Modifying Off-The-Shelf, Low Cost, Terrestrial Transceivers for Space Based Applications

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Abstract

The design, fabrication, and testing of low earth orbit satellite transceivers can get costly and time consuming for companies. As communication satellites proliferate, it is clear that lower cost materials, components, and processes will become standard procedure to stay competitive in the marketplace. This paper outlines the design and modifications done to off-the-shelf, terrestrial, ultra and very high frequency (UHF/VHF) communication equipment for just such a purpose. These low cost commercial products were successfully integrated and modified to survive the space environment. The work was accomplished by the Communications team of Stanford University's Space Systems Development Laboratories specifically to fly on the SAPPHIRE satellite. This was done without heavy R&D development time or cost overruns.

To verify the feasibility of this methodology, this paper will outline issues such as link margins, testing procedures, and cost. Overall performance results will be presented as well. The applicability to industry will be explored towards the conclusion.

1. Introduction

As with all engineers and engineering related companies, the Communications team for the SAPPHIRE satellite was under a specific set of constraints with which to solve a problem. They were charged with fabricating a UHF band transceiver that could operate in the LEO environment, was cheap, light-weight, and completed in one years time. The team began by hand designing every section of the transceiver. Although the educational experience was unparalleled, it failed to meet the program requirements of fast delivery. As the deadlines drew near, the team decided it would be prudent to take an off-the-shelf, commercial grade transceiver and modify it to space flight quality.

The performance requirements as handed down from the mission and the subsystem bus were:

- operation from 300-800 km orbital altitude
- < 12W consumption while transmitting
- < 4W consumption in steady state
- low RF power beacon capability
- commandable output power levels
- deactivation control of all units
- both digital and analog capability
- min. digital transmission rate of 1200bps
- min. bit error rate of 10^{-6}
- min. energy per bit to noise ratio of 14dB
- must survive all LEO environmental testing
- maximum mass of 2 pounds (.907kg)
- delivery in 1 year

The calculated link budget indicated that a minimum output RF power of 2W (33dBm) was needed to achieve these results from an orbital altitude of 800 km. The link budget can be found in Table 1.

Given these constraints and the one year timeline, the choice to modify off-theshelf technology was a good one. What follows in this paper are the details of the spaceflight modifications performed to achieve all the aforementioned baseline requirements.

COMM. SUBSYSTEM LINK BUDGET	UPLINK	DOWNLINK	Units
Frequency	144	437	MHz
Distance to Satellite (Slant range at horizon)	3290	3290	km
Transmitter Power (C)	16.99	3.01	dBW
Transmitter Antenna Gain (G)	14	-5	dBi *
EIRP (Effective Isotropic Radiated Power)	30.99	-1.99	dBW
Free Space Loss	145.95	155.60	dB
Atm. Refraction/Absorption Losses	0.24	0.71	dB
Pointing/Polarization Losses	1.50	1.50	dB
Receiver Antenna Gain	-15	14	dBi *
Receiver System Noise Temp. (Te)	33.01	26.02	dBK *
Bit Rate (1200 bits/s)	30.79	30.79	dBHz
Boltzman's Constant	-228.60	-228.60	dBW/K/Hz
G/Te (Rec. Ant. Gain/Noise Temp. Ratio)	-48.01	-12.02	dB/K
Desired Eb/No (Bit Energy/Noise Ratio)	15	14	dB
Eb/No at Receiver Input	33.10	25.99	dB
Margin	18.10	11.99	dB
C/No (Aver. Carrier Power/Noise Ratio)	63.89	56.78	dBW/Hz

* **Worst case approximations.**

2. The Design Solution/ Subsystem Overview

The baseline communications subsystem provides two-way data packet transmission as well as downlink analog output. Two different modulation modes will be used. One is terrestrial Audio Frequency Shift Keying (AFSK) and the other is standard frequency modulation (FM). Amateur radio (HAM) frequencies were obtained through the help of AMSAT, the uplink carrier will be on 437.100 MHz and the downlink carrier will be on 145.945 MHz. The AMSAT community has been instrumental in the design and public support for the SAPPHIRE satellite. The subsystem is composed of four distinct units. The transmitter, receiver, terminal node controller, and multiplexer board (Figure 1).

The transmitter is a 70cm band, model TA451 from Hamtronics Inc. of New York. It has a maximum RF output power of 2.5W continuous duty. It is a standard frequency modulated HAM radio transmitter with a 15 kHz bandwidth. Sized at 3x5 inches and weighing less than 0.3 pounds it was ideal for our application.

