# Icom AH4 Auto-Tuner Protocol Emulator for the MFJ-994BRT Remote Auto-Tuner

Version 0.03
25 November 2022

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# Chapter 1 - LICENSE

# Chapter 2 - MFJ-994BRT REMOTE TUNER AND ICOM AH4 AUTO TUNER EMULATOR

My station includes an Icom transceiver driving an Elecraft KPA-500 amplifier and an Elecraft KAT-500 auto-tuner. I recently installed an Inverted-L antenna that is located more than 200-feet from the radio installation. Using the KAT-500 auto-tuner to match the Inverted-L with over 200-feet of LMR-400 feed-line resulted in an inability to tune the antenna on a large number of frequencies.

Operationally, the main goal is to achieve a high-power Automatic Link Establishment, using ION2G, primarily supporting operation on NTIA channels that are outside of Part 97 frequency allocations.

My past experience with the Inverted-L demonstrated that when coupled with a remote auto-tuner, located at the base of the vertical segment of the antenna, there were no frequencies that the auto-tuner could not produce a proper impedance match. My prior experience was with an LDG RT-100 ATU, a 100-watt ATU that powers the ATU through the coaxial feed-line via a Bias-T. LDG had manufactured a higher power remote ATU, the RT-600 with a 600-watt rating. Unfortunately, the RT-600 ATU is no longer available.

The search for a remote ATU kept landing on MFJ. I have not been a big fan of MFJ products, but decided to give the MFJ-994BRT a go. Like the LDG RT-600, the MFJ-994BRT is rated for 600-watts power, and this provides some adequate headroom above the KPA-500 amplifier's 500-watt output.

No matter which remote ATU I chose, there are some significant differences between the Elecraft KAT-500 ATU and the available remote ATU offerings. Among these differences are the following critical features found in the Elecraft KAT-500 / KPA-500 configuration:

- The Elecraft KAT-500 implements the Icom AH4 Auto-Tuner control protocol, which fully automates the tuning process.
- When the AH4 protocol has the KAT-500 actively tuning, the key-line from the Icom transceiver (ie. SEND) is blocked from keying the KAT-500 amplifier, allowing the normal transceiver produced tuning power level to be applied during the tuning process.

Lacking the above features that are inherent with the Elecraft configuration, using a remote auto-tuner reverts to a largely manual process that requires the following steps:

1. Place the Elecraft KPA-500 into bypass mode.
2. Set the transceiver power output level to a level appropriate for the auto-tuning process.
3. Key the transceiver with a carrier or tone (I usually use the TUNE button in the FLDIGI application), and remain keyed while monitoring the transceiver VSWR until the VSWR stabilizes.
4. Un-key the transceiver.
5. Restore the transceiver power output setting to a level appropriate for driving the Elecraft KPA-500 amplifier.
6. Restore the operating mode (if changed to accomplish step 3 above).

Comparing this to the KPA-500 / KAT-500 configuration required a single push of the TUNE button on the KAT-500 auto-tuner to achieve proper operation after changing frequency.

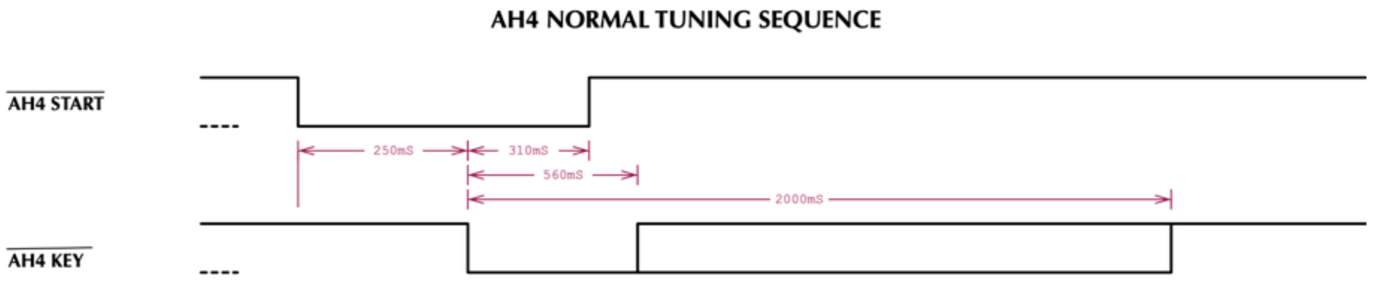
The increased operating complexity with the remote auto-tuner is undesirable. If using digital communications that are frequency agile, such as Automatic Link Establishment, the increased operational complexity is unacceptable.

What is needed is an emulation of the Icom AH4 auto-tuner protocol, with the addition of blocking the key-line to the KPA-500 amplifier during a tuning sequence, to restore an automated one-touch operation.

# Chapter 3 - Icom AH4 Auto-Tuner Protocol

## Icom AH4 Normal Tuning

The Icom AH4 protocol is implemented with two signals, START and KEY. A normal AH4 auto-tuning sequence occurs as follows:

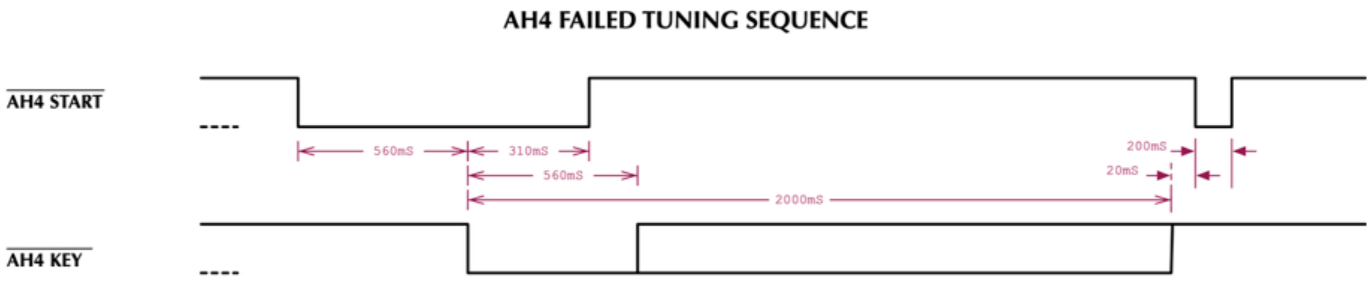


1. The START signal is driven from the transmitter and signals the auto-tuner that a request to tune is being made.
2. The auto-tuner responds to the START signal by asserting a KEY signal back to the transceiver, causing the transceiver to key up with a carrier in a low-power state that will not result in damage to the auto-tuner.
3. The transceiver responds to the KEY signal by negating the START signal and then waits for the KEY signal to be negated by the auto-tuner when the auto-tuning sequence has completed.
4. When the auto-tuning sequence completes (usually due to resolving the tuning problem and achieivng a stable low VSWR), the auto-tuner negates the KEY signal.
5. The transciever responds to the negated KEY signal by un-keying the transceiver before restoring the selected operating mode.

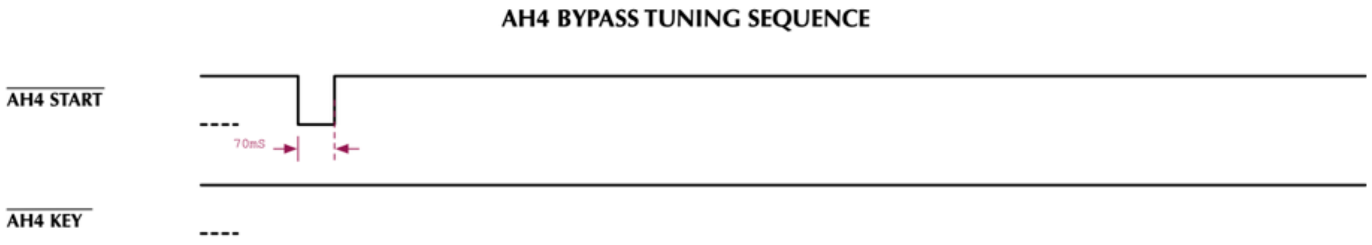
To emulate the AH4 protocol, a microcontroller is needed to model the state transitions that occur with the AH4 protocol signals, and an ability to determine when the VSWR has stabilized so that the KEY request to the transceiver can be terminated. An Arduino Pro Mini is used to implement the AH4 protocol state machine, and a Fox Delta FD-HFB3-1213 Balanced Bridge is interfaced to the Arudino to provide VSWR sensing.

***NOTE:*** *This project is emulating only the normal AH4 tuning protocol. Not supported are the AH4 protocols for placing the auto-tuner into BYPASS mode, or the AH4 protocol for indicating an auto-tuning error (ie. when no tuning solution was determined). There is no method of determing an auto-tuning error from the MFJ-994BRT remote auto-tuner, other than possibly an unacceptable VSWR. The non-remote version of the MFJ-994 does support a BYPASS mode, but with the control board buttons inside the case of the MFJ-994BRT remote tuner, placing the auto-tuner into BYPASS mode is only possible by removing the DC power to the remote tuner (which is best done with the power switch on the BIAS-T device).*

