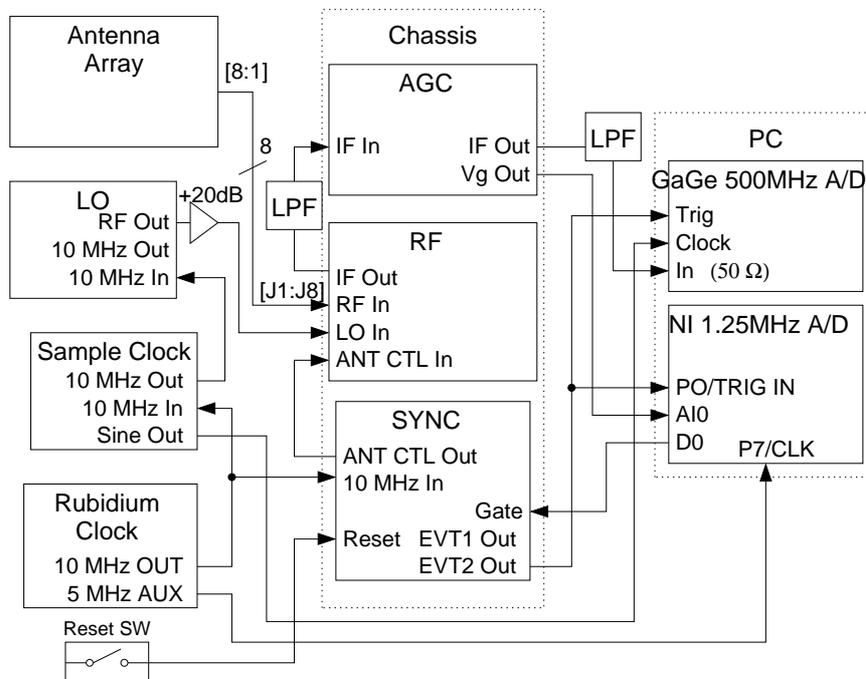
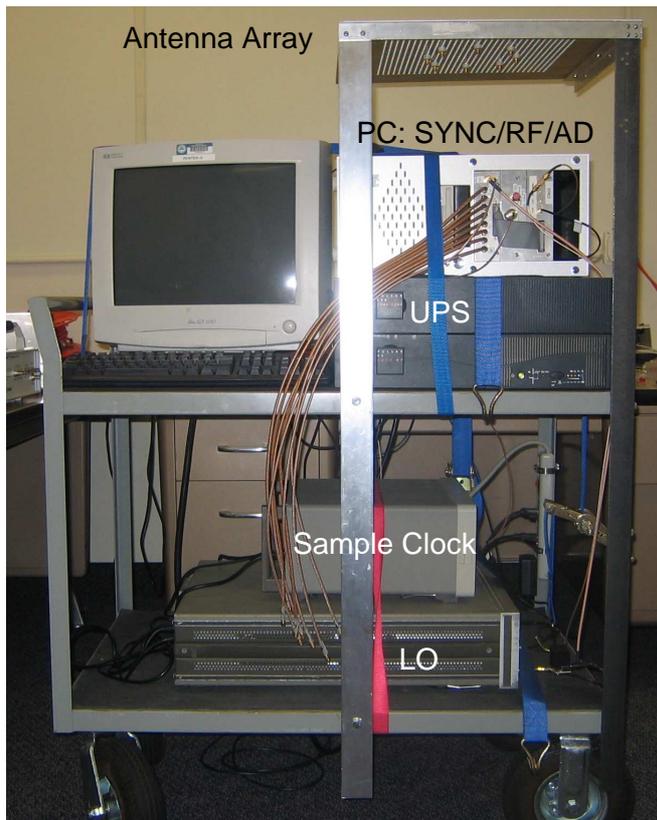
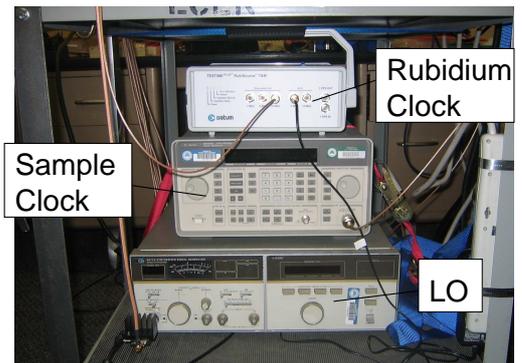


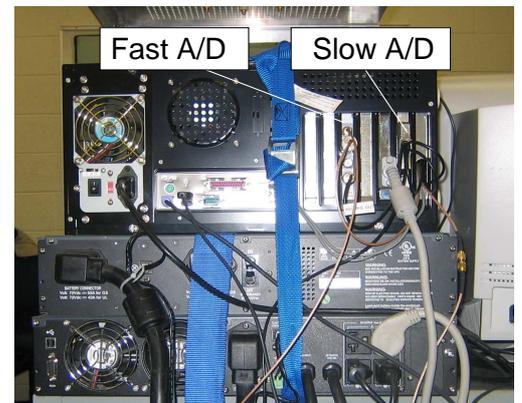
Figure 3.18: Block diagram and connections of the receive subsystem



(a) Side View



(b) Front View



(c) Back View

Figure 3.19: Photos of the (a) side, (b) front, and (c) back of the receive system, showing the major instruments and modules

As with the transmitter, synchronization is accomplished using an identical SYNC unit and all clocks are referenced to another rubidium 10 MHz reference. An additional RF source is used as the sample clock for the GaGe A/D card, since if the internal clock on the card is used, phase deviations will be present in the measured signals.

Two different A/D cards are used for data acquisition: (1) a high speed card from GaGe Instruments supporting up to 500 MS/s on a single channel and (2) a moderate speed card from National Instruments (NI) supporting 1.25 MS/s combined sample rate on up to 16 receive channels. The fast A/D card is used to sample the wideband IF signal, whereas the slower A/D card samples the gain voltage control signal that indicates how much gain has been applied by the AGC. Although both signals are needed to reconstruct the received signal, the AGC signal varies much more slowly than the IF signal. Note that the NI card also has general purpose digital outputs, one of which is used to drive the GATE signal on the SYNC board. The GATE signal and additional connections are required to ensure that both A/D boards are triggered simultaneously.

The optional low pass filters (LPF) were included to improve the noise performance of the system, and ideally identical LPFs are used. The first LPF limits the bandwidth of the IF signal leaving the RF module, and the corner frequency is selected according to the probing bandwidth. This filter removes both thermal noise produced by the LNA and mixer as well as out-of-band interference. The second LPF placed at the output of the AGC is to remove thermal noise that is produced by the wideband AGC chip, which we found to be substantial.

2.1 Instruments

As with the transmitter, a separate Rubidium reference provides the 10 MHz clock to all of the time-sensitive receiver components. The 10 MHz signal is connected via a 3-way “Tee” to the high-impedance SYNC module input. Since instruments generally terminate the reference clock input, either an In/Out cabling procedure should be followed (as shown in the diagram) or a 10 MHz distribution buffer should be used for the remaining instruments.

The LO provides the single microwave tone required by the RF module, necessary for down-conversion of the signals.

A separate instrument is currently used to generate the 100 MHz to 500 MHz sample clock required by the GaGe Instruments high-speed acquisition card. An alternative (used in the Pretoria channel sounder) is to sample both the 10 MHz reference and the IF signal simultaneously using a two-channel high-speed acquisition card that has a free-running clock. The IF waveform can then be resampled later in software to achieve phase coherence.

Two PC-based data acquisition boards (A/D) are used to acquire the received sounding data. The high-speed card samples the wideband IF waveform at a high sample rate (around 500 MS/s), whereas the low-speed card samples the slowly-varying AGC gain output (500 kS/s). Waveforms are stored in RAM on the PC and then dumped to disk after an acquisition.

The specific instruments used in the BYU sounder are listed in Table 3.5, along with

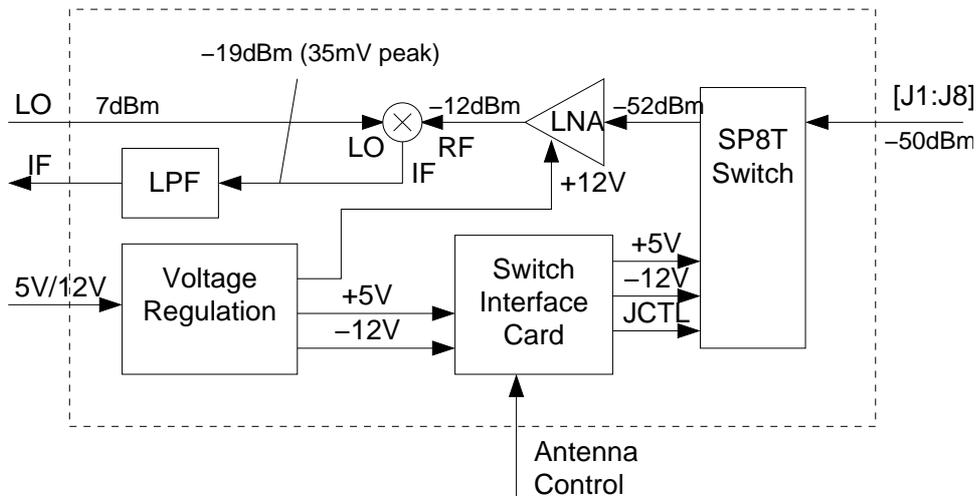


Figure 3.20: Block diagram of receive RF module. Nominal RF power levels are also shown.

notes on specific operational parameters.