The receiver is also a standard FM unit, Hamtronics model R144. The unit is 4x3.5 inches in size and has a maximum rated sensitivity of -125dBm. It only draws 200mW in steady state which is also ideal for our system.

To give a high reliability of transmission quality, an AFSK 1200 baud packet modem was chosen to be used. The modem (Model KPC-3) was made by Kantronics Inc. of Missouri. In the amateur radio community, these radio packet modems are called Terminal Node Controllers or TNC's. It utilizes full hand shaking, AX.25 packet format with error detection algorithms to insure error free transmissions. The AX.25 protocol has addressable source bits as well as destination bits.

It was decided to fabricate a unit by hand to control the transmitter power levels and to control the activation/deactivation of the other various units. This fourth and final unit, named the Multiplexer Board (MUX board), allows either analog or digital transmissions to be used with the same RF channel amplifier of the transmitter. It also holds all the switches to both reset the modem, and to deactivate the transmitter.

Structurally, the transmitter and receiver units are housed in their own boxes. The TNC and the MUX board however are housed in one single box.

3. Space Flight Modifications

Various modifications were necessary to insure proper compliance with the requirements. These commercial products were never designed to endure the harsh environments of space nor were they optimized to perform in such regimes. Some of the modifications necessary were performed on all the units. For example, all the electrolytic capacitors were replaced with tantalum capacitors. All the tuning caps and coils were either epoxied into place or back filled with space grade sealant (Dow Coming 6-1104). All the variable components were replaced with fixed value components. Mylar capacitors were used wherever possible to reduce thermal shifts. All the boards were cleaned and conformal coated as well (with the help of Lockheed Martin) to reduce particulate contamination and prevent outgassing.

What follows are detailed descriptions of the individual issues that faced each unit, and the engineering solutions implemented to answer them.

Transmitter (437.100 MHz)

The TA451 had many issues that had to be resolved. The first of which was the fact that it only had one output power level. The unit operated under a +12 volt power supply. As you can see in the schematic of Appendix A, the power line was severed between the front stage modulation sections and the power amplifier chain. The supply going to the modulation sections was fixed at +12V. But to change the RF output power level, the supply going to the final amplifier stages could be switched between +5V and +12V. This effect of lowering the supply voltage re-biased the final stage power amplifier (Phillips BLX-65E) to a lower efficiency thereby reducing the RF output level to effectively 200 milliwatts.

To deactivate the unit in case of wild transmissions or faulty software programming, a kill switch was employed so that the CPU could turn off the +12V supply to the front modulation section. This was done by turning off the TNC which holds the Push-To-Talk control for the transmitter. Even a free running input to an unbiased front end developed no leakage current to the

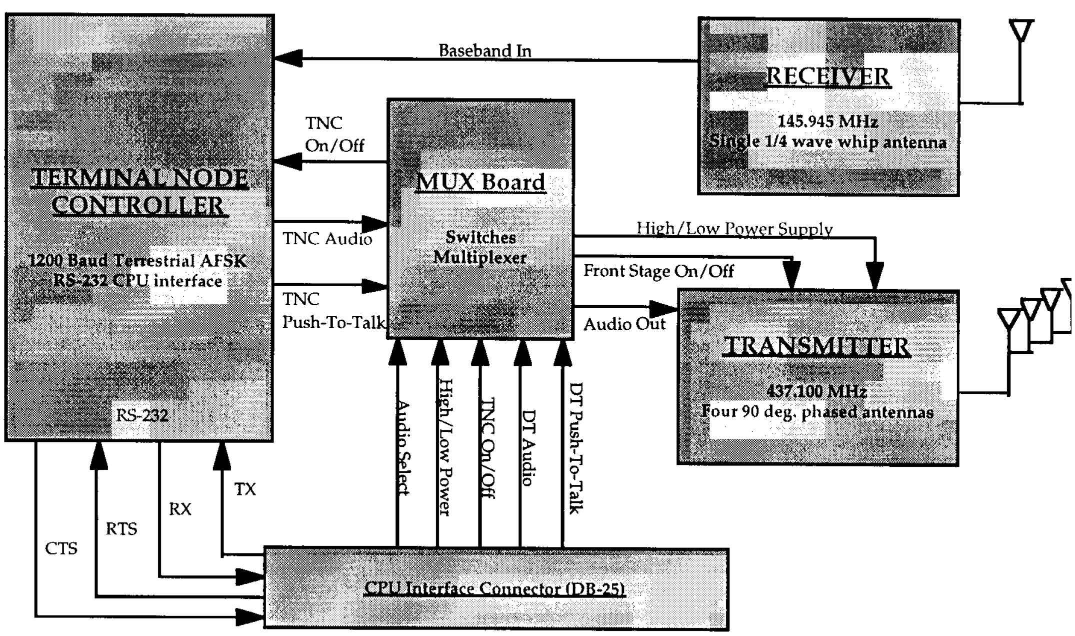


Figure 1: System Block Diagram

power amplifier stage. Thus tuming off the +12V supply to this section deactivated the transmitter output.