## Icom AH4 Normal Tuning - Failed Tuning



## Icom AH4 Bypass Tuning



# Chapter 4 - ICOM IC-7610 AH4 TUNER INTERFACE

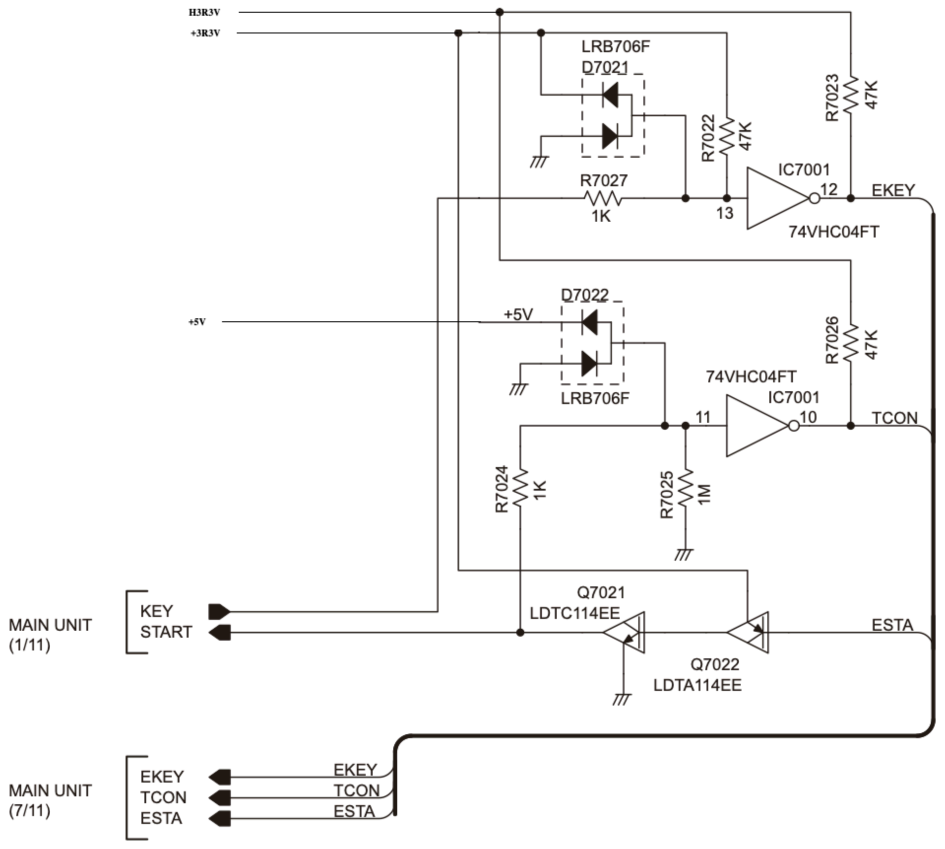
The Icom IC-7610 AH4 Tuner Interface has a weak pull-down termination (R7025) on the START signal. The START signal has a strong pull-up that is located in the auto-tuner. If no auto-tuner is present, the weak pull-down on the START signal will result in a low being presented to the TCON signal and the IC-7610 will then determine that no external auto-tuner is attached during power-on boot. If the START signal is read as high during the power-up boot of the IC-7610, via the TCON signal, the IC-7610 determines that an external auto-tuner is attached.

The IC-7610 provides a strong pull-up termination (R7022) of the KEY signal, an input to the IC-7610. The auto-tuner should provide a weak pull-down of the KEY signal, and should have the ability to read the state of the KEY signal. If the KEY signal is read by the auto-tuner, and a low is detected while the auto-tuner is not driving the KEY signal low, the auto-tuner should determine that the IC-7610 is powered off, and should wait for the KEY signal and the START signal to go high prior to responding to any low assertion of the START signal.

The 1KΩ series resistors (R7024 & R7027) on each of the AH-4 Signals limit the current through the clamping diodes (D7022 & D7021) that prevent the I/O signals from exceeding the signal levels specified by the I/O logic devices.

The auto-tuner/emulator should provide a strong pull-up termination of the START signal. This is necessary to overcome the weak pull-down in the IC-7610 for both signal termination and so that the IC-7610 properly detects the presence of the tuner during power-on boot.

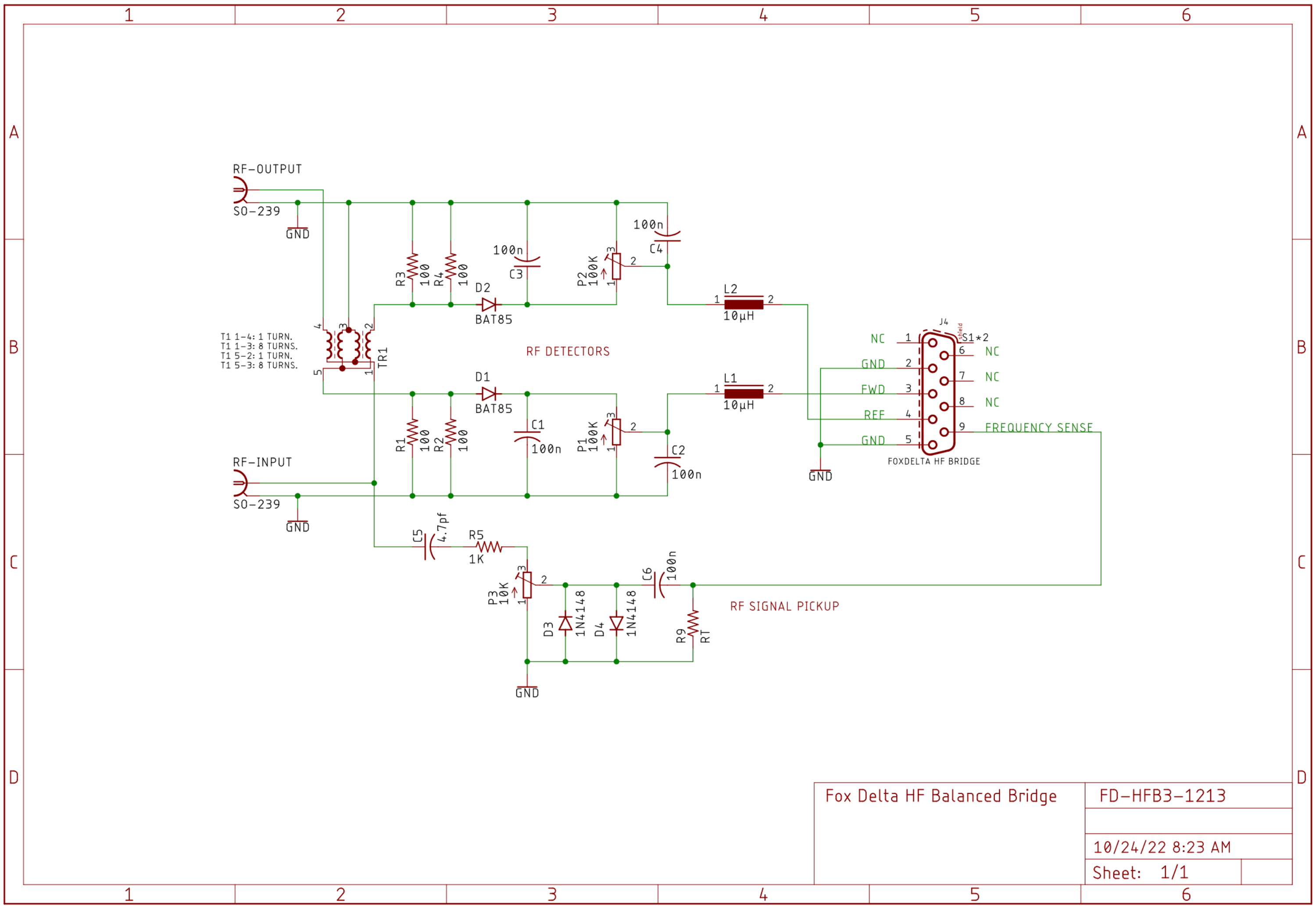
The auto-tuner/emulator should provide a weak pull-down termination of the KEY signal. This is necessary so that the KEY SENSE signal properly indicates when the IC-7610 is not powered on, and is used to gate accepting an assertion of the START signal to only occur when the IC-7610 is powewred-on.



# Chapter 5 - FOX DELTA HFB3-1213 HF BALANCED BRIDGE

The Fox Delta FD-HFB3-1213 Balanced Bridge is available in kit form. The HFB-3 provides two adjustable outputs that represent a forward voltage and a reflected voltage. These outputs are adjustable and can be scaled to remain within the 0 to full-scale range of an analog to digital converter (ADC).

The following schematic depicts the Fox Delta HFB3 circuit. Note that this schematic corrects two errors on the schematic provided by Fox Delta, where the Forward and Reflected voltages were depicted as being routed off the top of the trim resistors. The corrected circuit has the Forward and Reflected voltages taken from the variable tap on the trim resistors. This error only appears on the schematic. The printed circuit board is implemented correctly.



# Chapter 6 - FOX DELTA HFB3-1213 HF BALANCED BRIDGE CALIBRATION

**Calibration of the Fox Delta HFB3-1213 HF Balanced Bridge should be performed before connecting the HFB3 to the Arduino Pro Mini. Note that the HFB3 is limited to transmitters operating at 100-watts or less.**

The following steps can be used to calibrate the HFB3 to produce Forward output voltage that is compatible with the 5-volt Arduino Pro Mini:

1. Connect transmit antenna port to RF-Input port on the HFB3.
2. Connect a Dummy Load to the RF-Output port on the HFB3.
3. Adjust the transmitter for 100-Watts output.
4. Place the transmitter in CW mode.
5. Key the transmitter.
6. Adjust P1 so that the FWD signal on pin 3 of the D-SUB 9-pin connector is at 5.0000 volts.
7. Un-key the transmitter.

The following steps can be used to calibrate the HFB3 to produce Reflected output voltage that is compatible with the 5-volt Arduino Pro Mini:

1. Connect transmit antenna port to RF-Output port on the HFB3.
2. Connect a Dummy Load to the RF-Input port on the HFB3.
3. Adjust the transmitter for 100-Watts output.
4. Place the transmitter in CW mode.
5. Key the transmitter.
6. Adjust P2 so that the REF signal on pin 4 of the D-SUB 9-pin connector is at 5.0000 volts.
7. Un-key the transmitter.