2.2 RF Module

The RF module houses the microwave components required to route the microwave signal from the proper receive antenna to a common RF receiver that down-converts this signal to a convenient intermediate frequency (IF) that can be sampled by the A/D card. A block diagram of the receive module is shown in Figure 3.20. A top view of the completed RF module is shown in Figure 3.21 and a close-up of the front connections of the RF module is depicted in Figure 3.22.

A list of the commercial components used in this module are listed in Table 3.6. Total cost of parts for the receive RF module was about \$4000.

The receiver RF module operates by routing one of the microwave inputs (J1-J8) to the common RF receive chain via the microwave SP8T microwave switch. The LNA amplifies the signal by 40 dB, after which the mixer performs single stage downconversion to a convenient IF, where the IF is controlled by properly selecting the offset of the transmit and receive LOs. After low-pass filtering, the IF signal is presented on an external connector, which is attached to the AGC module.

As in the transmit RF module, the switch is controlled by via external TTL signals present on the ribbon cable interface. Note that the switch control card and voltage regulation card are identical to those used in the transmitter.

A complete list of components required for the receive RF module are listed in Table 3.7.

2.3 NI A/D Cable

An interface cable is required to convert signals from SMA connections to the 68-pin high-density connector used by the NI A/D card and vice versa. The connections are

Component	Instrument Used	Notes/Operating Parameters
Rubidium Clock	Symmetricon RubiSource T&M	Identical to Rubidium reference on transmitter. The 5 MHz square wave output is used as the sample clock in the low speed A/D card.
LO	HP 8672A	Synthesized microwave source providing the local oscillator in the range from 2 GHz to 18 GHz. The 10 MHz In port is on the back panel. The switch FREQ STD EXT should be set (on back). An N-connector on the front panel provides RF output up to around 0 dBm. A +20 dB Mini-Circuits amplifier (MC ZRON-8G) is used to boost this signal to the level required by the receive mixer. This unit was acquired used on another project for about \$4000.
Sample Clock	Agilent 8648D	This is an RF source, but it is used here as the sample clock for the high-speed A/D board. The amplitude should be set to 500 mV emf. Depending on the desired sample rate, the frequency can be set from 100 to 500 MHz.
Fast A/D	GaGe Instruments 8500	This is a single channel 8-bit 500 MS/s A/D board with 512 MS onboard memory. The board can be used in one of two modes: single-shot or multiple record, and is triggered by the EVT2 output of the SYNC board. In order to ensure phase coherence, the sample clock is supplied externally. Note that the external clock is an option on this card. At the time of purchase, the GaGe 8500 card had a list price of around \$13000. The board has separate BNC or SMA connectors for the trigger, clock, and signal in.
Slow A/D	National Instruments M-Series Card	This is a multiple-channel card supporting up to 1.25 MS/s combined sample rate. Only a single channel is used at either 1 MS/s or 500 KS/s. The interface to this board is a high-density 68-pin connector. The card is triggered using the P0/TRIG IN input. A 5 MHz square wave applied to the P7/CLK input allows the sampling to be synchronized with the rest of the system. The D0 digital output is also used to control the GATE signal on the SYNC card so that simultaneous triggering of the slow and fast A/D boards is ensured.
PC		A generic PC based on the ASUS A7N8X-X motherboard with 1.5GB of RAM was used.

Table 3.5: Specific instruments and operating parameters of the receive subsystem used in the BYU wideband channel sounder

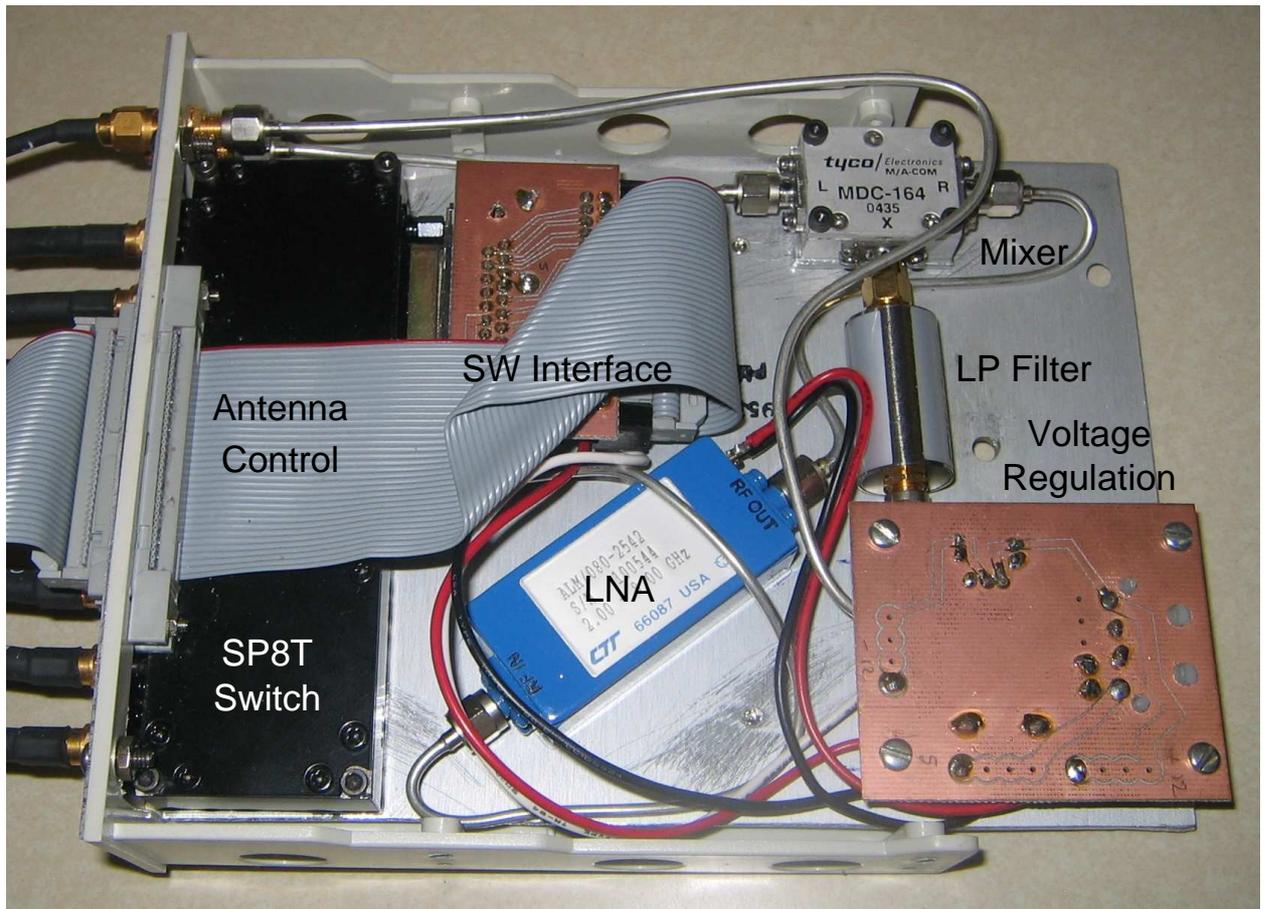


Figure 3.21: Top view of the completed receive RF module

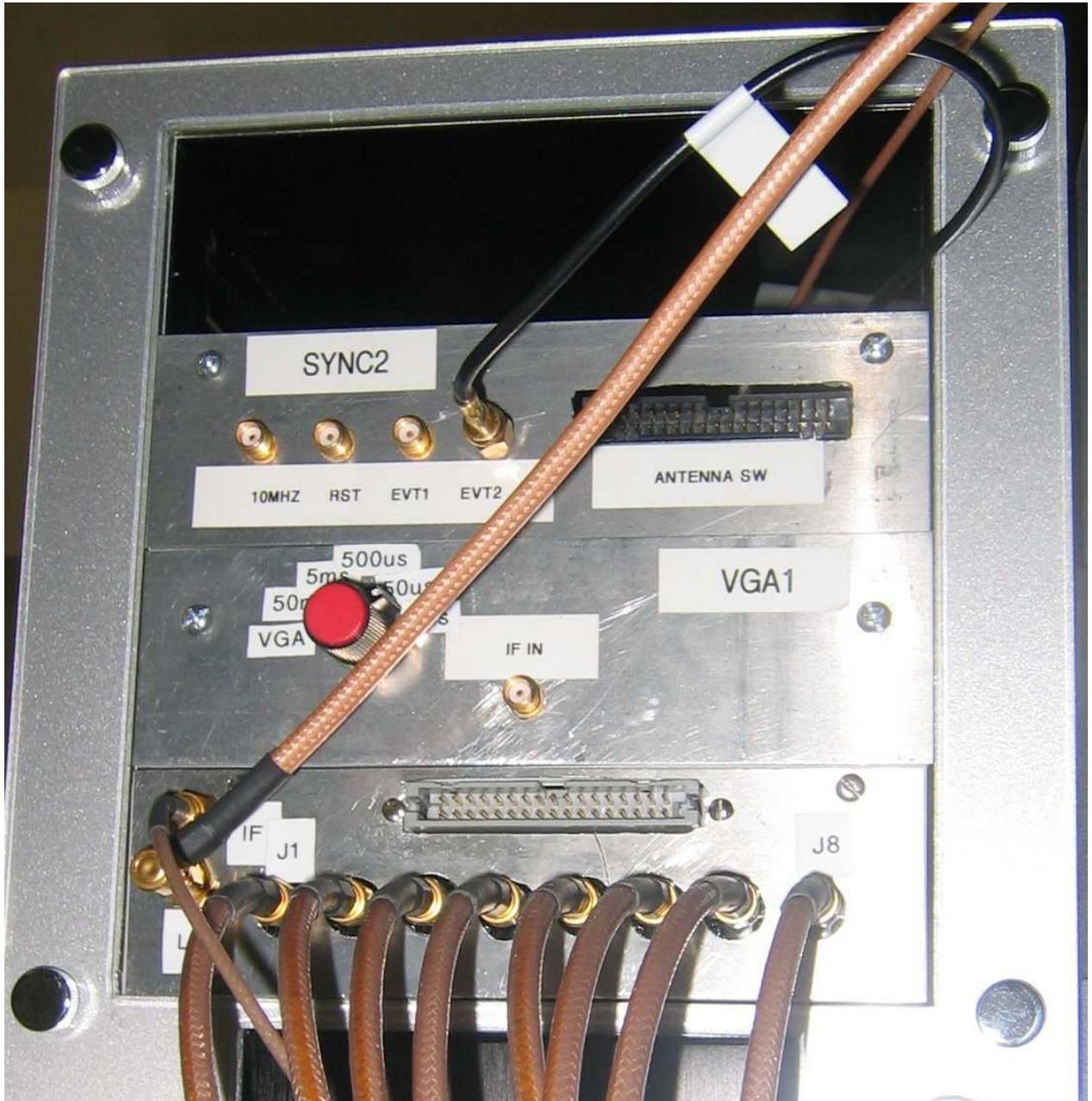


Figure 3.22: Front view of the modules in the receive subsystem PC: SYNC module, AGC, and RF module