The final power amplifier stage draws the most current. C~n full power it will dissipate approximately 3.5W of heat. So a specially made heat sink conductively connects the amp to the chassis of the unit's box. This is the hottest running element of the entire communications tray and it thus required special thermal sinking attention.

The output of the transmitter is sent to 4 separate 1/4 wave whip antennas. The antennas are phased 90 degrees from one another to set up a circular polarization. Th~ phasing is done by adjusting the phase lengths of the 50 ohm co-ax leading to the antennas. A matching stub was placed on output ports of one of the 3dB splitters to correctly add enough inductance so that a proper impedance match was achieved between the transmitter and the antennas. The 50Q output impedance of the transmitter had to be matched to the 12.5Q input impedance of the individual antennas in four way parallel. Utilizing Smith Charts and matching network software, the correct stub length was calculated, installed, and then experimentally verified.

Finally, the crystal oscillator at 12.141667 MHz was pulled out and a high Q, vacuum sealed, cold welded, 20ppm, crystal was put in place to stabilize the local oscillators due to thermal shifts.

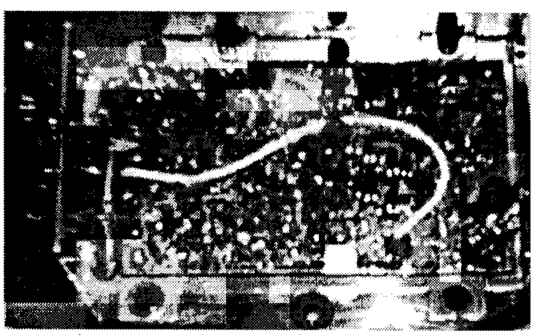


Figure 2: Picture of Transmitter Unit

Receiver (145.945 MHz)

The R144 receiver had several modifications as well. For a low earth orbit satellite the observed Doppler shift from similar altitude satellites was measured to be in the region of 3 to 4 kHz. The front stage of this unmodified terrestrial receiver has a tuning pot to change its receive frequency. This was of course removed. But the receiver's intermediate frequency (IF) bandwidth was not wide enough to account for Doppler shifts in uplink frequency. So the IF filters were replaced with wider passbands and an Automatic Frequency Control circuit (AFC) was put in with the IF stage to attain an effective capture range of 18 kHz (see Appendix B). This AFC helps track the uplink carrier to compensate for the Doppler shifts .

The receiver had many components to drive an extemal speaker. All of this circuitry was removed and the output signal was taken straight off the discriminator as shown on the schematic. The squelch control circuitry was also removed. Just like the transmitter, the crystal oscillator was replaced by a similar quality crystal that was more resilient to temperature changes and had lower aging drift.

The removal of these components reduced the steady state power consumption to a little over 400 mW.

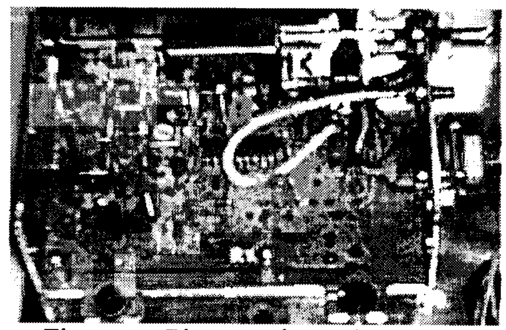


Figure 3: Picture of Receiver Unit

Terrninal Node Controller

The 1200 baud packet modem had to be modified in some major ways as well. Repackaging of the commercial modem required stripping the board out of its box and taking off the non-flight qualified connectors. The standard RS-232 interface was tapped right off the board and fed into the connector leading to the CPU digital harness. The same connector also contained signal lines for the manual CPU reset function. See Appendix C for a complete schematic.

If the CPU ever went into a loop and the watchdog timer ever failed as well, the ground station now has the capability to manually reset the processor and thereby clear the memory and reboot. The receiver sends its raw signals to the demodulator of the TNC where the signal is directly tapped from the level driver (TCM3105NL) on the board which leads to the AX.25 packet demodulator. This tapped signal gets routed out and straight to the CPU tray where circuitry decodes the string and if the correct 128 character combination is received, the CPU is reset.