Although not used in this project, the following steps can be used to calibrate the Frequency Sense output voltage:

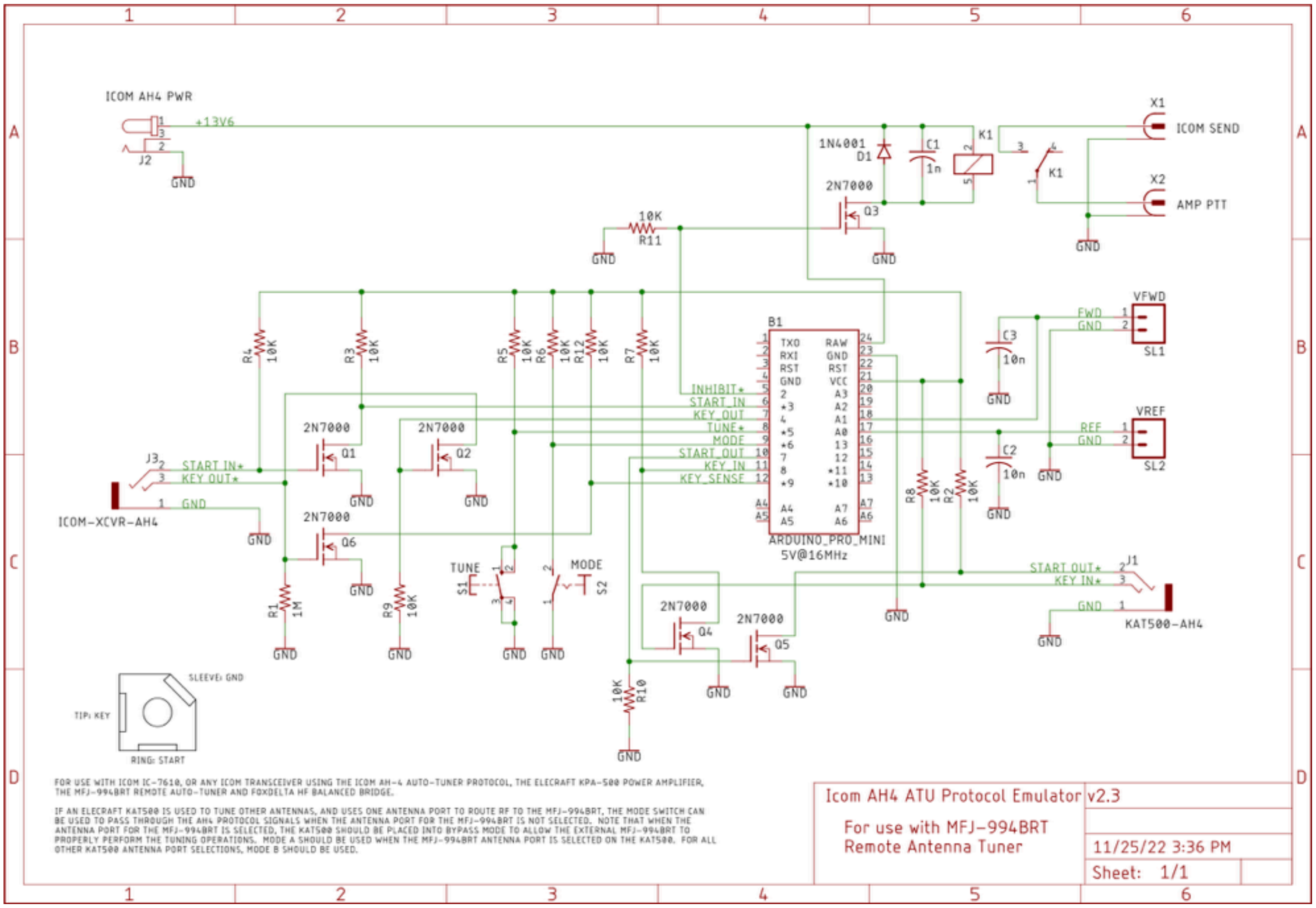
1. Connect transmit antenna port to RF-Input port on the HFB3.
2. Connect a Dummy Load to the RF-Output port on the HFB3.
3. Adjust the transmitter for the minimum output power level that the transmitter may be operated at.
4. Place the transmitter in CW mode.
5. Adjust P3 to its minimum value.
6. Key the transmitter.
7. Adjust P3 so that the Frequency Sense signal on pin 9 of the D-SUB 9-pin connector produces a square wave as observed on an oscillocope.
8. Un-key the transmitter.

# Chapter 7 - ARDUINO AH4 PROTOCOL EMULATOR

The AH4 Protocol Emulator includes the following features:

- A MOSFET interface used to translate between the Icom transceiver AH4 interface levels and the Arduino microcontroller.
- A TUNE button interface.
- A SPDT relay that is used to block keying of the Elecraft KPA-500 amplifier. The normally open contacts are used so that, in the event of a relay driver failure, the amplifier is prevented from keying so that the MFJ-994BRT is protected from possible tuning scenarios occurring at a high transmit power level.
- An Analog to Digital Converter (ADC) interface to the external Fox Delta HFB3 HF Balanced Bridge for VSWR measurements.
- A Mode switch to support dynamic configuration as an AH4 protocol emulator or an AH4 repeater.

The Mode switch is used in a configuration that has another auto-tuner, such as an Elecraft KAT500, providing RF routing through antenna switches. In such a configuration, one antenna port/switch will route RF to the MFJ-994BRT Remote Tuner and the remaining ports/switches will route RF to other antennas. When the antenna port assigned to the MFJ-BRT994 Remote Tuner is selected, the KAT500 must be placed into <u>BYPASS</u> mode and the AH4 ATU Protocol Emulator MODE switch must be placed into MODE A / EMULATION. When another antenna port is selected, that does not route RF to the MFJ-994BRT, the AH4 ATU Protocol Emulator MODE switch must be placed into MODE B.



FOR USE WITH ICOM IC-7610, OR ANY ICOM TRANSCEIVER USING THE ICOM AH-4 AUTO-TUNER PROTOCOL, THE ELECRAFT KPA-500 POWER AMPLIFIER, THE MFJ-994BRT REMOTE AUTO-TUNER AND FOXDELTA HF BALANCED BRIDGE.

IF AN ELECRAFT KAT500 IS USED TO TUNE OTHER ANTENNAS, AND USES ONE ANTENNA PORT TO ROUTE RF TO THE MFJ-994BRT, THE MODE SWITCH CAN BE USED TO PASS THROUGH THE AH4 PROTOCOL SIGNALS WHEN THE ANTENNA PORT FOR THE MFJ-994BRT IS NOT SELECTED. NOTE THAT WHEN THE ANTENNA PORT FOR THE MFJ-994BRT IS SELECTED, THE KAT500 SHOULD BE PLACED INTO BYPASS MODE TO ALLOW THE EXTERNAL MFJ-994BRT TO PROPERLY PERFORM THE TUNING OPERATIONS. MODE A SHOULD BE USED WHEN THE MFJ-994BRT ANTENNA PORT IS SELECTED ON THE KAT500. FOR ALL OTHER KAT500 ANTENNA PORT SELECTIONS, MODE B SHOULD BE USED.