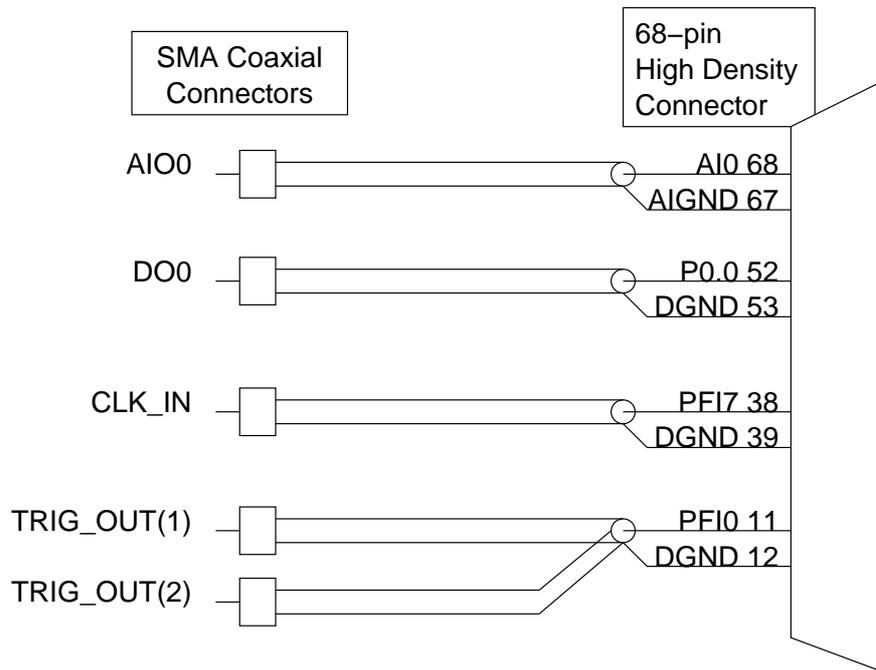


Figure 3.23: Connections for the NI adapter cable

depicted in Figure 3.23. Connections inside the housing are made directly to RG-174/U cables (see Figure 3.24) which have SMA connectors on the other end. The connector and housing are AMP part numbers 5749621-7 and 5749195-2 (Digikey A31795-ND and A33492-ND), respectively. The connector does not terminate any of the signals, since they are all relatively low frequency.

2.4 Automatic Gain Control

The purpose of the automatic gain control (AGC) module is to maintain the IF signal at a fairly constant signal level at the input of the high-speed A/D card, so that the full resolution of the card can be used. Figure 3.25 shows a schematic of the AGC module, which is available as a gEDA schematic under `./design/schem/agc.board.sch`. Figure 3.26 provides a layout of the board, which was generated from the ADS project under `./design/ads/agc.board_prj`.

The AGC board consists of a single Analog Devices AD8367 500 MHz variable gain amplifier with integrated power detector, allowing an AGC loop to be created. The gain of the amplifier in dB is proportional to an analog control voltage input, covering a range of 45 dB. Since the impedance of the inputs and outputs on the AD8367 is 200 Ω , transformers are used to convert the impedance to 50 Ω .

In our design, the capacitor that controls the time constant is selected with a 6-position rotary dial, and capacitor values of 500 pF, 0.005 μF , \dots , 5 μF yield time constants of 5 μs , 50 μs , \dots , 50 ms. For real measurements, the value of 5 μs setting is most frequently used. A single position on the dial is left open to allow the gain to be controlled by an external voltage if desired. The open position can also be used to reset the AGC chip if it gets saturated. Saturation can occur if the receive power

Component	Model	Notes/Operating Parameters
Mixer	TYCO M/A-COM MDC-164	“Termination insensitive” mixer operating with LO/RF from 0.9 to 9 GHz and IF from 10 to 2000 MHz. Typical conversion loss is 6.5 dB and nominal LO drive is 7 to 13 dBm.
LNA	CTT ALM/080-2542	This low noise amplifier from CTT microwave operates from 2 to 8 GHz with 40 dB of gain and a noise figure of 2.5 dB. The amplifier is supplied with 12 VDC at 180 mA.
SP8T Switch	Herley F9180W	PIN diode switch operating from 1-18 GHz with terminated “OFF” ports (non-reflective). The switch operates linearly at about 100-200 mW, and can handle up to 1 W peak average input power. Isolation between output ports is 60 dB and insertion loss is about 3 dB. Switching time is 250 ns. Power and TTL control signals are supplied to the switch via a 15-pin female sub-D connector.
LPF	Mini-Circuits SLP250	The low pass filter has a corner frequency of 200 MHz, which is considered the upper end required for the sounder. External filters are used to make the response narrower when required.

Table 3.6: Commercial components used in the receive RF module



Figure 3.24: Photo showing connections for NI adapter cable

Item	Source	P/N	Qty.	Description
1	CTT	ALM/080-2542	1	2-8 GHz +40 dB LNA
2	Herley	F9180W	1	SP8T Switch
3	M/A-COM	MDC 164	1	1-9 GHz Mixer
4	Mini-Circuits	SLP250	1	200 MHz Low-pass Filter
5	Newark	97F922	2	Bulkhead connectors
6	Pasternack	PE-SR405AL		Semi-rigid cable
7	Digikey	MPL34K-ND	1	34-pos header (panel)
8	Digikey	J488-ND	8	Semi-rigid SMA connectors
9	Digikey	A2097-ND	1	Male D-sub connector (RA)
10	Digikey	A26295-ND	2	34-pos Header (RA)
11	Digikey	P1.00KCCT-ND	8	1 kOhm Resistors
12	Digikey	P5540-ND	2	100 uF electrolytic capacitors
13	Digikey	PT78NR112H-ND	1	voltage regulator
14	Digikey	MSC34A-ND	3	34-pos ribbon cable connector
15	Jameco	P/N 117567	1	Disk Drive Connector
16	Jameco	125794		20AWG Hookup wire
17	Jameco	38842	1	8-pos DIP switch
18	Jameco			34-cond ribbon cable
19	Tiger Direct		1	5 1/4" Disk Drive Adapter
20	Rogers	RO4003C	1	Substrate

Table 3.7: List of components for the receive RF module

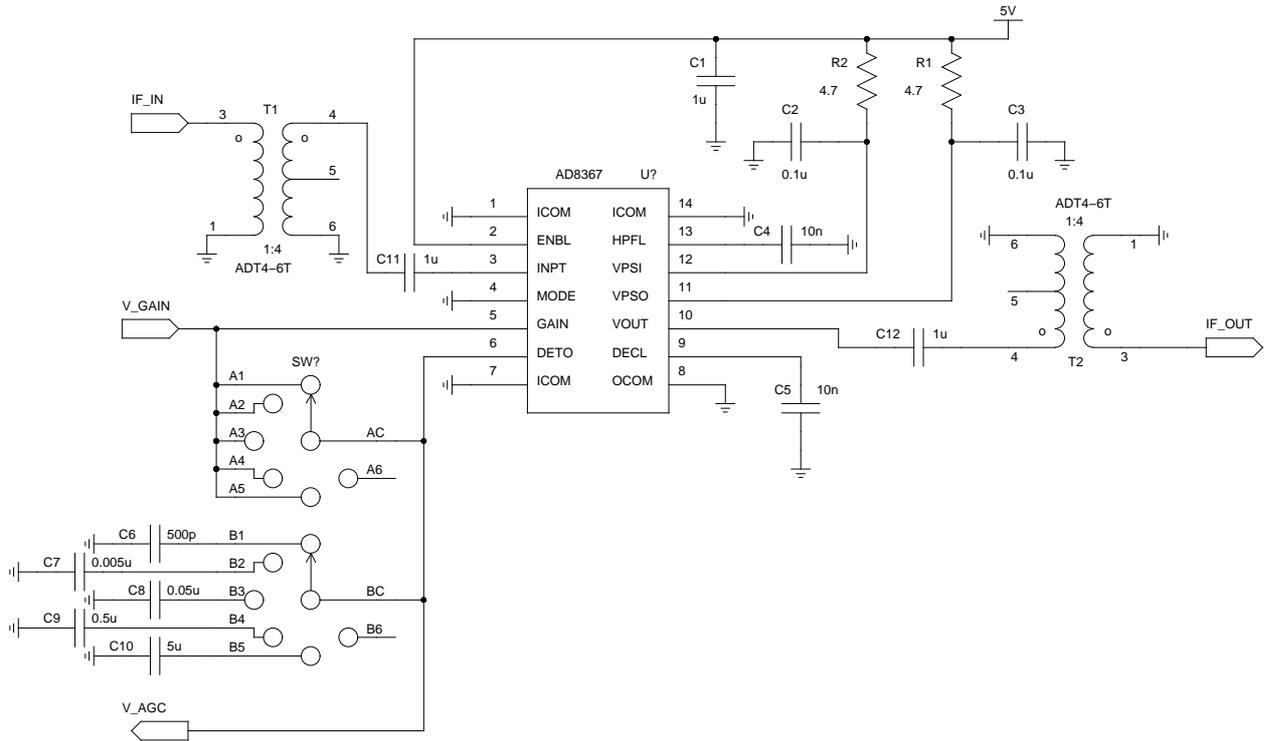


Figure 3.25: Schematic diagram of the automatic gain control (AGC) module

level is very high for an extended period of time. For future designs, we recommend implementing a voltage clamp on the AGC loop to avoid this saturation condition.