The TNC's EEPROM which holds the modem's software was replaced by a reprogrammed radiation hardened PROM (28COlOERP) from Space Electronics Inc. of San Diego, CA. This was the only sensitive chip on the communications tray that could absolutely not be upset by a single event upset since the CPU would not know to reset the TNC if such a failure occurred. Upon reset the TNC was kicked into a certain undesirable mode, but we managed to get a custom source code from Kantronics so that the TNC always came alive with our special settings. One such setting is that the TNC will beacon automatically when not actively being operated by a user. This beacon will come down on the low power setting and "ping" every 1 minute. We burned this new code into our rad-hard PROM.

A lithium battery held certain settings in the RAM of the TNC on power down. But since we no longer needed this, the battery was removed and the power line at that particular point was grounded.

Multiplexer Board

The MUX Board consists of several solid state switches (see Appendix D for a full schematic). It also has a Motorola 74HC4051 8 to 1 multiplexer. The MUX is configured to take input from either the TNC or from the analog voice payload. The CPU has complete control of all switching. The inputs are biased at +2.5V because the 4051 is a CMOS component that is designed for positive as well as negative power supplies. Since the SAPPHIRE satellite does not have a negative supply, the inputs had to be centered between the ground and the +5V hot rail. This was done easily by capacitively coupling the input signals and biasing the point with a 500K resistor divider (lM series resistance chosen to reduce the wasted current draw). The inputs were also zener clamped to prevent the possibility of latch-up that can occur with CMOS devices.

As mentioned earlier the transmitter power amplifier stage is powered by either a +5V supply or an unregulated +12V supply. A power darlington pair was used to switch this current to the power amplifier stage. The pair is taken in a PNP configuration to minimize the diode drop loss when full power is activated.

Standard transistor switches are used to tum on and off the power bus to the transmitter front end modulator section and the TNC as well. The transistors are driven into saturation for full output current. All the transistors are thermally mounted upsidedown on the MUX Board to give maximum conductive contact.

The board was hand designed and simulated in PSPICE. The board itself was layed out using PADS layout design software. It is single sided to minimize cost and thick 50 mil traces were used to handle the current draw. Fabricated boards were then stuffed and tested stand alone.

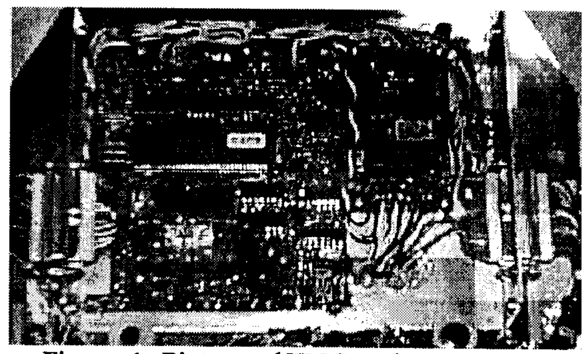


Figure 4: Picture of TNC and MUX Units

4. Testing and Verification

The issue that commercial products _ not survive the environment or be as reliable as "space-grade" equipment was put to the test in this stage of development. Before the tray went into environmental testing, certain things had to be done to the boxes. The hardware holding down the boards were all wedge epoxied. Sealant (61104) was used over any component or harness that could possibly move during shake. And the subsystem performance was accurately measured before and after environmental tests to detect any shifts in operation due to those tests.

The tray was constructed in a modular fashion so that testing of the units stand alone was possible. A computer was interfaced to the TNC to make it output a single tone. Frequency deviation distortions, spurious sidebands, intermodulation products, output power levels, and DC consumption can now be accurately measured.

The tray was placed in a thermal chamber and cycled from -17°C to 37°C. It was found during the thermal tests that the front end amplifiers of the transmitter failed when the temperature dropped below -13°C. This was due to the biasing arrangement of the transistors. As you can see from the schematic of Appendix A, the front stage transistors were DC coupled to each other. This had the effect of multiplying any change in current due to temperature shifts by the Beta of the subsequent amplifier. The solution was to rebias the arrangement so that any Beta shifts would not alter the operating point to anywhere outside the linear region of the subsequent amplifier. The lesson learned was that even though all the individual components were rated at specific temperature ranges, the collective circuit was not.

For the shake, the input spectrum was an amalgamation of a Delta II and Ariane worst spectrums. The final level of the shake was 18 Grms, the maximum level being 0.36 G2/Hz. This meets twice the level of NASA's protoflight specifications for vehicles under 501bs.