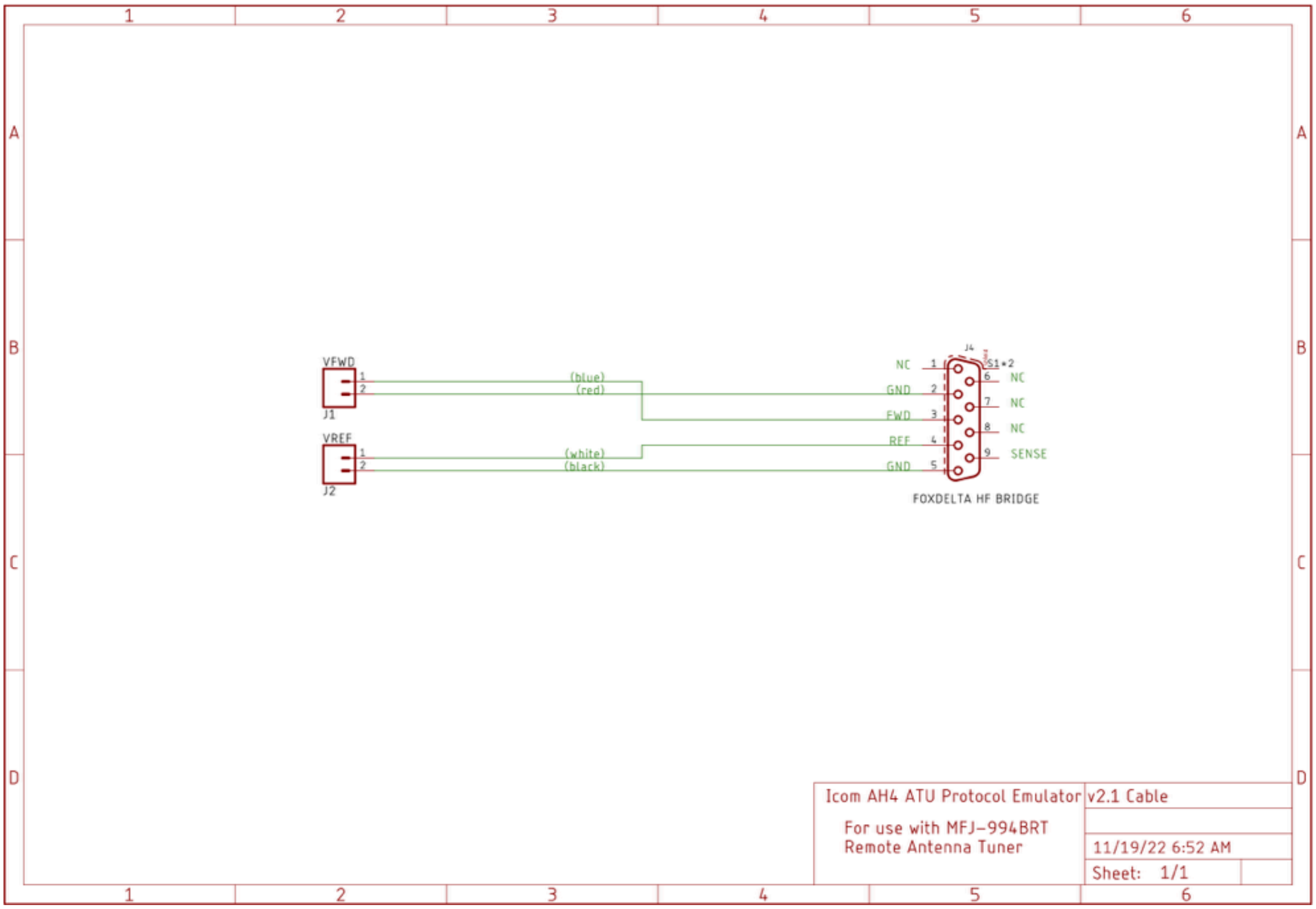
Icom AH4 ATU Protocol Emulator v2.3

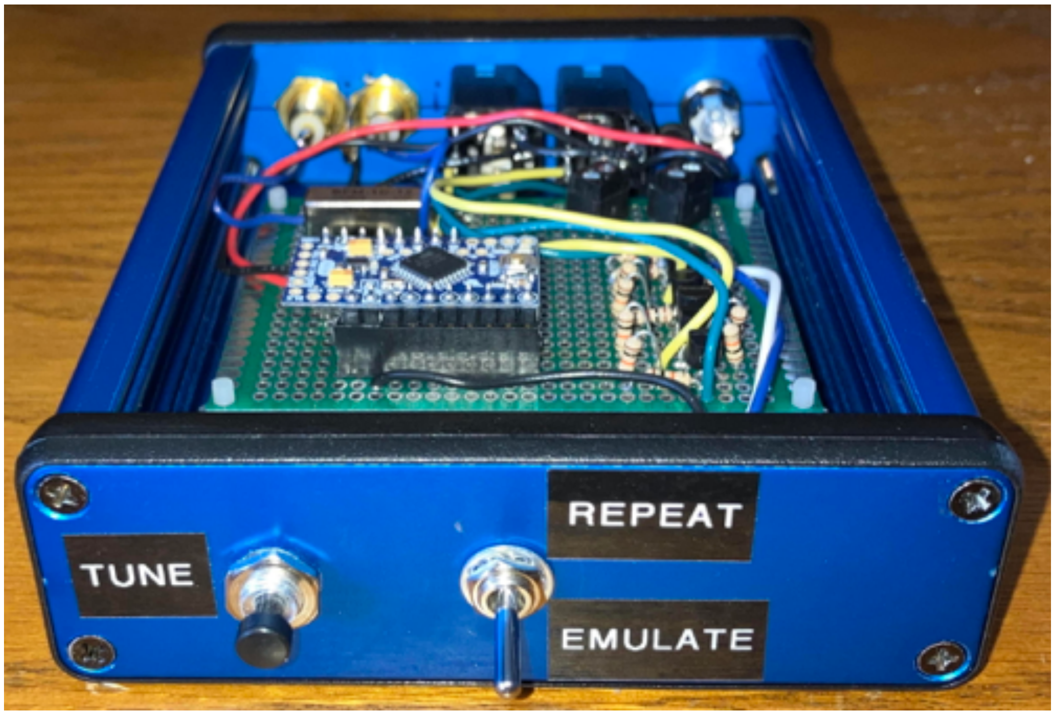
For use with MFJ-994BRT Remote Antenna Tuner

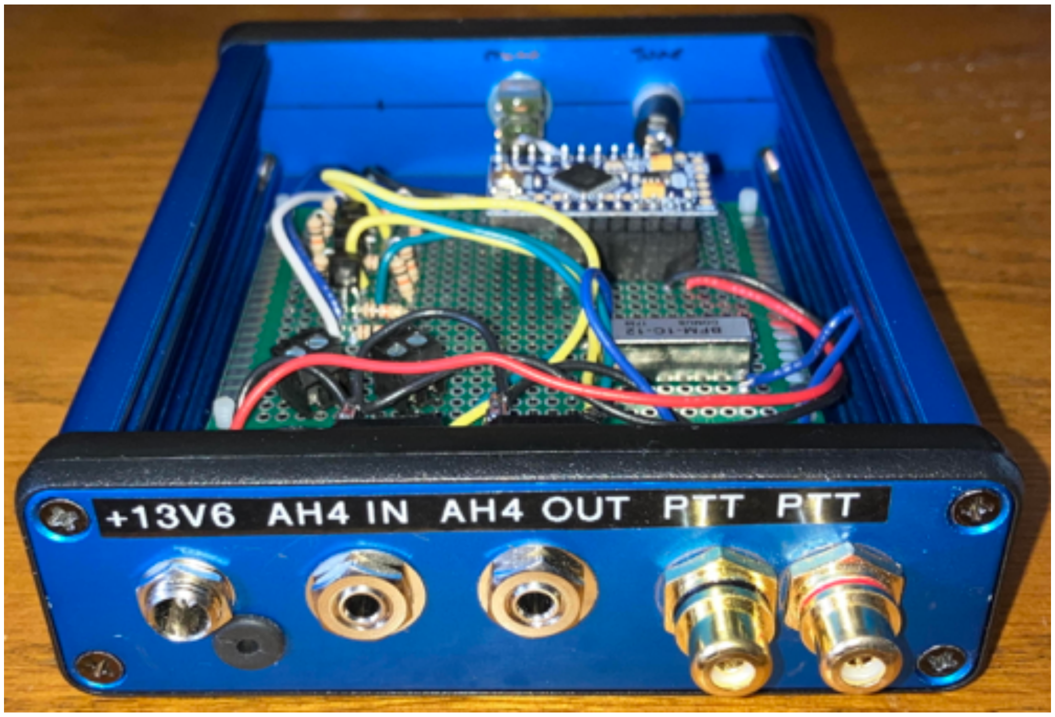
11/25/22 3:36 PM

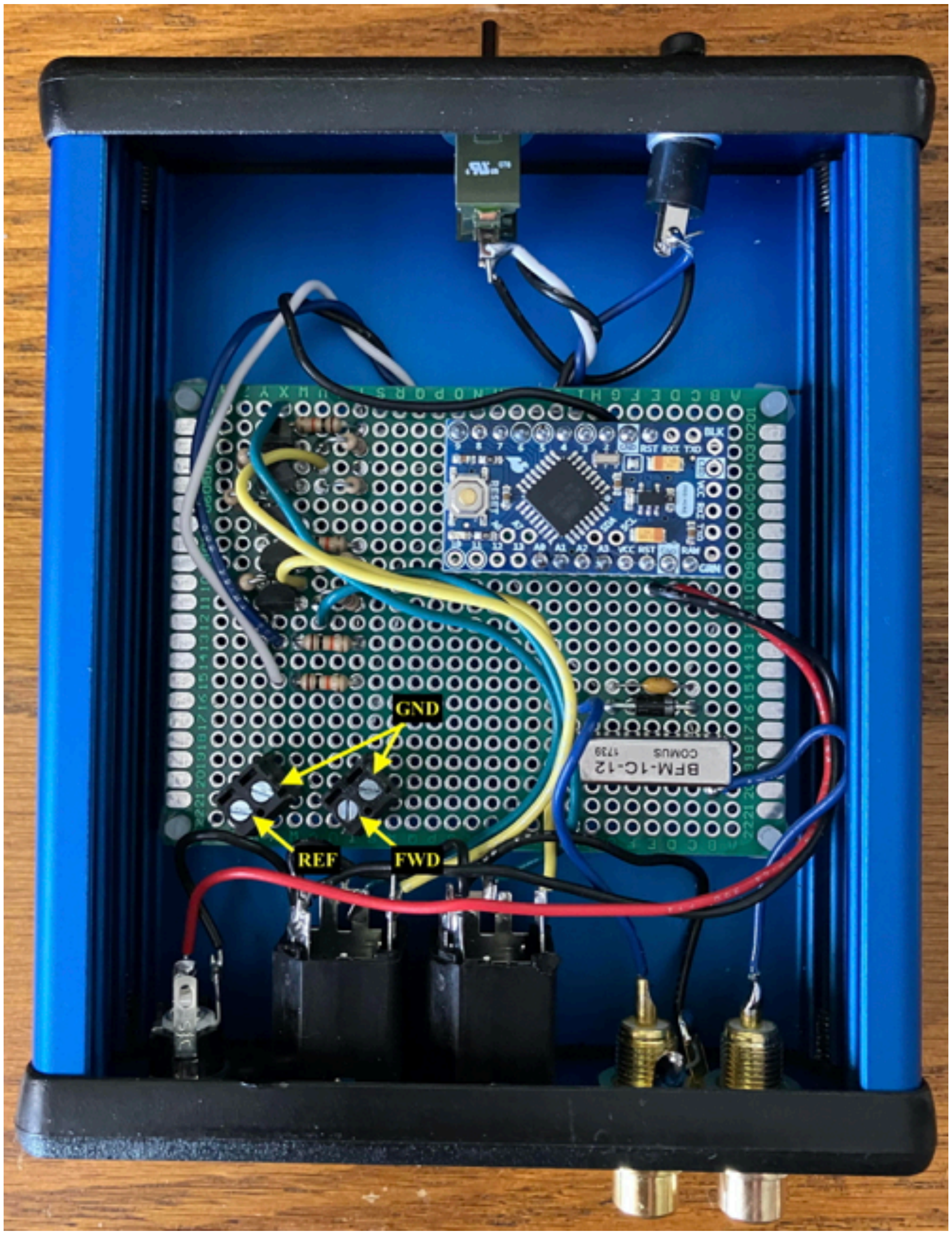
Sheet: 1/1

When in MODE B, the AH4 ATU Protocol Emulator will enable the amplifier keying and act as a repeater for the AH4 protocol (ie. AH4 START from the transceiver is forwarded to the KAT500, and AH4 KEY from the KAT500 is forwarded to the transceiver). The AH4 ATU Protocol Emulator TUNE button is disabled in MODE B.




TUNE
REPEAT
EMULATE


+13V6
AH4 IN
AH4 OUT
PTT
PTT


GND
REF
FWD
BFM-1C-12
COMUS
1739

# Chapter 9 - SOFTWARE OVERVIEW

The source code is written in the **C** programming language and can be compiled with the Arduino IDE. Source code tab-stops are based on a 4-character per tab-stop setting.

The source code implements a state machine that provides the AH4 protocol emulation. State machine execution is as follows:

1. **WAIT RADIO POWERUP**

   This is the initial state. Should the KEY SENSE signal be sensed low when the KEY signal is not being driven by the AH4 Emulator, execution will return to this state under the assumption that the transceiver has been powered down.

   When the KEY SENSE signal indicates that the transceiver has powered up, the state machine will advance to the IDLE state.

2. **IDLE**

   The IDLE state detects an assertion of the START signal to start the tuning process. If START is detected, this state will block the keying of the KPA-500 amplifier. A timer is then primed to produce the delay between START assertion and KEY assertion before advancing to the POST START DELAY state.

   Alternatively, a manual tuning sequence can be initiated by depressing the TUNE button. Like a START initiated tuning sequence, , this state will block the keying of the KPA-500 amplifier. A timer is then primed to produce the delay between START assertion and KEY assertion before advancing to the POST START DELAY state.

3. **POST START DELAY**

   This state runs the delay timer to terminal count before advancing to the ASSERT KEY state.

4. **ASSERT KEY**

   If the START signal remains asserted, or manual tuning was started via pressing the TUNE button, this state will assert the KEY signal. The timer is then primed to support a delay to allow the transceiver transmitter to key before checking for a tuning solution in the next state. The state is then advanced to the Wait For Transmit RF state.

   If the START signal is not asserted and the tuning was not started manually, the state advances to the Wait For Tune Button Release state.

5. **WAIT FOR TRANSMIT RF**

   This state runs the timer down to terminal count while sampling RF to determine if the transmitter has keyed. If the transmitter RF is detected before the timer reaches terminal count, the state is advanced to the Wait For Stable VSWR state.

   If no transmitter RF is detected and the timer reaches terminal count, the state advances to the Negate Key state.