The signal output level of the AGC chip has a built-in set point of 350 mV RMS, which after transformation to 50 Ω results in a signal level of 175 mV RMS fed into the A/D.

A complete list of components for the board is listed in Table 3.8

3 Antennas

Any antennas with 50 Ω input impedance and an operational frequency in the 2-8 GHz range may be used with the system. In our propagation measurements, two types of antennas were successfully used with this system: fixed planar patch antennas and positionable monopole antennas.

3.1 Patch Antennas

Dual-polarization patch antennas were designed using a square patch having nominal dimensions of $\lambda/2$ in the substrate material (Rogers RO4003C), which has a dielectric constant of 3.55. The vertical and horizontal input ports are edge-fed and matched to 50 Ω using quarter-wave transformers. In this design, $3\lambda/4$ lines were used for the quarter-wave transformers to reduce the amount of metal near the patch, thus reducing mutual coupling and distortion of the radiation patterns.

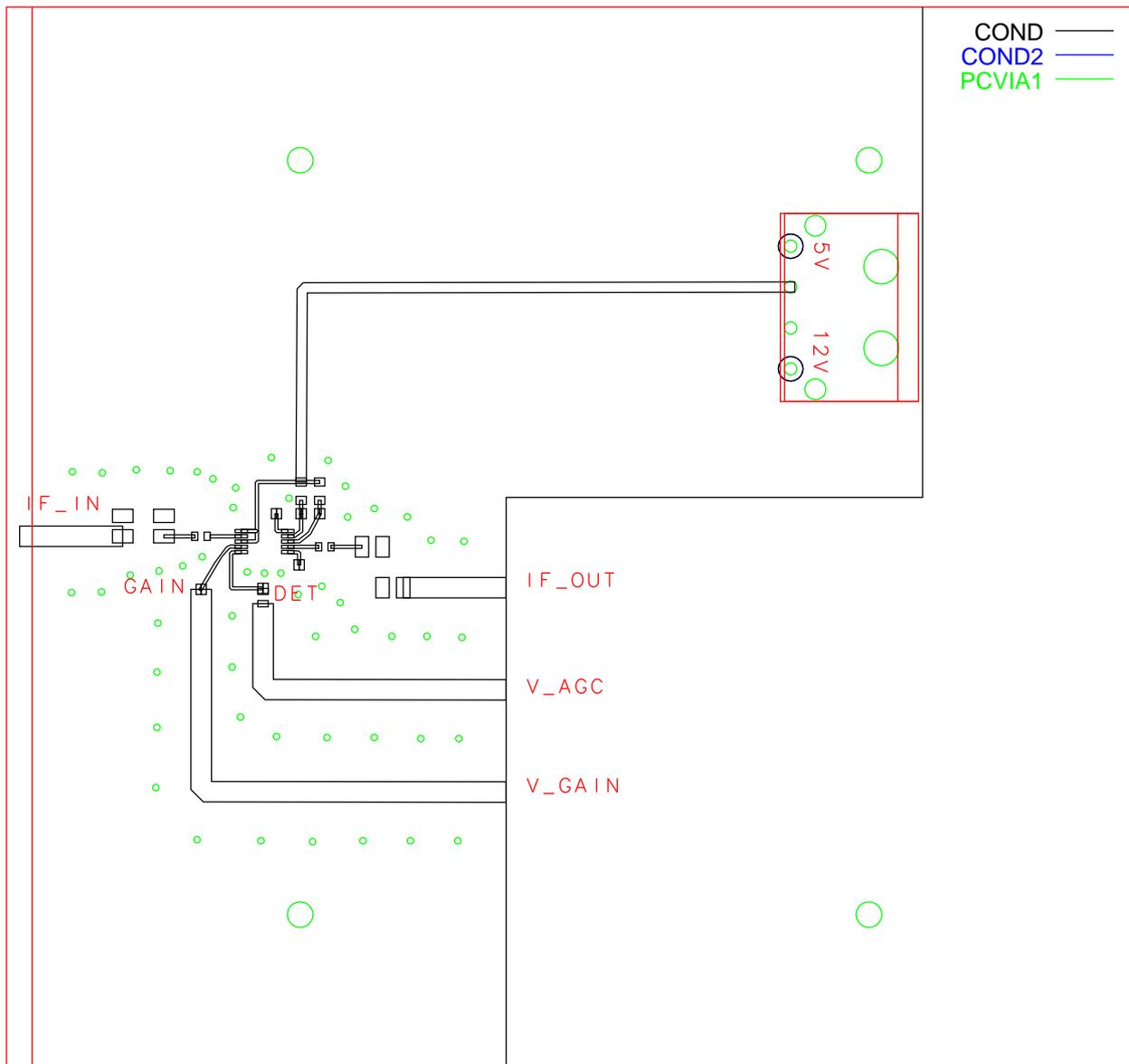


Figure 3.26: Layout showing top of the AGC board

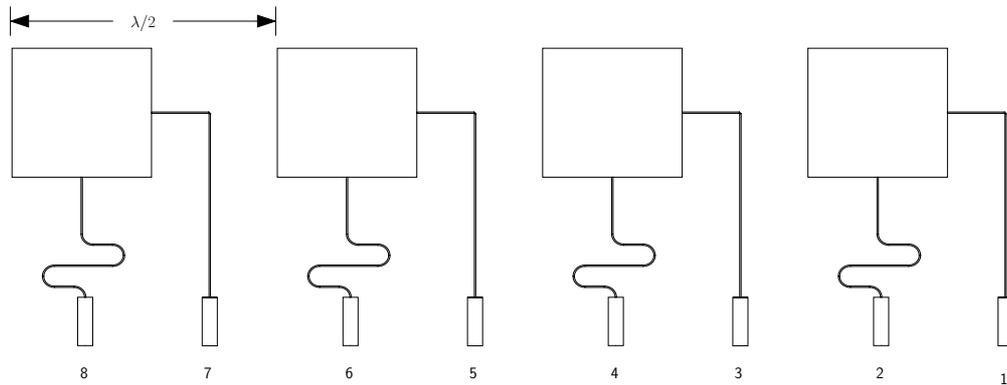


Figure 3.27: Layout of the dual-polarized 8-element patch array operating at 2.45 GHz

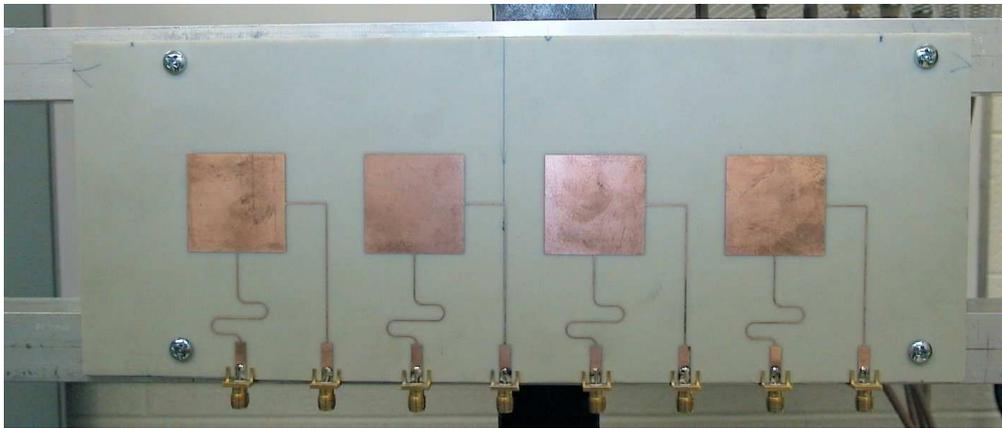


Figure 3.28: Photo showing completed and mounted 8-element dual-polarization patch array

Figure 3.27 shows the layout of an 4-element patch array operating at 2.45 GHz. Figure 3.28 depicts the completed array.

3.2 Positionable Monopole Antennas

Disadvantages of the patch antennas are that they cannot be positioned, the bandwidth is fairly narrow, and the positions do not cover the full 360° in azimuth. To overcome these limitations, simple quarter-wave monopole antennas were fabricated with a very low-cost design using bulkhead connectors (Johnson part number 142-0901-401). A copper whip is soldered to the center contact of the bulkhead connector, which can then be mounted directly on a pre-drilled ground plane. Nylon spacers and washers go around the bulkhead connector below the ground plane to control the extension of the metal sheath above the ground plane. Proper tuning of this sheath length allows a good match to 50Ω without the need of additional components. These monopole antennas exhibit uniform radiation in the azimuthal plane and fractional bandwidths of around 20%.