5. Achieved Performance Results

The entire tray was completed in 4 months. The analysis concludes that good reception can be achieved after the satellite comes up above 15 degrees on the horizon. This effectively gives an 80 percent contact time of a pass (8-12 min. for a zenith pass). Highlights Include:

• 2.13 W (33.24dBm) RF output power in high power mode.
• 283 mW (24.38dBm) RF output power in low power mode.
• at 3.5 kHz deviation (mark) there is 13% distortion.
• at 2.8 kHz deviation (space) there is 2.4% distortion.
• the receiver sensitivity is -125dBm.
• 18 kHz receiver capture range.
• Spurious sidebands were at least 50dB below the carrier.
• Total mass was less than 1.5 pounds.
• Nominal quiescent DC power draw of less than 400mW.

Table 2 - Material Cost Summary

Unit		Cost
TRANSMITTER		
Commercial Unit		$149
High Grade Crystal		$27
Replacement Components		$15
RECEIVER		
Commercial Unit		$89
High Grade Crystal		$27
Replacement Components		$12
TNC		
Commercial Unit		$129
Rad Hard PROM	*	$3,200
Replacement Components		$10
MULTIPLEXER BOARD		
Layout/Fabrication		$250
Components		$22
CONNECTORS		
D-Type Connectors (8)	*	$960
SMC Connectors (4)		$32
HARNESS	*	$15
BOXES		$25
CONFORMAL COAT	*	$200
EPOXY/SEALANTS	*	$400
TOTAL		$5,562

* actual space grade products used, present industry costs

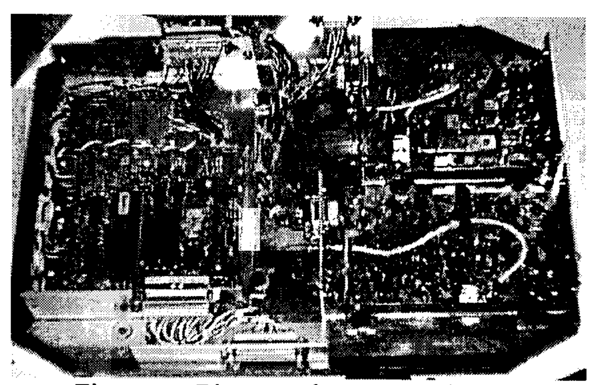


Figure 5: Picture of Integrated Tray

6. Applicability to Industry

There are many applications for such a low cost UHF transceiver system. It could be used as a low power channel for system maintenance. Since the data throughput is limited and system maintenance rarely requires high data rates, this could be a low cost option to such a scenario.

The transceiver can also be used as an emergency uplink/downlink channel. Since the DC power draw is so low, it could sit latent unless required or activated by emergency software. In the event of a problem the system can be easily configured to relay down critical telemetry data if the primary telemetry stream is interrupted or malfunctioning.

The use of UHF/VHF frequency transceivers is also a great way to get HAM radio involvement. Amateur radio enthusiasts can be allowed to listen in on telemetry or non-essential/non-proprietary transmissions. The company can thus get more involved in community activities. There are presently several hundred thousands of registered amateur radio enthusiasts nationally. The publicity generated will look good and also help to promote the recruitment of very talented engineers.

Most importantly, since this transceiver is orders of magnitude less expensive than those presently being used it can be an affordable redundancy alternative to such emergency or telemetry systems. The design time is proven to be very short, but the author realizes that true industry verifications of the unit would extend the delivery time. Even so, it should be faster than the industry norm which is always important from a scheduling and/or customer milestone perspective.

7. Conclusion

Current industry standards for the design of space flight transceivers necessitates low cost and speedy delivery schedules. In the following years, the companies that can produce communication satellites at costs and schedules far below the present levels will be the ones who will win the market. The work performed on the communications subsystem for the SAPPHIRE satellite provides evidence that off-theshelf commercial grade equipment can indeed be modified for space flight operations. As proven, these modifications can be tested and verified so that there is good confidence of survivability to the space environment. As long as issues such as radiation hardening, frequency drifting, material property, impedance matching, and power efficiency can be addressed properly, there is a great probability of success.

The author does not intend to profess that this particular solution is applicable to just any program, but the moral of the story is clear. With an off-the-shelf process, both cost and schedule can be driven down without appreciable loss of reliability. Like all engineering choices, there are tradeoffs. The choice to place such commercial grade, commodity-like equipment into non-critical portions of subsystems, is a sound one. It makes sense from a design point of view, a schedule point of view, a cost point of view, and ultimately a business point of view.