- **WAIT FOR STABLE VSWR**

  This state accumulates transmitter RF detection samples and waits for a stable VSWR state. If a stable VSWR is detected before the timer reaches terminal count, the state is advanced to the Negate Key state to terminate the tuning sequence.

  A stable VSWR is defined as meeting the following metrics:

  - The maximum VSWR that is encountered over eight consecutive measurments must be no higher than 2.0:1.
  - The average VSWR over eight consecutive measurements must be equal to or less than the mid-point between the maximum and minimum VSWR encountered over the same eight measurements if the minimum VSWR is not equal to the maximum VSWR.
  - The range of VSWR measurements over an eight sample span must be less than or equal to 0.250.
  - The minimum VSWR over an eight sample span must be equal to or greater than 92% of the maximum VSWR encountered over the same eight sample span.

  Once transmit RF is detected, VSWR samples are aquired with a minimum interval of 50 milliseconds between samples until either a tuning sollution is found or the tuning timer reaches terminal count. The timer will reach terminal count after 15-seconds.

- **NEGATE KEY**

  This state negates the KEY signal. If a stable and viable VSWR was detected, the state will advance to the Negate Amp Inhibit state. If the VSWR was not stable, or not viable, the amp keying will remain inhibiting by skipping over the Negate Amp Inhibit state, in order to protect the amplifier, and go directly to the Wait For Tune Button Release state.

- **NEGATE AMP INHIBIT**

  This state enables the keying of the KPA-500 amplifier by the Icom transceiver and then advances to the Wait For Tune Button Release.

- **WAIT FOR TUNE BUTTON RELEASE**

  This state waits for the TUNE button to be released and then advances to the Idle state.

Supporting functions include:

- **float getVswrData ( void )**

  This function reads the two Analog to Digital Converters to obtain the voltage that represents the Forward and Reflected power, and then calculates the VSWR using the VSWR = ( Forward + Reflected ) ÷ ( Forward - Reflected ) formula. The VSWR is only represented to a tenth value, with the value rounded to the nearest tenth.

- **float analogReadPinAndScale ( int pin )**

  This function reads the integer value of the specified Analog Digital Converter (ie. Forward or Reflected) and converts the integer value into a float value that represents the voltage that was read.

- **void pushVswrData ( float vswrData )**

  A small buffer is maintained to store VSWR measurement samples. The contents of the buffer can be evaluated, external to this function, to determine when the VSWR has stabilized. This function is used to enter a VSWR measurement sample into the buffer.

- **uint8_t getNumberOfVswrMeasurements ( void )**

  This function returns the number of VSWR measurement samples contained in the buffer.

- **boolean checkIfVswrIsStable ( void )**

  This function evaluates all of the VSWR measurement samples contained in the buffer to determine if the VSWR has stabilized. This function returns true if the VSWR has stabilized.

- **void setAh4TunerKeyOutState ( boolean ah4KeyState )**

  Passing TRUE to this function will assert the KEY signal to the transceiver AH4 interface. Passing FALSE to this function will negate the KEY signal to the transceiver AH4 interface.

- **boolean ah4TuneStartInIsAsserted ( void )**

  Returns TRUE if the transceiver AH4 START signal has been asserted by the transceiver.

- **boolean ah4TunerKeyInIsAsserted ( void )**

  Returns TRUE if the second auto-tuner, used in MODE B operations where the AH4 Emulator acts like an AH4 protocol repeater, has asserted the KEY signal on the AH4 interface between the second auto-tuner and the AH4 Emulator.

- **boolean ah4TunerKeySenseIsAsserted ( void )**

  Returns TRUE if the KEY IN SENSE is in a low state. This signal should only be observed if the KEY OUT signal has not been driven low (asserted) by the AH4 Emulator.

- **void setAmplifierEnableState ( boolean ampEnableState )**

  This function controls the relay that is used to enable the keying of the amplifier or to place the amplifier into bypass mode. When passing a TRUE argument, the amplifier keying is enabled. When passing a FALSE argument, the amplifier is bypassed.

- **boolean tuneButtonIsAsserted ( void )**

  This function returns FALSE if the TUNE button is released. This function returns TRUE if the TUNE button is pressed.

- **boolean isInModeA ( void )**

  This function is used to determine if the operator has placed the AH4 emulator into emulation mode or into repeater mode. When in emulation mode (ie. controlling the MFJ-994BRT), a value of TRUE is returned. When in repeater mode (ie. controlling another AH4 compatible auto-tuner), a value of FALSE is returned.

- **void setAh4TunerStartOutState ( boolean ah4StartOuttate )**

  This function is used only when the AH4 emulator is in repeater mode, and is used to control the state of the START signal from the AH4 emulator to the second auto-tuner that is AH4 protocol compatible.

- **boolean xmitRfDetected ( void )**

  This function reads the Forward and Reflected voltages from the Fox Delta HFB3 HF Balanced Bridge to determine if the transmitter is active. If the transmitter is active, this function returns TRUE. If the transmitter is inactive, this function returns FALSE.

- **void stateMachine ( void )**

  This function is executed at intervals that are no shorter than 1 millisecond, and both monitors and controls the state of the AH4 protocol interface signals in order to implement, or repeat, the AH4 auto-tuner protocol.

- **void repeatAh4Protocol ( void )**

  This function is executed with the AH4 emulator is in repeat mode. This function then repeats the START signal from the transceiver to the second auto-tuner, and repeats the KEY signal from the second auto-tuner back to the transceiver.

- **void setup ( void )**

  This function is executed once at AH4 emulator power-up time and performs all AH4 hardware and software initialization tasks.

- **void loop ( void )**

  This function is executed repeatedly. This function monitors the current time and then enables further execution only when at least 1 millisecond has transpired since the last time that further execution occurred.

  When in AH4 emulation mode, further execution passes control to the stateMachine () function.

  When in AH4 repeater mode, further execution passes control to the repeatAh4Protocol () function.

  Further execution also includes ensuring an orderly transition between emulation and repeater modes. A transition from emulation mode to repeater mode, or from repeater mode to emulation mode, will be delayed until any pending AH4 protocol sequences have self terminated.