Figure 3.29 shows the basic dimensions of a single monopole antenna for a design frequency of 2.42 GHz. Figure 3.30 shows single monopole elements designed for

Item	Source	P/N	Qty.	Description
1	Arrow	AD8367ARU	1	500 MHz AGC IC
2	Digikey	P4.7ACT-ND	2	4.7 Ohm Resistors
3	Digikey	PCC2313CT-ND	5	0.1uF Chip Cap
4	Digikey	490-1323-1-ND	3	10nF Chip Cap
5	Digikey	PCC2287CT-ND	3	1 uF Chip Cap
6	Digikey	J658-ND	4	Edge Launch SMA Connectors
7	Mini-Circuits	ADT4-6T	2	Transformers
8	Jameco	117567	1	Disk Drive Connector
9	Rogers	RO4003C	1	Substrate
10	Tiger Direct		1	5.25" Disk Drive Adapter
11	Digikey		1	DP6T Dial

Table 3.8: List of components for the automatic gain control (AGC) module

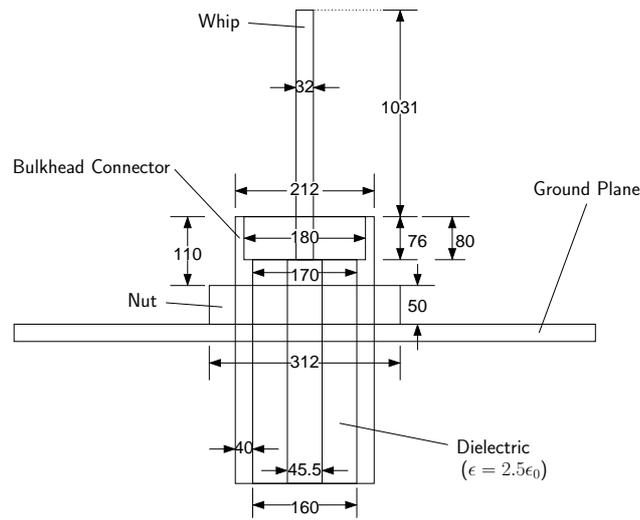
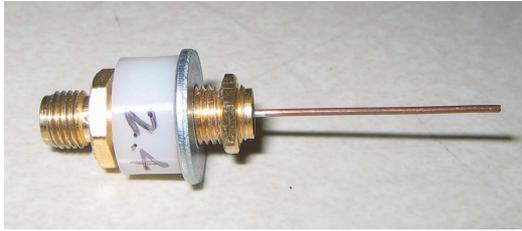


Figure 3.29: Dimensions of a single monopole antenna in mils

(a) 2.4 GHz Monopole



(b) 5.2 GHz Monopole



(c) Pre-drilled Groundplane

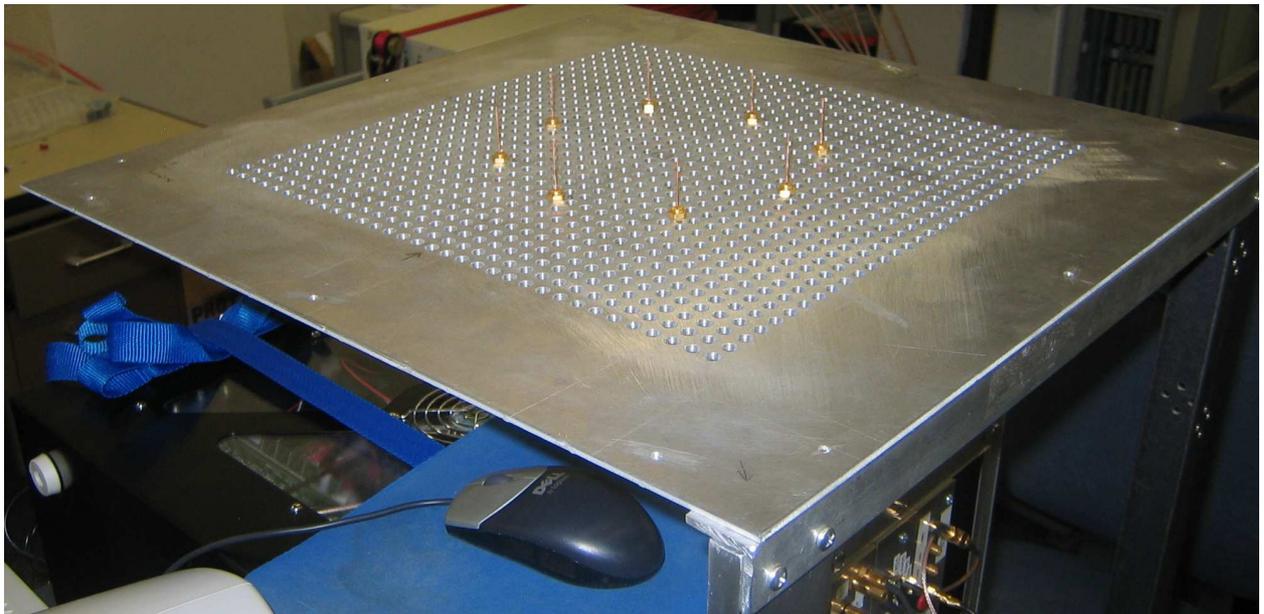


Figure 3.30: Positionable monopole antenna design for (a) 2.4 GHz and (b) 5.2 GHz. The antennas are mounted in a pre-drilled ground plane (c).

(a) 2.4 GHz and (b) 5.2 GHz. These elements can then be easily mounted in the pre-drilled ground plane depicted in Figure 3.30c.

Chapter 4: System Deployment

This section details how the system is used in practice. The basic steps required for performing measurements are enumerated below, and a chapter is dedicated to each of these tasks:

1. A transmit baseband excitation signal must be created and downloaded to the arbitrary waveform generator (Section 1).
2. The system must be calibrated in order to unembed the system impulse response from measurements (Section 2).
3. Measurement scripts are created and run (Section 3).
4. Raw data stored on the system is post processed to obtain wideband channel matrices (Section 3.2).

Software for controlling the system is written in MATLAB .m or .MEX files, so that everything is done from a MATLAB shell. Since the user mainly interacts with this software when using the system, numerous references will be made to the Functional Reference in Chapter 5.

1 Probing Signal Generation

To enable probing of the channel response over a broad frequency range, the system uses a multitone excitation signal, where the number and spacing of tones can be controlled. The baseband multitone signal is of the form

$$x(t) = \sum_{i=0}^{N_F-1} \cos(2\pi f_i t + \phi_i) \quad (1.1)$$

$$= \frac{1}{2} \sum_{i=0}^{N_F-1} \left(e^{j(2\pi f_i t + \phi_i)} + e^{-j(2\pi f_i t + \phi_i)} \right), \quad (1.2)$$

where f_i and ϕ_i are the frequency and phase of the i th tone, respectively. For equally spaced tones, $f_i = (i + 0.5)\Delta f$. Note that each term in (1.2) actually represents two tones, so that the probing signal produces $2N_F$ tones with a total probing bandwidth of $(2N_F - 1)\Delta f$. Post processing is simplified if each tone corresponds to a single FFT bin, which is guaranteed when $\Delta f = 2kf_s/N$, where f_s is the sample rate, N is the number of samples in each record, and k is an integer.

An obvious advantage of multitone signaling is that the channel response is obtained directly by selecting the appropriate FFT bins. One of the drawbacks, however, is that the envelope is not constant, and care must be taken to ensure that the linearity of TX power amplifiers and switches is sufficient to avoid corruption of the measurements. Usually, one minimizes the signal peak-to-average ratio by adjusting the phase on each of the tones. Here, the phases were optimized by simply realizing a large set of signals, each with a unique randomly-generated phase weighting on the tones, and retaining the signal with the lowest peak-to-average ratio.

Table 4.1: Parameters of the example multitone signal

Parm.	N_F	Δf	T_1	T_2	σ	f_s	N
Value	4	1 MHz	6 μ s	7 μ s	0.3 μ s	400 MS/s	20,000

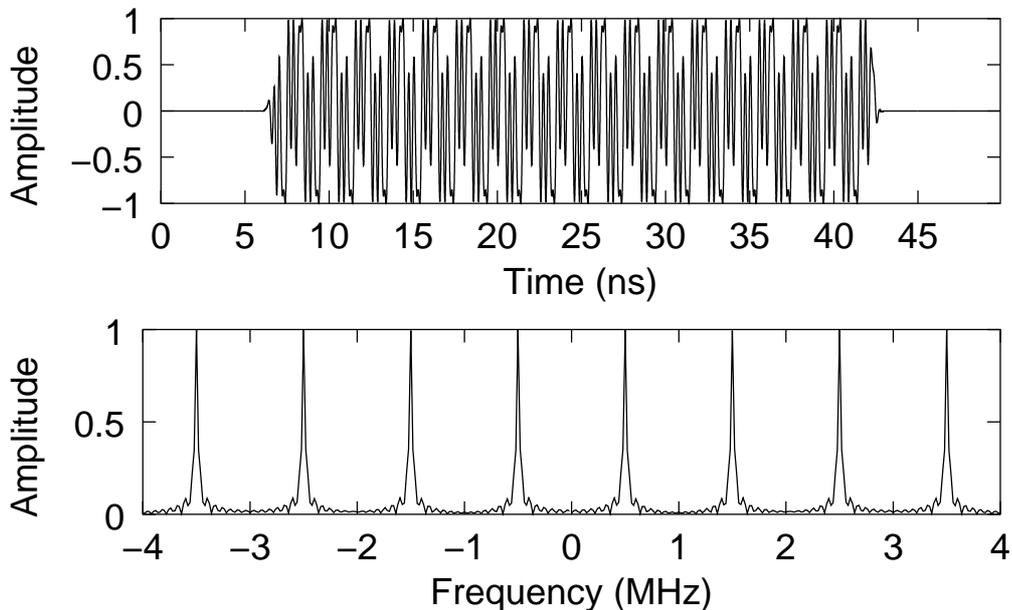


Figure 4.1: Example multitone signal plotted versus time and frequency

One consideration with switched measurements is that most PIN diode switches are not designed for *hot switching*, where high signal level exists during a switching operation. Also, channel estimation is simpler if the acquired signals for the different antenna combinations have no temporal overlap. To avoid these issues, the multitone signal is multiplied by a Gaussian window of the form

$$w(t) = \begin{cases} e^{-(T_1-t)^2/(2\sigma^2)}, & 0 \leq t < T_1 \\ e^{-(T_2-t)^2/(2\sigma^2)}, & T_2 \leq t \leq T \\ 1, & \text{otherwise,} \end{cases} \quad (1.3)$$

where T_1 and T_2 are the limits of the window, and the standard deviation σ controls the rise and fall time of the window. Typically, the guard time $T_1 + T_2$ is chosen to be much larger than the channel delay spread. Guard time also allows the AGC to adapt between switch events.