8. Acknowledgements

Profound appreciation is extended to the Stanford Space Systems Development Laboratory, along with its director, Professor Robert J. Twiggs. In addition, the entire SAPPHIRE team is to be commended for their dedication, support, humor, and their hard, very hard, work. Without them this project would never have been possible, only as a team did the project succeed.

Many corporations have donated flight grade components and have generously offered technical services in the development of SAPPHIRE. These companies will hopefully extend their involvement to ongoing, working relationships with many future students of the laboratory. Their help has been greatly understated in this paragraph. They include, in no particular order: ITT Canon, Space Electronics, RayChem, Space Systems Loral, Lockheed Martin, Motorola, National Semiconductor, Eagle Pitcher, PADS, Penstock Microwave, Harris Semiconductor, NASA JPL, TiNi, and Analog Devices.

But the highest thanks goes to the satellite mentors that donated literally hundreds of hours to teach us the black art of communications electronics. In particular, the following people were absolutely invaluable for their guidance, patience, and tutelage: Kit Blanke, John Ellis, Lars Karlson, Bill Kaiser, and Dick Kors.

9. APPENDICES

Brief summaries of the appendices follows:

Appendix A: Schematic for the modified Hamtronics TA451 transmitter. Schematic from Hamtronics with component modifications.

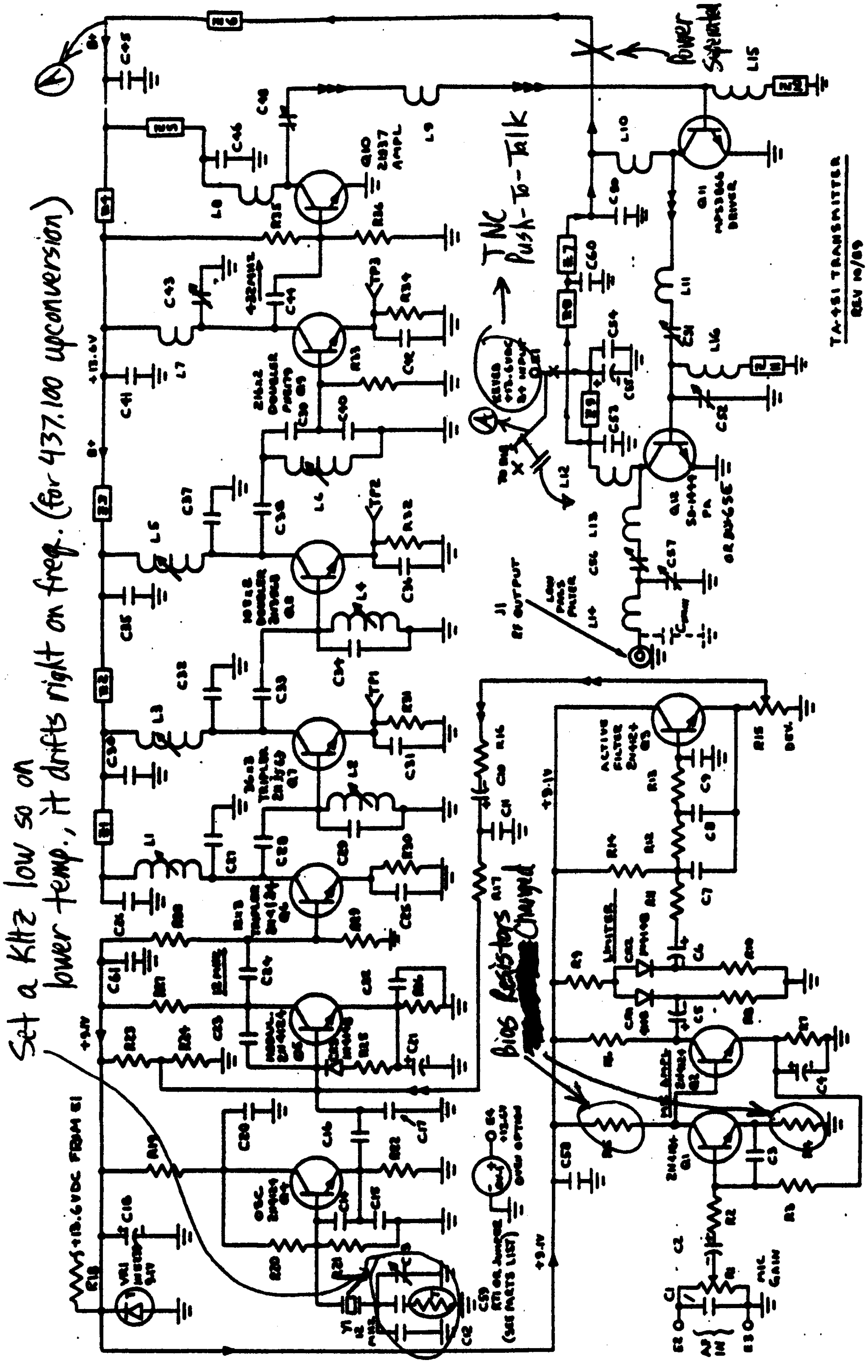
Appendix B: Schematic for the modified Hamtronics R144 receiver. Schematic from Hamtronics with component modifications.