# Chapter 10 - SOURCE CODE

```
/*
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    ARISING IN ANY WAY OUT OF THE USE OF THIS SOFTWARE, EVEN IF ADVISED OF THE
    POSSIBILITY OF SUCH DAMAGE.

    ----------------------------------------------------------------------------------

    ICOM AH4 ATU PROTOCOL EMULATOR FOR MFJ-994BRT AUTO-TUNER

    This source code supports an Arduino Pro Mini interfaced to an Icom AH-4 Auto-Tuner
    interface and a FoxDelta HFB3 VSWR bridge, and emulates the AH-4 auto-tuner
    protocol to provide feed back to the transceiver regarding a request to KEY the
    transmitter with a low power carrier and terminating that request when the VSWR
    has stabilized.  It is assumed that a stabilized VSWR is the result of obtaining
    a proper tuning solution, and that the auto-tuner has ceased the tuning process.

    It is possible that a stable VSWR is the result of not obtaining a match solution
    and that no additional L/C combinations are available to test.

    During the auto-tuning sequence, the KEY line to a power amplifier is blocked
    so that amplification is disabled during tuning, resulting in a power level that
    is within the limits of the auto-tuner when performing the auto-tuning sequence.

    This project is being used with an MFJ-994BRT auto-tuner and Elecraft KPA-500
    amplifier.

    Last edit:

    20 OCT 2022     Initial edit.

     7 NOV 2022     Added revision 2 support.

    23 NOV 2022     Added support for KEY_SENSE to detect whether the transceiver
                    has been powered-on.  The START IN signal is ignored if the
                    KEY SENSE indicates that the transceiver is not powered-on.
                    This is dependent on changing the strong pull-up resistor that
                    was originally installed on KEY IN to a weak pull-down resistor.

    25 NOV 2022     Fixed repeat mode.
*/
#define kBUILD_FOR_SERIAL_DEBUG             0               //  Set to 1 to serial debug

//  ------------------------------------------------------------------------------
//  PIN ASSIGNMENTS

const unsigned int  kPIN__AMP_ENABLE_H          =   2;
const unsigned int  kPIN__AH4_START_IN_H        =   3;
const unsigned int  kPIN__AH4_KEY_OUT_H         =   4;
const unsigned int  kPIN__TUNE_BUTTON_L         =   5;
const unsigned int  kPIN__MODE                  =   6;
const unsigned int  kPIN__AH4_START_OUT_H       =   7;
const unsigned int  kPIN__AH4_KEY_IN_H          =   8;
const unsigned int  kPIN__AH4_KEY_SENSE_H       =   9;
const unsigned int  kPIN__VSWR_REVERSE          =   A0;
const unsigned int  kPIN__VSWR_FORWARD          =   A1;

//  --------------------------------------------------------------------------------
//  PIN LEVELS

const unsigned int  kAMP_ENABLE_ASSERTED        =   HIGH;
const unsigned int  kAMP_ENABLE_NEGATED         =   LOW;

const unsigned int  kAH4_START_IN_ASSERTED      =   HIGH;
const unsigned int  kAH4_START_IN_NEGATED       =   LOW;

const unsigned int  kKEY_OUT_ASSERTED           =   HIGH;
const unsigned int  kKEY_OUT_NEGATED            =   LOW;

const unsigned int  kTUNE_BUTTON_ASSERTED       =   LOW;
const unsigned int  kTUNE_BUTTON_NEGATED        =   HIGH;

const unsigned int  kMODE_A_SELECTED            =   HIGH;
const unsigned int  kMODE_B_SELECTED            =   LOW;

const unsigned int  kAH4_START_OUT_ASSERTED     =   HIGH;
const unsigned int  kAH4_START_OUT_NEGATED      =   LOW;

const unsigned int  kKEY_IN_ASSERTED            =   HIGH;
const unsigned int  kKEY_IN_NEGATED             =   LOW;

const unsigned int  kKEY_SENSE_ASSERTED         =   HIGH;
const unsigned int  kKEY_SENSE_NEGATED          =   LOW;

#define kMODE_EMULATION                             true
#define kMODE_REPEAT                                false

//  --------------------------------------------------------------------------------
//  PIN INITIALIZATION

typedef struct {
    uint8_t     pin_address;
    uint8_t     pin_data_direction;
    uint8_t     pin_initial_state;
} PIN_INITIALIZATION_STRUCT;

const PIN_INITIALIZATION_STRUCT kPIN_INITIALIZATION_TABLE[] = {
    {   kPIN__AMP_ENABLE_H,     OUTPUT,     kAMP_ENABLE_ASSERTED    },
    {   kPIN__AH4_START_IN_H,   INPUT,      kAH4_START_IN_NEGATED   },
    {   kPIN__AH4_KEY_OUT_H,    OUTPUT,     kKEY_OUT_NEGATED        },
    {   kPIN__TUNE_BUTTON_L,    INPUT,      kTUNE_BUTTON_NEGATED    },
    {   kPIN__MODE,             INPUT,      kMODE_A_SELECTED        },
    {   kPIN__AH4_START_OUT_H,  OUTPUT,     kAH4_START_OUT_NEGATED  },
    {   kPIN__AH4_KEY_IN_H,     INPUT,      kKEY_IN_NEGATED         },
    {   kPIN__AH4_KEY_SENSE_H,  INPUT,      kKEY_SENSE_NEGATED      } };

const int kPIN_LOOP_COUNT = sizeof ( kPIN_INITIALIZATION_TABLE ) / sizeof ( PIN_INITIALIZATION_STRUCT );

//  --------------------------------------------------------------------------------
//  TIMER INITIALIZATION VALUES (IN MILLISECONDS)

const unsigned int  kAH4_START_250mSEC_DELAY                =     250;
const unsigned int  kAH4_START_NEGATED_320mSEC_DELAY        =     320;
const unsigned int  kAH4_MAX_TUNE_TIME                      =   15000;
const unsigned int  kDEFAULT_SAMPLE_DELAY                   =      50;
const unsigned int  kRADIO_POWER_UP_DELAY                   =     100;

//  --------------------------------------------------------------------------------
//  VSWR BUFFER

const unsigned int  kVSWR_BUFFER_SIZE_BIT_WIDTH             =   3;
const unsigned int  kVSWR_BUFFER_SIZE                       =   1 << kVSWR_BUFFER_SIZE_BIT_WIDTH;
const unsigned int  kVSWR_BUFFER_INDEX_MASK                 =   ( 1 << kVSWR_BUFFER_SIZE_BIT_WIDTH ) - 1;

//  --------------------------------------------------------------------------------
//  ADC & VSWR MEASUREMENTS
```
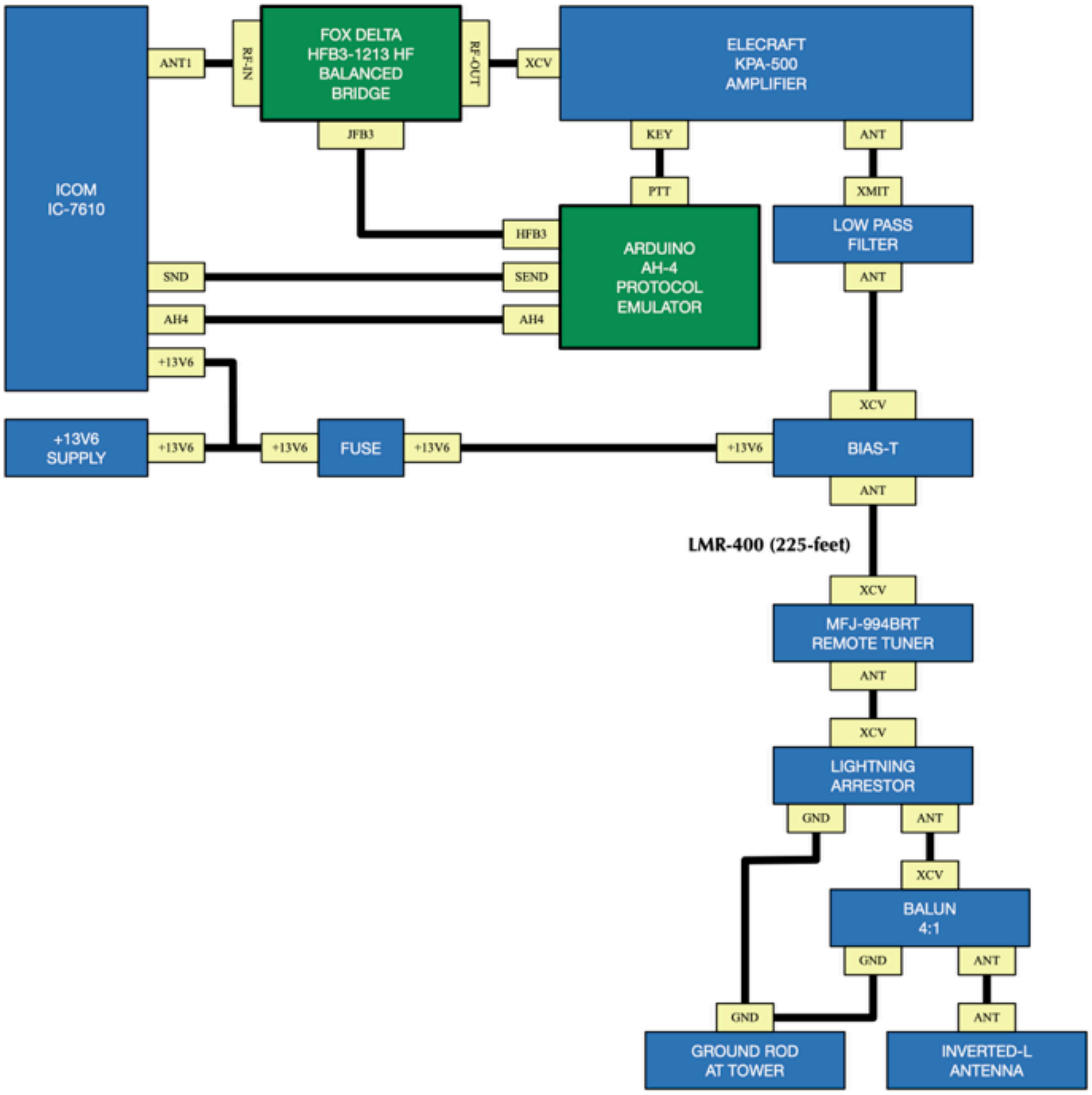

```
#define kVSWR_SENSOR_FULL_SCALE_VOLTAGE              5.0
#define kADC_RESOLUTION_BITS                        10
#define kVSWR_ADC_RESOLUTION_BITS                 1023.0
#define kVSWR_ADC_VOLTS_PER_COUNT              ( kVSWR_SENSOR_FULL_SCALE_VOLTAGE / kVSWR_ADC_RESOLUTION_BITS )
#define kZERO_REFERENCE_OFFSET                 ( 10.0 * kVSWR_ADC_VOLTS_PER_COUNT )
#define kVSWR_STABILITY_TOLERANCE                   90.000
#define kATU_MAX_VSWR_WHEN_TUNED                     2.000
#define kINFINITE_VSWR                         9999999.999
#define kRF_SENSE_SAFETY_OFFSET                      0.100
#define kRF_MAX_PERMISSIBLE_VSWR_RANGE               0.250

//  ----------------------------------------------------------------------------------
//  STATE MACHINE

enum {
    kSTATE__WAIT_RADIO_POWERUP = 0,
    kSTATE__IDLE,
    kSTATE__AH4_POST_START_DELAY,
    kSTATE__AH4_ASSERT_KEY,
    kSTATE__AH4_WAIT_XMIT_RF,
    kSTATE__AH4_WAIT_STABLE_VSWR,
    kSTATE__AH4_NEGATE_KEY,
    kSTATE__NEGATE_AMP_INHIBIT,
    kSTATE__WAIT_TUNE_BUTTON_RELEASE,
    kSTATE__NUM_STATES
} TUNING_STATES;

//  ----------------------------------------------------------------------------------
//  GLOBALS

typedef struct {
    float               noXmitFwdRefLevel;
    float               noXmitRefRefLevel;
    float               vswrBuffer[kVSWR_BUFFER_SIZE];
    unsigned long int   masterTime;
    unsigned int        delayTimer;
    unsigned int        keyAssertTimer;
    boolean             previousTuneButtonState;
    boolean             vswrIsStable;
    boolean             previousMode;
    uint8_t             state;
    uint8_t             writePtr;
    uint8_t             readPtr;
    uint8_t             sampleDelayTimer;
#if kBUILD_FOR_SERIAL_DEBUG
    unsigned long int   tuningTimer;
    unsigned int        ah4StartInState     : 1;
    unsigned int        ah4KeyOutState      : 1;
    unsigned int        ah4StartOutState    : 1;
    unsigned int        ampEnableState      : 1;
    unsigned int        keyInState          : 1;
    unsigned int        keySenseState       : 1;
#endif
} GLOBALS;

GLOBALS globals;

/*  ----------------------------------------------------------------------------------
           Vfwd + Vref
    VSWR = ------------
           Vfwd - Vref

    Result is rounded down to nearest tenth.  A negative result is converted to a
    positive result of 9999999.0.
*/

float   getVswrData ( void )
{
    float       vFwd = analogReadPinAndScale ( kPIN__VSWR_FORWARD );
    float       vRef = analogReadPinAndScale ( kPIN__VSWR_REVERSE );
    float       result = ( vFwd + vRef ) / ( vFwd - vRef );
    int         valX100 = result * 100;
    int         valX10 = result * 10;

    if ( 5 < valX100 % 10 ) { valX10 += 1; }
    result = (float)valX10 / 10.0;
    if ( 0.0 > result ) { result = kINFINITE_VSWR; }

    return result;
}

//  --------------------------------------------------------------------------------

float   analogReadPinAndScale ( int pin )
{
    return kVSWR_ADC_VOLTS_PER_COUNT * (float)analogRead ( pin );
}

//  --------------------------------------------------------------------------------

void pushVswrData ( float vswrData )
{
    globals.vswrBuffer[globals.writePtr++] = vswrData;

    if ( kVSWR_BUFFER_SIZE <= globals.writePtr )
    {
        for ( int index = 0; index < ( kVSWR_BUFFER_SIZE -1 ); index++ )
        {
            globals.vswrBuffer[index] = globals.vswrBuffer[index + 1];
        }
        globals.writePtr--;
    }
}

//  --------------------------------------------------------------------------------

uint8_t getNumberOfVswrMeasurements ( void )
{
    return globals.writePtr;
}

//  --------------------------------------------------------------------------------

boolean checkIfVswrIsStable ( void )
{
    boolean         result = false;
    float           minVswr = kINFINITE_VSWR;