A simple 8 MHz multitone signal used for outdoor channel probing is depicted in Figure 4.1, with the important parameters listed in Table 4.1. The window spreads the tones slightly, which is unavoidable for a finite-length signal. The active portion of the time-domain signal has a peak-to-average ratio of 1.74 which is close to that of a constant sine wave ($\pi/2 \approx 1.57$).

This example signal was generated with the script `./design/software/awg/signals/make_mt_byu_041208.m`, which calls the function `make_mt_signal`. The function creates a multi-tone signal with random phases on the tones 1000 times, and chooses the resulting waveform with the lowest peak-to-average ratio.

Downloading of the probing signal to the arbitrary waveform generator (AWG) is accomplished in different ways, depending on what instrument is used. The table below describes how this is accomplished for different AWGs.

LeCroy LW410	<p>The LW410 is a single channel 400 MS/s (100 MHz real bandwidth) AWG. This AWG has the ability to import MATLAB files stored in ASCII .DAT files directly. If s is a vector containing the real data samples, the waveform is first saved in MATLAB with the command</p> <pre>save -ascii wavfile.dat s</pre> <p>This file can be stored on a floppy disk and imported into the AWG on the project menu. Note that s is the real voltage level in volts. Typically a level of about 200-500 mV p-to-p is used in the measurements, but the exact level will depend on the waveform and the center frequency. Also, the p-to-p voltage level can be changed using the edit commands on the AWG.</p>
Agilent Source	<p>ESG The I/F outputs of an Agilent ESG source may be used as a 2-channel 100 MS/s arbitrary waveform generator. Signals can be downloaded with an RS-232 cable using the function <code>esg_store_arb</code>. Although the downloaded waveform can be complex, for the purposes of this system, the waveforms are real, so that signals will only be present on the I output. To use the waveform after downloading, the waveform record must be moved from non-volatile memory to volatile memory, which must be done each time power is cycled on the ESG source. The program <code>esg_monitor.c</code> can be used to monitor the ESG source and reload the desired AWG waveform if power is cycled.</p>

2 System Calibration

Since the RF components in the system are not ideal, raw measurements include both the channel and system response. Also, microwave switches are often constructed with unequal length transmission lines on the various ports, leading to phase errors. These effects can be removed by a careful calibration method.

2.1 Calibration Types

Figure 4.2a depicts the measurement setup, where the ideal channel response from the n th TX antenna to the m th RX antenna at baseband frequency f_k is $h_{k,mn}$. One way to accomplish system calibration is to connect TX to RX as depicted in Figure 4.2b, where the switches and antennas have been replaced with a single attenuator with loss L W/W. This measurement yields y_k^{cal} , which is the value of the FFT bin corresponding to the baseband tone at frequency f_k . The response of the switches is measured on a network analyzer giving broadband S-parameters $S_{n0}^{\{\text{TX,RX}\}}(f)$, where 0 and n refer to the indices of common and switched ports, respectively, and f is frequency.

Assuming near-linear response of the RX subsystem, a measurement taken with the

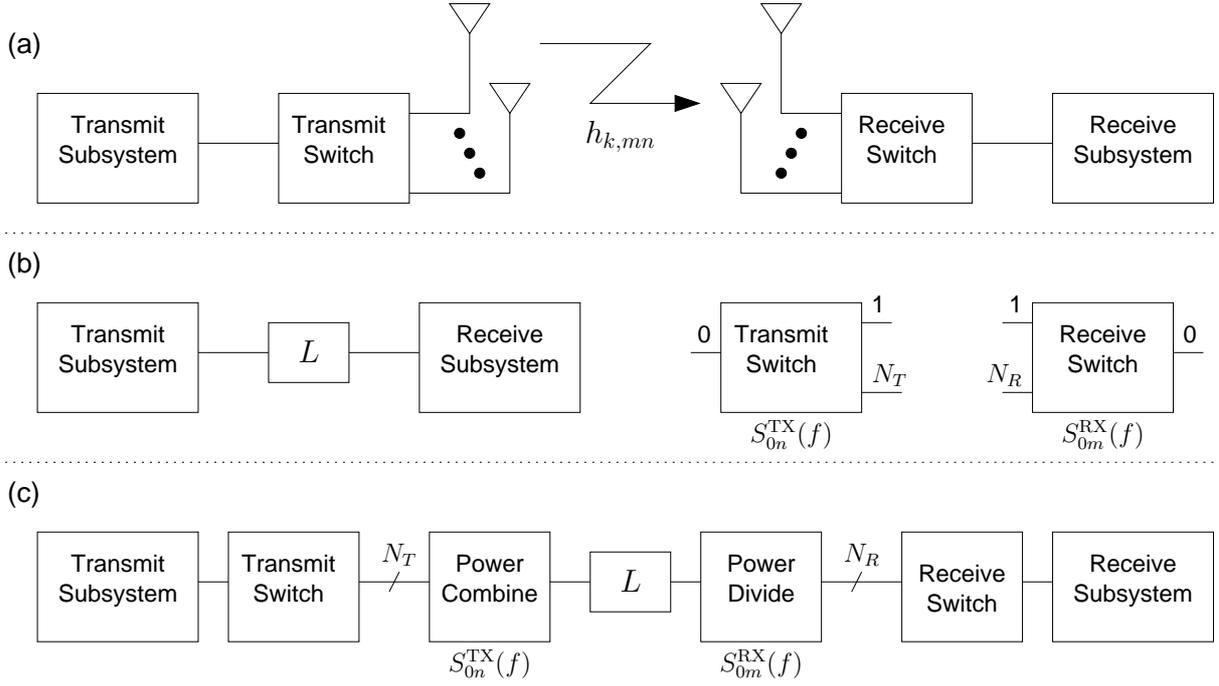


Figure 4.2: Procedures for system calibration: (a) original measurement setup, (b) single-channel calibration, and (c) direct matrix calibration

setup in Figure 4.2a results in

$$y_{k,mn} = Ly_k^{\text{cal}} h_{k,mn} S_{0n}^{\text{TX}}(f_k + f_c) S_{0m}^{\text{RX}}(f_k + f_c), \quad (2.4)$$

where k , m , and n are the frequency, RX, and TX indices, and f_c is the carrier frequency. The ideal (or calibrated) channel response h is then obtained from

$$h_{k,mn} = \frac{y_{k,mn}}{Ly_k^{\text{cal}} S_{0n}^{\text{TX}}(f_k + f_c) S_{0m}^{\text{RX}}(f_k + f_c)}. \quad (2.5)$$

Another calibration method involves the connection strategy in Figure 4.2c. In this case, the switches remain and the TX and RX are connected via an N_T - and N_R -way power divider and combiner, with measured S-parameters $S_{n0}^{\{\text{TX},\text{RX}\}}(f)$. To avoid RX saturation, a loss of L may also be inserted. A measurement of all TX and RX combinations yields $y_{k,mn}^{\text{cal}}$. Similar to the first approach, the ideal channel response is computed as

$$h_{k,mn} = \frac{y_{k,mn}^{\text{cal}} S_{0n}^{\text{TX}}(f_k + f_c) S_{0m}^{\text{RX}}(f_k + f_c)}{Ly_{k,mn}^{\text{cal}}}. \quad (2.6)$$

Note that the position of the S-parameters has changed since the divider and combiner are present in the calibration but not the measurement, whereas before the switches were present in the measurement but not the calibration.

The quantity of required calibration information for this procedure can be reduced by noting that the matrix $\mathbf{Y}_k^{\text{cal}}$ is rank one, so that $y_{k,mn}^{\text{cal}} = s_k u_{k,m} v_{k,n}^*$, where \mathbf{u}_k and

\mathbf{v}_k are the left and right singular vectors associated with the single nonzero singular value s_k for frequency bin k . This rank-one approximation may also improve the calibration accuracy, since information from multiple antennas is averaged.

2.2 Calibration Functions

Typically, the measurement setup in Figure 4.2(c) is used. Both the power combiner and divider are realized with Mini-Circuits ZB8PD-4 8-way dividers, and these are measured just once with a vector network analyzer (VNA).

Additional loss L is introduced such that the power level at the receiver is around -60 dBm. When the external power amplifiers are not used, this means the total loss should be around 80 dB, which is accomplished by adding a loss $L=60$ dB (each divider introduces around 10 dB of loss). The loss is typically distributed by putting a 40 dB pad (attenuator) on each transmit port and a common pad (20 dB in this case) between the combiner and divider. For high-power measurements with external 5W power amps, an additional 10 dB is placed between the power combiner/divider, giving $L=70$ dB.