Appendix C: Schematic for the modified Kantronics KPC-3 terminal node controller. Schematic from Kantronics.

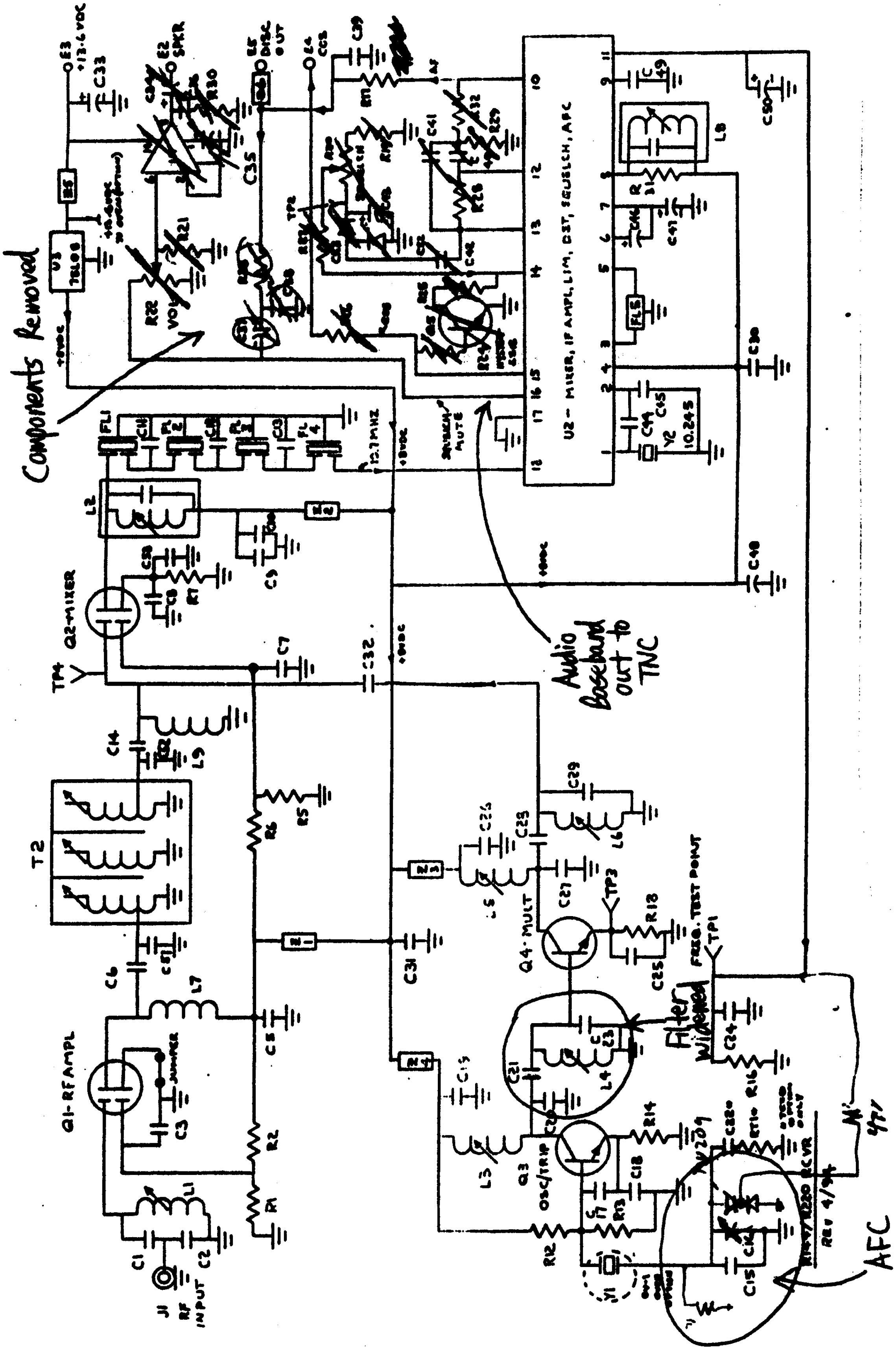
Appendix D: Schematic for the handbuilt Multiplexer Board. Includes PADS generated schematic and artwork layout. The board was tumed around in one week.