    float           maxVswr = 0.0;
    float           range = 0.0;
    float           minVswrPercentage = 0.0;
    float           average = 0.0;
    float           midPoint = 0.0;
    uint8_t         count = getNumberOfVswrMeasurements ();
    int             walkingBits = 0;

    if ( ( kVSWR_BUFFER_SIZE -1 ) == globals.writePtr )
    {
        for ( int index = 0; index < globals.writePtr; index++ )
        {
            if ( minVswr > globals.vswrBuffer[index] )
            {
                minVswr = globals.vswrBuffer[index];
            }

            if ( maxVswr < globals.vswrBuffer[index] )
            {
                maxVswr = globals.vswrBuffer[index];
            }

            average += globals.vswrBuffer[index];
        }

        average /= (float)( kVSWR_BUFFER_SIZE -1 );
        range = maxVswr - minVswr;
        midPoint = ( maxVswr + minVswr ) / 2.0;
        minVswrPercentage = ( ( minVswr / maxVswr ) * 100.0 );

        if ( kATU_MAX_VSWR_WHEN_TUNED >= maxVswr )
        {
            walkingBits |= ( 1 << 0 );
            if ( ( minVswr == maxVswr ) || ( ( minVswr < maxVswr ) && average <= midPoint ) )
            {
                walkingBits |= ( 1 << 1 );
                if ( kRF_MAX_PERMISSIBLE_VSWR_RANGE >= range )
                {
                    walkingBits |= ( 1 << 2 );
                    if ( kVSWR_STABILITY_TOLERANCE <= minVswrPercentage )
                    {
                        result = true;
                    }
                }
            }
        }

#if kBUILD_FOR_SERIAL_DEBUG
        Serial.print ( "\tMIN: " );
        Serial.print ( minVswr );
        Serial.print ( "\tMAX: " );
        Serial.print ( maxVswr );
        Serial.print ( "\tMID: " );
        Serial.print ( midPoint );
        Serial.print ( "\tAVG: " );
        Serial.print ( average );
        Serial.print ( "\tRANGE: " );
        Serial.print ( range );
        Serial.print ( "\tPERCENT: " );
        Serial.print ( minVswrPercentage );
        Serial.print ( "\tSTABLE: " );
        Serial.print ( result ? "YES" : "NO" );
        Serial.print ( "\tSTATUS: " );
        Serial.print ( walkingBits, BIN );
        Serial.println ( "" );
#endif
    }

    return result;
}

//  ------------------------------------------------------------------------------

void setAh4TunerKeyOutState ( uint8_t ah4KeyOutState )
{
#if kBUILD_FOR_SERIAL_DEBUG
    if ( globals.ah4KeyOutState != ah4KeyOutState )
    {
        globals.ah4KeyOutState = ah4KeyOutState;
        Serial.print ( "KEY OUT:    " );
        Serial.println ( ah4KeyOutState ? "ASSERTED" : "NEGATED" );
    }
#endif
    digitalWrite ( kPIN__AH4_KEY_OUT_H, ah4KeyOutState );
}

//  ------------------------------------------------------------------------------

uint8_t readAh4TunerKeyOut ( void )
{
    return digitalRead ( kPIN__AH4_KEY_OUT_H );
}

//  ------------------------------------------------------------------------------

uint8_t readAh4TuneStartIn ( void )
{
    uint8_t result = digitalRead ( kPIN__AH4_START_IN_H );
#if kBUILD_FOR_SERIAL_DEBUG
    if ( result )
    {
        Serial.print ( "START IN:   " );
        Serial.println ( result ? "ASSERTED" : "NEGATED" );
    }
#endif
    return result;
}

//  ------------------------------------------------------------------------------

uint8_t readAh4TunerKeyIn ( void )
{
    uint8_t result = digitalRead ( kPIN__AH4_KEY_IN_H );
#if kBUILD_FOR_SERIAL_DEBUG
    if ( globals.keyInState != result )
    {
        globals.keyInState = result;
        Serial.print ( "KEY IN:  " );
        Serial.println ( result ? "ASSERTED" : "NEGATED" );
    }
#endif
    return result;
}

//  ------------------------------------------------------------------------------

uint8_t readAh4TunerKeySense ( void )
{
    boolean result = kKEY_SENSE_ASSERTED == digitalRead ( kPIN__AH4_KEY_SENSE_H );
#if kBUILD_FOR_SERIAL_DEBUG
    if ( globals.keySenseState != result )
    {
        globals.keySenseState = result;
        Serial.print ( "KEY SENSE:  " );
        Serial.println ( result ? "ASSERTED" : "NEGATED" );
    }
#endif
    return result;
}

//  ------------------------------------------------------------------------------

void setAmplifierEnableState ( uint8_t ampEnableState )
{
#if kBUILD_FOR_SERIAL_DEBUG
    if ( globals.ampEnableState != ampEnableState )
    {
        globals.ampEnableState = ampEnableState;
        Serial.print ( "AMP ENABLE: " );
        Serial.println ( ampEnableState ? "ENABLE" : "DISABLE" );
    }
#endif
    digitalWrite ( kPIN__AMP_ENABLE_H, ampEnableState );
}

//  ------------------------------------------------------------------------------

uint8_t readTuneButtonI ( void )
{
    return digitalRead ( kPIN__TUNE_BUTTON_L );
}

//  ------------------------------------------------------------------------------

boolean isInModeA ( void )
{
    return kMODE_A_SELECTED == digitalRead ( kPIN__MODE );
}

//  ------------------------------------------------------------------------------

void setAh4TunerStartOutState ( uint8_t ah4StartOutState )
{
#if kBUILD_FOR_SERIAL_DEBUG
    if ( globals.ah4StartOutState != ah4StartOutState )
    {
        globals.ah4StartOutState = ah4StartOutState;
        Serial.print ( "START OUT:  " );
        Serial.println ( ah4StartOutState ? "ASSERTED" : "NEGATED" );
    }
#endif
    digitalWrite ( kPIN__AH4_START_OUT_H, ah4StartOutState );
}
//  ------------------------------------------------------------------------------

boolean xmitRfDetected ( void )
{
    boolean     result = false;
    float       vFwd = analogReadPinAndScale ( kPIN__VSWR_FORWARD );
    float       vRef = analogReadPinAndScale ( kPIN__VSWR_REVERSE );

    if ( ( globals.noXmitFwdRefLevel + kRF_SENSE_SAFETY_OFFSET ) < vFwd ||
         ( globals.noXmitRefRefLevel + kRF_SENSE_SAFETY_OFFSET ) < vRef )
    {
        result = true;
    }

#if kBUILD_FOR_SERIAL_DEBUG
    Serial.print ( "xmitRfDetected: " );
    Serial.println ( result ? "YES" : "NO" );
#endif
    return result;
}

//  --------------------------------------------------------------------------------

void stateMachine ( void )
{
    uint8_t     entryState = globals.state;

    switch ( globals.state )
    {
        case kSTATE__WAIT_RADIO_POWERUP:
        {
            if ( kKEY_SENSE_NEGATED == readAh4TunerKeySense () && kKEY_OUT_NEGATED == readAh4TunerKeyOut () )
            {
                if ( 0 != globals.delayTimer )
                {
                    globals.delayTimer--;
                }

                if ( 0 == globals.delayTimer )
                {
                    globals.state = kSTATE__IDLE;
                }
            }
            else
            {
                //  If the radio powers up and then powers down before the
                //  stabilization delay has completed, reset the stabilization
                //  timer so that the next power up is handled correctly.

                globals.delayTimer = kRADIO_POWER_UP_DELAY;
            }
        }
        break;

        case kSTATE__IDLE:
        {
            globals.writePtr = 0;
            globals.readPtr= 0;
#if kBUILD_FOR_SERIAL_DEBUG
            if ( 0 != globals.tuningTimer )
            {
                Serial.print ( "TUNING TIME: " );
                Serial.print ( globals.tuningTimer );
                Serial.println ( " mSec" );

                globals.tuningTimer = 0;

                Serial.println ( "TUNING TIME HAS BEEN RESET" );
            }
#endif

            globals.previousTuneButtonState = false;
            if ( kKEY_SENSE_ASSERTED == readAh4TunerKeySense () )
            {
                globals.state = kSTATE__WAIT_RADIO_POWERUP;
                globals.delayTimer = kRADIO_POWER_UP_DELAY;
            }
            else if ( kTUNE_BUTTON_ASSERTED == readTuneButtonI () && !globals.previousTuneButtonState )
            {
                globals.previousTuneButtonState = true;
                setAmplifierEnableState ( kAMP_ENABLE_NEGATED );
                globals.delayTimer = kAH4_START_250mSEC_DELAY;
                globals.state = kSTATE__AH4_POST_START_DELAY;
            }
            else if ( kAH4_START_IN_ASSERTED == readAh4TuneStartIn () )
            {
                setAmplifierEnableState ( kAMP_ENABLE_NEGATED );
                globals.delayTimer = kAH4_START_250mSEC_DELAY;
                globals.state = kSTATE__AH4_POST_START_DELAY;
            }
        }
        break;

        case kSTATE__AH4_POST_START_DELAY:
        {
#if kBUILD_FOR_SERIAL_DEBUG
            globals.tuningTimer++;
#endif
            if ( kKEY_SENSE_ASSERTED == readAh4TunerKeySense () )
            {
                globals.state = kSTATE__WAIT_RADIO_POWERUP;
                globals.delayTimer = kRADIO_POWER_UP_DELAY;
            }
            else
            {
                if ( 0 != globals.delayTimer )
                {
                    globals.delayTimer--;
                    if ( 0 == globals.delayTimer )
                    {
                        globals.state = kSTATE__AH4_ASSERT_KEY;
                        globals.keyAssertTimer = kAH4_MAX_TUNE_TIME;
                    }
                }
            }
        }
        break;

        case kSTATE__AH4_ASSERT_KEY:
        {
#if kBUILD_FOR_SERIAL_DEBUG
            globals.tuningTimer++;
#endif
            if ( kKEY_SENSE_ASSERTED == readAh4TunerKeySense () )
            {
                globals.state = kSTATE__WAIT_RADIO_POWERUP;
                globals.delayTimer = kRADIO_POWER_UP_DELAY;
            }
            else
            {
                if ( kAH4_START_IN_ASSERTED == readAh4TuneStartIn () || globals.previousTuneButtonState )