For this system, characterization of the power dividers was performed with an HP 5810 VNA. The multi-port networks are characterized by performing multiple 2-port measurements, where VNA Port 1 is always connected to the common device port (port 0 in Figure 4.2) and VNA Port 2 is connected to ports 1-8. During each measurement, unused ports are terminated with 50 Ω loads.

Measurements are performed using the Instrument Server in Agilent ADS. For each device, measurements are stored in a single dataset with a different block name for each port. The block name should be Jn , where n is the port number tested (1-8). Exporting the dataset to a Citifile type, it can be read with the function `read_cfile`.

A full calibration involves a power divider at transmit and receive. Assuming that the network S-parameter data files are read using `read_cfile` into st and sr for transmit and receive, the function `get_switch_freq` can then be used to generate a matrix of calibration values for the power combiner/divider combination at a specific center frequency. This function returns the $N_F \times N_R \times N_T$ array c that is used for later calibration. Note that we have

$$c_{k,mn} = S_{0n}^{\text{TX}}(f_c) S_{0m}^{\text{RX}}(f_c), \quad (2.7)$$

where over moderate fractional IF bandwidths we have assumed that the change in the response of the multiport RF components is approximately linear phase (constant delay).

Before a measurement, the calibration is performed using a script like `check_cal_mult`, which performs a measurement with the power combiner/divider connected between all ports of the transmit and receive, returning an $N_F \times N_R \times N_T$ array named hr which is equivalent to the $\mathbf{Y}_k^{\text{cal}}$ matrices above.

The calibrated channel matrices $h_{k,mn}$ are then computed from the raw measurement

$$y_{k,mn} \text{ as}$$

$$h_{k,mn} = \frac{y_{k,mn} c_{k,mn}}{L y_{k,mn}^{\text{cal}}}. \quad (2.8)$$

3 Measurements

This section describes how a measurement is typically carried out. Before the measurement, a calibration is performed as described in Section 2 where transmit and receive are directly connected through power dividers and combiners. After calibration, the transmit and receive channels are connected to the antennas. During the ensuing measurement, data is stored in raw binary files. Finally, the data is post-processed to obtain the channel matrices stored in MATLAB data files.

3.1 Data Acquisition

One of two measurement types are used: continuous and multiple-record acquisitions.

Channels can be measured in a continuous back-to-back fashion, using a script like `acquire_cont` which performs just a single continuous A/D operation.

To cover longer periods of time, additional dead time can be placed between channel snapshots using the multiple-record feature of the A/D card. Multiple record means that the A/D card acquires only the specified number of samples each time it is triggered and continues acquiring such records until memory is full. The extra space between the triggers is accomplished by making the number of receive antennas specified on the SYNC unit some integer multiple N of the number of real antennas, so that a trigger only occurs only 1 out of N scans through the antennas. The script `acquire_mr` illustrates how this is done.

3.2 Post Processing

During the acquisition stage, data is stored in a number of raw data files. For each data acquisition, 3 different data files are typically generated, with a base name of *fname*:

<i>fname</i> g.dat	High-speed A/D data (IF)
<i>fname</i> n.dat	Low-speed A/D data (AGC)
<i>fname</i> .mat	Matlab information for acquisition

Each acquisition can be converted to channel matrices using a function like `process_one`. This function works by reading consecutive records of samples, where a single record corresponds to a complete scan of all transmit and receive antennas. For each record, both the IF and AGC waveforms are read, and the level of the IF data is scaled appropriately. The record is then passed to the function `est_H_mt` that performs an FFT of the IF waveform for each antenna combination and picks off the appropriate frequency bins corresponding to the multiple tones. Finally, the data is calibrated using the stored response of the power combiner/divider, the raw measurement of the directly connected system, and the known additional loss L .

After calling `est_H_mt`, an $N_F \times N_R \times N_T \times N_S$ multi-dimensional array H is generated.

Chapter 5: Functional Reference

This chapter contains a reference of the most common high-level functions available in the supplied software, required for system calibration, data acquisition, and post processing. The low-level functions are currently not documented, but information can be found in the source code.

1 Acquire Functions

1.1 `acquire_agc_data2`

Location: `./design/software/acquire/acquire_agc_data2.m`

Syntax: `[d p] = acquire_agc_data2(fname, fs, T, gate_pol);`

Inputs:	<i>fname</i>	Optional output filename
	<i>fs</i>	Sample rate (in Hz). If a vector, the second element indicates a decimation factor (1, 2, 4, or 8 are supported). If $fs < 0$ then the internal timebase is used with rate $ fs $.
	<i>T</i>	Acquisition time in seconds
	<i>gate_pol</i>	Gate polarity: 0= low signal on gate inhibits triggers (default, original) 1= high signal on gate inhibits triggers (Britton's)
Outputs:	<i>d</i>	Immediate (corrected) data
	<i>p</i>	Structure with debug information

Description: Performs a data acquisition for the system with automatic gain control applied to the IF waveform and gated triggers on the GaGe and NI-DAQ cards. If a non-empty filename is supplied, the raw data files are stored as *fname*.dat for the GaGe data and *fnamen*.dat for the NI-DAQ data. If the output variable *d* is provided, the AGC corrected data will be returned immediately. Note that the immediate feature should only be used for relatively small data sets since memory can become quickly exhausted.

1.2 acquire_agc_data_mr2

Location:	./design/software/acquire/acquire_agc_data_mr2.m	
Syntax:	[d p] = acquire_agc_data_mr2(fname, fs, Nrec, T, Ttrig, gate_pol);	
Inputs:	<i>fname</i>	Optional output filename
	<i>fs</i>	Sample rate (in Hz). If a vector, the second element indicates a decimation factor (1, 2, 4, or 8 are supported). If $fs < 0$ then the internal timebase is used with rate $ fs $.
	<i>Nrec</i>	Number of records to acquire
	<i>T</i>	Acquisition time per record in seconds
	<i>Ttrig</i>	Time between triggers. Needed to align NI-DAQ and GaGe data.
	<i>gate_pol</i>	Gate polarity: 0= low signal on gate inhibits triggers (default, original) 1= high signal on gate inhibits triggers (Britton's)
Outputs:	<i>d</i>	Immediate (corrected) data
	<i>p</i>	Structure with debug information

Description: Performs a multiple-record data acquisition for the system with automatic gain control applied to the IF waveform and gated triggers on the GaGe and NI-DAQ cards. If a non-empty filename is supplied, the raw data files are stored as *fnameg.dat* for the GaGe data and *fnamen.dat* for the NI-DAQ data. If the output variable *d* is provided, the AGC corrected data will be returned immediately. Note that the immediate feature should only be used for relatively small data sets since memory can become quickly exhausted.

1.3 acquire_data

Location:	./design/software/acquire/acquire_data.m	
Syntax:	[d] = acquire_data(fname, fs, Nrec, T, level);	

Inputs:	<i>fname</i>	Optional output filename. Data stored in <i>fname.dat</i> .
	<i>fs</i>	Sample rate (in Hz). If a vector, the second element indicates a decimation factor (1, 2, 4, or 8 are supported).
	<i>Nrec</i>	Number of records to acquire (0=single record mode)
	<i>T</i>	Acquisition time per record in seconds
	<i>level</i>	Full scale signal level in volts. Check specs of GaGe card for allowed values
Outputs:	<i>d</i>	Immediate (corrected) data

Description: Performs a data acquisition with only the GaGe card. If a nonempty *fname* is supplied, data is stored in that file. If the return value *d* is supplied, immediate data is returned, but care should be taken since for large acquisitions, memory can quickly be exhausted. This function can perform either single-record or multiple-record acquisitions, depending on the *Nrec* input.

1.4 cal_recv_mult_agc

Location: `./design/software/acquire/cal_recv_mult_agc.m`

Syntax: `[Hr, Ho, vg, d1] = cal_recv_mult_agc(Nt, Nr, Ns, fs, fif, T, df, fmax, Hr1, L, w);`

Inputs:	<i>Nt</i>	Number of transmit channels
	<i>Nr</i>	Number of receive channels
	<i>Ns</i>	Number of snapshots to average
	<i>fs</i>	Sample rate or [sample_rate decimation]
	<i>fif</i>	Intermediate frequency
	<i>T</i>	Single record length (seconds)
	<i>df</i>	Spacing of frequency bins (Hz)

	<i>fmax</i>	Maximum frequency bin (Hz)
	<i>Hr1</i>	Optional single receive channel response
	<i>L</i>	Excess calibration loss in dB (attenuators)
Outputs:	<i>Hr</i>	$N_f \times N_r \times N_t$ network response
	<i>H</i>	Raw channel estimates
	<i>vg</i>	Average Vgain on AGC for the time slots
	<i>d1</i>	Raw data for debugging

Description: This function performs a calibration of multiple transmit and receive channels, which should be connected to a known power combiner/division matrix. Uses a multiple-record acquisition so that a better average is obtained.

1.5 est_H_mt

Location: ./design/software/acquire/est_H_mt.m

Syntax: [f H] = est_H_mt(d, T, Nt, Nr, Ns, Hi, fif1, fs, df, fmax);

Inputs:	<i>d</i>	Received signal d(1, samp*Nt*Nr*Ns)
	<i>T</i>	Length of single element snapshot (time)
	<i>Nt</i>	Number of transmitters
	<i>Nr</i>	Number of receivers
	<i>Ns</i>	Number of channel snapshots
	<i>Hi</i>	Known transmit spectrum ([] = ideal flat freq domain)
	<i>fif1</i>	IF of the receive signal (0=already baseband)
	<i>fs</i>	Sample rate

	<i>df</i>	Spacing of frequency bins (MHz)
	<i>fmax</i>	Maximum frequency
Outputs:	<i>H</i>	$Nf \times Nr \times Nt \times Ns$ multidimensional array containing channel matrices.