Note to readers: Further schmatics, layouts, wire lists, box designs, grounding diagrams, signal diagrams, dimensional drawings, photomasks, and component data are available upon request.

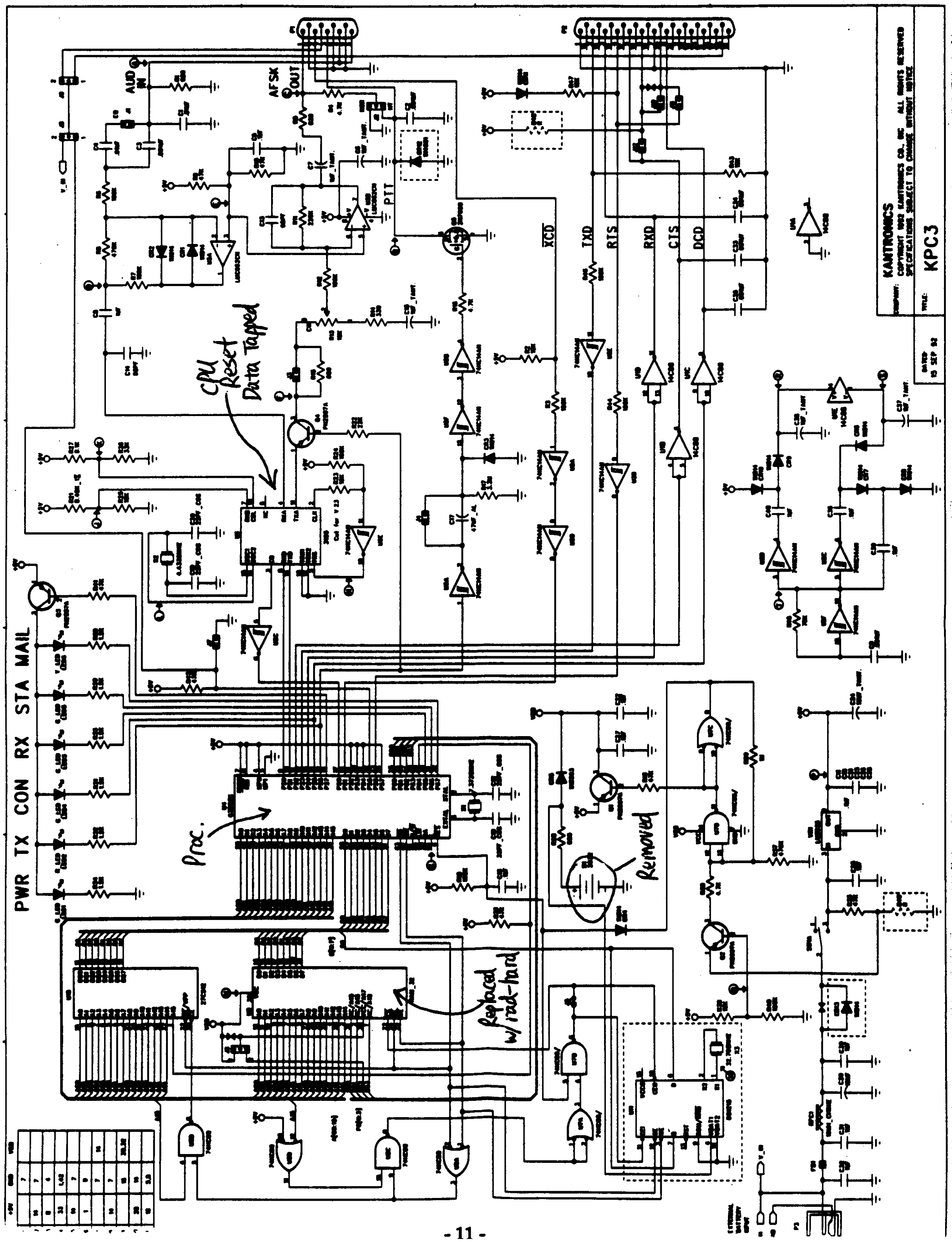
Appendix A: TA451 Transmitter Schematic



Appendix B: R144 Receiver Schematic



Appendix C: KPC-3 Terminal Node Controller Schematic



Appendix D: MUX Board Schematic