Description: Estimates the broadband channel matrix H given a multi-tone transmit signal.

1.6 read_agc_data_file

Location: `./design/software/acquire/read_agc_data_file.m`

Syntax: `[d vg] = read_agc_data_file(fname);`

Inputs:	<i>fname</i>	Base name of data to load
Outputs:	<i>d</i>	Vector of real (AGC corrected) data
	<i>vg</i>	Average Vgain on AGC for the time slots (debug)

Description: Reads the binary GaGe/NI-DAQ files containing the IF and AGC waveforms, performs the AGC correction, and returns the complete waveform.

1.7 read_agc_data_file_N

Location: `./design/software/acquire/read_agc_data_file_N.m`

Syntax: `[d p] = read_agc_data_file_N(fname, n {, dims_new});`

Inputs:	<i>fname</i>	Base name of data to load
	<i>n</i>	Record number to read
	<i>dims_new</i>	Optional new dimensions for raw data. Up to 3 dimensions may be specified here in a vector, but only 2 are strictly necessary.
Outputs:	<i>d</i>	Vector of real (AGC corrected) data
	<i>p</i>	Debug information

Description: Reads the binary GaGe/NI-DAQ files containing the IF and AGC waveforms, performs the AGC correction, and returns the complete waveform. Reads only the *n*th record from the file, allowing large data files to be processed in limited memory. The dimensions of the raw data can also be resized so that the size of the records can be adjusted.

1.8 read_raw_gage_data

Location: ./design/software/acquire/read_raw_gage_data.m

Syntax: [d t] = read_raw_gage_data(fname, fs);

Inputs: *fname* Filename to read

fs Sample rate

Outputs: *d* Multidimensional array of data

t Time samples

Description: Reads the raw GaGe data from a file and returns it as real data. Data is returned in a multi-dimensional array: d(samp, group, chan, board).

1.9 read_raw_gage_data_M

Location: ./design/software/acquire/read_raw_gage_data_M.m

Syntax: [d t] = read_raw_gage_data_M(fname, M {, dims_new});

Inputs: *fname* Filename to read

M Record to read

dims_new New dimensions (specify up to 3 dimensions)

Outputs: *d* Multidimensional array of data

dims Dimensions of data stored in file

Description: Reads the raw GaGe data from a file and returns it as real data. Reads only the *M*th record, to conserve memory.

1.10 test_panel_wb

Location: `./design/software/acquire/test_panel_wb.m`

Syntax: `[] = test_panel_wb(fs, T, Nt, Nr, range);`

Inputs:

<i>fs</i>	Sample rate
<i>T</i>	Dwell time per antenna
<i>Nt</i>	Number of transmitters
<i>Nr</i>	Number of receivers
<i>range</i>	Full-scale range on plots

Description: This is a helpful function for diagnosing problems with the setup. A grid of plots is displayed, one for each of the antenna combinations. The real time-domain data is displayed on each plot. Dead channels and synchronization problems can then be easily spotted.

2 Acquire/Process Scripts

2.1 acquire_common

Location: `./design/software/acquire/scripts/acquire_common.m`

Syntax: `acquire_common;`

Description: This is a user-defined script that should set certain global parameters that will be used for calibration, acquisition, and processing. See the provided sample script for details.

2.2 acquire_cont

Location: `./design/software/acquire/scripts/acquire_cont.m`

Syntax: `acquire_cont;`

Description: Example script showing how to do a continuous (back-to-back) acquisition of channels. The user presses enter to start the acquisition. Different beeping sounds are used to indicate beginning and end of the acquisition.

2.3 acquire_mr

Location: `./design/software/acquire/scripts/acquire_mr.m`

Syntax: `acquire_mr;`

Description: Example script showing how to do a multiple-record acquisition of channels. The user presses enter to start the acquisition. Different beeping sounds are used to indicate beginning and end of the acquisition.

2.4 check_cal_mult

Location: `./design/software/acquire/scripts/check_cal_mult.m`

Syntax: `check_cal_mult;`

Description: This script performs a calibration measurement, assuming the transmitter and receiver are connected with a combiner/divider network. The network should also have excess loss L to avoid damage or saturation of the receiver.

It is assumed that the common operating parameters for the calibration/data measurement are set by the script `acquire_common.m`.

This script produces the following variables:

Hr $Nf \times N \times Nt$ array containing the average calibration values that were computed using Ns snapshots.

Hd The snapshots that were recorded and used to compute the calibration.

d Raw time-series data for calibration

A plot is also generated showing the fractional variance (in dB) for the different frequency bins across the Ns snapshots. Values greater than -20 dB indicate that something is not connected properly, and values of -30 to -40dB indicate a good calibration.

The variable Hr should be stored in a Matlab `.MAT` file for later post-processing.

2.5 process_one

Location: `./design/software/acquire/scripts/process_one.m`

Syntax: `[f Ho t] = process_one(fname, Ncmax);`

Inputs: $fname$ Base name of files to process

$Ncmax$ Maximum number of channels to process. `[]`=all.

Outputs:	f	Frequency samples
	Ho	Output channels
	t	Time samples

Description: Processes the given raw data set, applies the calibration, and returns H matrices. Assumes existence of the following files:

cal/cal_pdiv.mat Power divider calibration file containing the variable c , which is the $Nf \times Nr \times Nt$ frequency response of the power combiner/divider obtained with the vector network analyzer measurements.

cal/cal_Hr.mat Data file containing the response of the complete system with transmit and receive directly connected through the power combiner/divider and excess loss. Should contain the variable Hr which has dimensions $Nf \times Nr \times Nt$.

3 AWG Functions

3.1 esg_store_arb

Location: ./design/software/awg/esg_store_arb.m

Syntax: [] = esg_store_arb(port, data, name);

Inputs:	$port$	Serial port to use (e.g. 'com1')
	$data$	Vector of real or complex data to download. Length must be a multiple of 16.
	$name$	Name of waveform when stored on ESG

Description: Downloads a waveform to the ESG arbitrary waveform generator. It is assumed that the full-scale value of the real data is +/-1.0.

3.2 make_mt_signal

Location: ./design/software/awg/make_mt_signal.m

Syntax: `[s, info, mt] = make_mt_signal(t, fs, df, fmax, Tz1, Tz2, Nd, win);`
`[s, info, mt] = make_mt_signal(mt_in);`

Inputs:

- t* Temporal length of code
- fs* Sample rate
- df* Desired spacing between frequency bins
- fmax* Maximum frequency
- Tz1* Amount of extra zero pad at front
- Tz2* Amount of extra zero pad at end
- Nd* Number of samples to discard from end (necessary for some AWGs to have rearm time)
- win* Array containing optional window parameters:
 - [0] square window
 - [1 *rise_samp std*] Gaussian Window with a rise time of *rise_samp* for *std* standard deviations.
- mt_in* Output of a previous call of `make_mt_signal`

Outputs:

- s* Real time-domain signal
- info* Structure containing some useful info on the waveform:
 - df* Actual spacing of frequency bins
 - phi* Phases used for frequency bins
 - xf* Frequency samples
 - Y* FFT of signals
 - xfb* Frequencies of sampled frequency bins
 - Yb* Response at sampled frequency bins
- mt_struct* Structure containing all info about waveform that is needed to regenerate it with this function.

Description: This function generates a single multitone signal where the phase of each tone is uniformly distributed on $[0, 2\pi]$. Normally, the function is called repeated times to find a multitone signal with an acceptable peak-to-average ratio. The function returns the time-domain signal to be sent to the waveform generator as well as a structure containing info that can be used to regenerate the signal.

3.3 serial

Location: `./design/software/awg/serial.c`

Syntax: `[str] = serial(port, command {, wait});`

Inputs:

<i>port</i>	Port to send to (e.g. 'com1')
<i>command</i>	ASCII command string
<i>wait</i>	Optional timeout in ms

Outputs: *str* Reply received

Description: This function is used to perform a simple send/reply mechanism that allows instruments to be controlled using ASCII commands. Compiles to a MATLAB .MEX file.

4 VNA Functions

4.1 get_switch_freq

Location: `./design/software/na/get_switch_freq.m`

Syntax: `[c, idx] = get_switch_freq(st, sr, f, Nt, Nr, Nf);`

Inputs:

<i>st, sr</i>	Raw s-parameter record for transmit/receive
<i>f</i>	Desired frequency (GHz)
<i>Nt, Nr</i>	Number of transmitters and receivers
<i>Nf</i>	Number of frequency bins to fill

Outputs: *s_out* Output s-parameter calibration

Description: Returns the combined switch calibration for switches/dividers at the frequency closest to f . Also fills N_f identical frequency bins with this value. Assumes st and sr are full 2-port S parameters that have been read using `read_cfile`. This function assumes that the unique block names for the different ports are $J1 \dots JN_t$ and $J1 \dots JN_r$ for the transmit and receive networks, respectively.

4.2 read_cfile

Location: `./design/software/na/read_cfile.m`

Syntax: `[s] = read_cfile(fname);`

Inputs: *fname* Name of the Citifile to process

Outputs: *s* Structure containing S-parameters:
 .name.f Frequencies for record *name*,
 .name.s S-parameters for record *name*,
 .name.sn S-parameter tags for record *name*

Description: Reads data from a Citifile type generated by the network analyzer. Data is output in a record containing a field for each unique name found in the data set. Under each unique name, this function stores the frequencies swept, the s parameters, and tags.