                {
                    setAh4TunerKeyOutState ( kKEY_OUT_ASSERTED );
                    globals.delayTimer = kAH4_START_NEGATED_320mSEC_DELAY;
                    globals.state = kSTATE__AH4_WAIT_XMIT_RF;
                }
                else
                {
                    setAmplifierEnableState ( kAMP_ENABLE_ASSERTED );
                    globals.state = kSTATE__WAIT_TUNE_BUTTON_RELEASE;
                }
            }
        }
        break;

        case kSTATE__AH4_WAIT_XMIT_RF:
        {
#if kBUILD_FOR_SERIAL_DEBUG
            globals.tuningTimer++;
#endif
            if ( 0 != globals.keyAssertTimer )
            {
                globals.keyAssertTimer--;
            }

            if ( 0 == globals.keyAssertTimer )
            {
                globals.state = kSTATE__AH4_NEGATE_KEY;
            }
            else
            {
                if ( xmitRfDetected () )
                {
                    globals.sampleDelayTimer = kDEFAULT_SAMPLE_DELAY;
                    globals.state = kSTATE__AH4_WAIT_STABLE_VSWR;
                }
            }
        }
        break;

        case kSTATE__AH4_WAIT_STABLE_VSWR:
        {
#if kBUILD_FOR_SERIAL_DEBUG
            globals.tuningTimer++;
#endif
            globals.vswrIsStable = false;
            if ( 0 != globals.sampleDelayTimer )
            {
                globals.sampleDelayTimer--;
                if ( 0 == globals.sampleDelayTimer )
                {
                    pushVswrData ( getVswrData () );
                    globals.vswrIsStable = checkIfVswrIsStable ();
                    globals.sampleDelayTimer = kDEFAULT_SAMPLE_DELAY;
                }
            }

            if ( globals.vswrIsStable )
            {
                globals.state = kSTATE__AH4_NEGATE_KEY;
            }
            else
            {
                if ( 0 != globals.keyAssertTimer )
                {
                    globals.keyAssertTimer--;
                }

                if ( 0 == globals.keyAssertTimer )
                {
                    globals.state = kSTATE__AH4_NEGATE_KEY;
                }
            }
        }
        break;

        case kSTATE__AH4_NEGATE_KEY:
        {
#if kBUILD_FOR_SERIAL_DEBUG
            globals.tuningTimer++;
#endif
            setAh4TunerKeyOutState ( kKEY_OUT_NEGATED );
            if ( globals.vswrIsStable )
            {
                globals.state = kSTATE__NEGATE_AMP_INHIBIT;
            }
            else
            {
                globals.state = kSTATE__WAIT_TUNE_BUTTON_RELEASE;
            }
        }
        break;

        case kSTATE__NEGATE_AMP_INHIBIT:
        {
#if kBUILD_FOR_SERIAL_DEBUG
            globals.tuningTimer++;
#endif
            setAmplifierEnableState ( kAMP_ENABLE_ASSERTED );
            globals.state = kSTATE__WAIT_TUNE_BUTTON_RELEASE;
        }
        break;

        case kSTATE__WAIT_TUNE_BUTTON_RELEASE:
        {
            if ( kTUNE_BUTTON_NEGATED == readTuneButtonI () )
            {
                if ( kKEY_SENSE_ASSERTED == readAh4TunerKeySense () )
                {
                    globals.state = kSTATE__WAIT_RADIO_POWERUP;
                }
                else
                {
                    globals.state = kSTATE__IDLE;
                }
                globals.delayTimer = kRADIO_POWER_UP_DELAY;
            }
        }
        break;
    }

#if kBUILD_FOR_SERIAL_DEBUG
    if ( entryState != globals.state )
    {
        Serial.print ( "± stateMachine entry: " );
        displayStatePosition ( entryState );
        Serial.print ( " , next: " );
        displayStatePosition ( globals.state );
        Serial.println ( "" );
    }
#endif
}

//  --------------------------------------------------------------------------------

#if kBUILD_FOR_SERIAL_DEBUG
void displayStatePosition ( int statePosition )
{
    switch ( statePosition )
    {
        case kSTATE__WAIT_RADIO_POWERUP:        Serial.print ( "WAIT_RADIO_POWERUP" );          break;
        case kSTATE__IDLE:                      Serial.print ( "IDLE" );                        break;
        case kSTATE__AH4_POST_START_DELAY:      Serial.print ( "AH4_POST_START_DELAY" );        break;
        case kSTATE__AH4_ASSERT_KEY:            Serial.print ( "AH4_ASSERT_KEY" );              break;
        case kSTATE__AH4_WAIT_XMIT_RF:          Serial.print ( "AH4_WAIT_XMIT_RF" );            break;
        case kSTATE__AH4_WAIT_STABLE_VSWR:      Serial.print ( "AH4_WAIT_STABLE_VSWR" );        break;
        case kSTATE__AH4_NEGATE_KEY:            Serial.print ( "AH4_NEGATE_KEY" );              break;
        case kSTATE__NEGATE_AMP_INHIBIT:        Serial.print ( "NEGATE_AMP_INHIBIT" );          break;
        case kSTATE__WAIT_TUNE_BUTTON_RELEASE:  Serial.print ( "WAIT_TUNE_BUTTON_RELEASE" );    break;
    }
}
#endif

//  --------------------------------------------------------------------------------
//  Enforce a maximum tuning time when repeating

void    repeatAh4Protocol ( void )
{
    setAmplifierEnableState ( kAMP_ENABLE_ASSERTED );
    setAh4TunerStartOutState ( readAh4TuneStartIn () );
    setAh4TunerKeyOutState ( readAh4TunerKeyIn () );
}

//  --------------------------------------------------------------------------------

void setup ()
{
#if kBUILD_FOR_SERIAL_DEBUG
    Serial.begin ( 115200 );
    while ( !Serial ) {}
    Serial.println ( "Serial: 115200, 8N1" );
#endif

    for ( int index = 0; index < kPIN_LOOP_COUNT; index++ )
    {
        pinMode ( kPIN_INITIALIZATION_TABLE[index].pin_address,
                  kPIN_INITIALIZATION_TABLE[index].pin_data_direction );

        if ( OUTPUT == kPIN_INITIALIZATION_TABLE[index].pin_data_direction )
        {
            digitalWrite ( kPIN_INITIALIZATION_TABLE[index].pin_address,
                           kPIN_INITIALIZATION_TABLE[index].pin_initial_state );
        }
    }
    globals.previousMode = kMODE_EMULATION;
    globals.state = kSTATE__WAIT_RADIO_POWERUP;
    globals.delayTimer = kRADIO_POWER_UP_DELAY;
    globals.noXmitFwdRefLevel = analogReadPinAndScale ( kPIN__VSWR_FORWARD ) + kZERO_REFERENCE_OFFSET;
    globals.noXmitRefRefLevel = analogReadPinAndScale ( kPIN__VSWR_REVERSE ) + kZERO_REFERENCE_OFFSET;
    globals.previousTuneButtonState = readTuneButtonI ();
#if kBUILD_FOR_SERIAL_DEBUG
    globals.ah4KeyOutState = kKEY_OUT_NEGATED;
    globals.ah4StartOutState = kAH4_START_OUT_NEGATED;
    globals.ampEnableState = kAMP_ENABLE_ASSERTED;
    readAh4TuneStartIn ();
    readAh4TunerKeyIn ();
    readAh4TunerKeySense ();

    Serial.println ( "" );
    Serial.println ( "AH-4 EMULATOR INITIALIZED" );
    Serial.print ( "INITIAL globals.noXmitFwdRefLevel: " );
    Serial.println ( globals.noXmitFwdRefLevel );
    Serial.print ( "INITIAL globals.noXmitRefRefLevel: " );
    Serial.println ( globals.noXmitRefRefLevel );
    Serial.print ( "CURRENT MODE: " );
    Serial.println ( globals.previousMode ? "EMULATION" : "REPEATER" );
    Serial.print ( "INITIAL TUNE BUTTON STATE: " );
    Serial.println ( kTUNE_BUTTON_ASSERTED == globals.previousTuneButtonState ? "PRESSED" : "RELEASED" );
    Serial.print ( "STATE: " );
    displayStatePosition ( globals.state );
    Serial.println ( "" );
#endif
}

//  --------------------------------------------------------------------------------

void loop ()
{
    unsigned long int   currentTime = millis ();
    boolean             requestedMode = isInModeA ();

    if ( globals.masterTime != currentTime )
    {
        globals.masterTime = currentTime;
        if ( globals.previousMode != requestedMode )
        {
            if ( kMODE_EMULATION == globals.previousMode )
            {
                //  When in EMULATION, a transition to REPEAT must wait
                //  until the state machine has gone idle.
#if kBUILD_FOR_SERIAL_DEBUG
                Serial.println ( "REQUEST SWITCH TO REPEAT MODE" );
#endif

                stateMachine ();
                if ( kSTATE__IDLE == globals.state )
                {
                    globals.previousMode = requestedMode;
#if kBUILD_FOR_SERIAL_DEBUG
                    Serial.println ( "COMPLETED SWITCH TO REPEAT MODE" );
#endif
                }
            }
            else // kMODE_REPEAT == globals.previoiusMode
            {
                //  When in REPEAT, a transition to MULATION must wait
                //  until the AH4 protocol has gone idle.
#if kBUILD_FOR_SERIAL_DEBUG
                Serial.println ( "REQUEST SWITCH TO EMULATION MODE" );
#endif

                repeatAh4Protocol ();
                if ( kAH4_START_IN_NEGATED == readAh4TuneStartIn () && kKEY_IN_NEGATED == readAh4TunerKeyIn () )
                {
                    globals.previousMode = requestedMode;
#if kBUILD_FOR_SERIAL_DEBUG
                    Serial.println ( "COMPLETED SWITCH TO EMULATION MODE" );
#endif
                }
            }
        }
        else
        {
            if ( kMODE_EMULATION == globals.previousMode )
            {
                stateMachine ();
            }
            else
            {
                if ( kSTATE__IDLE == globals.state )
                {
                    if ( kKEY_OUT_NEGATED == readAh4TunerKeyOut () && kKEY_SENSE_ASSERTED == readAh4TunerKeySense () )
                    {
                        globals.state = kSTATE__WAIT_RADIO_POWERUP;
                        globals.delayTimer = kRADIO_POWER_UP_DELAY;
                    }
                    else
                    {
                        repeatAh4Protocol ();
                    }
                }
                else
                {
                    stateMachine ();
                }
            }
        }
    }
}
```

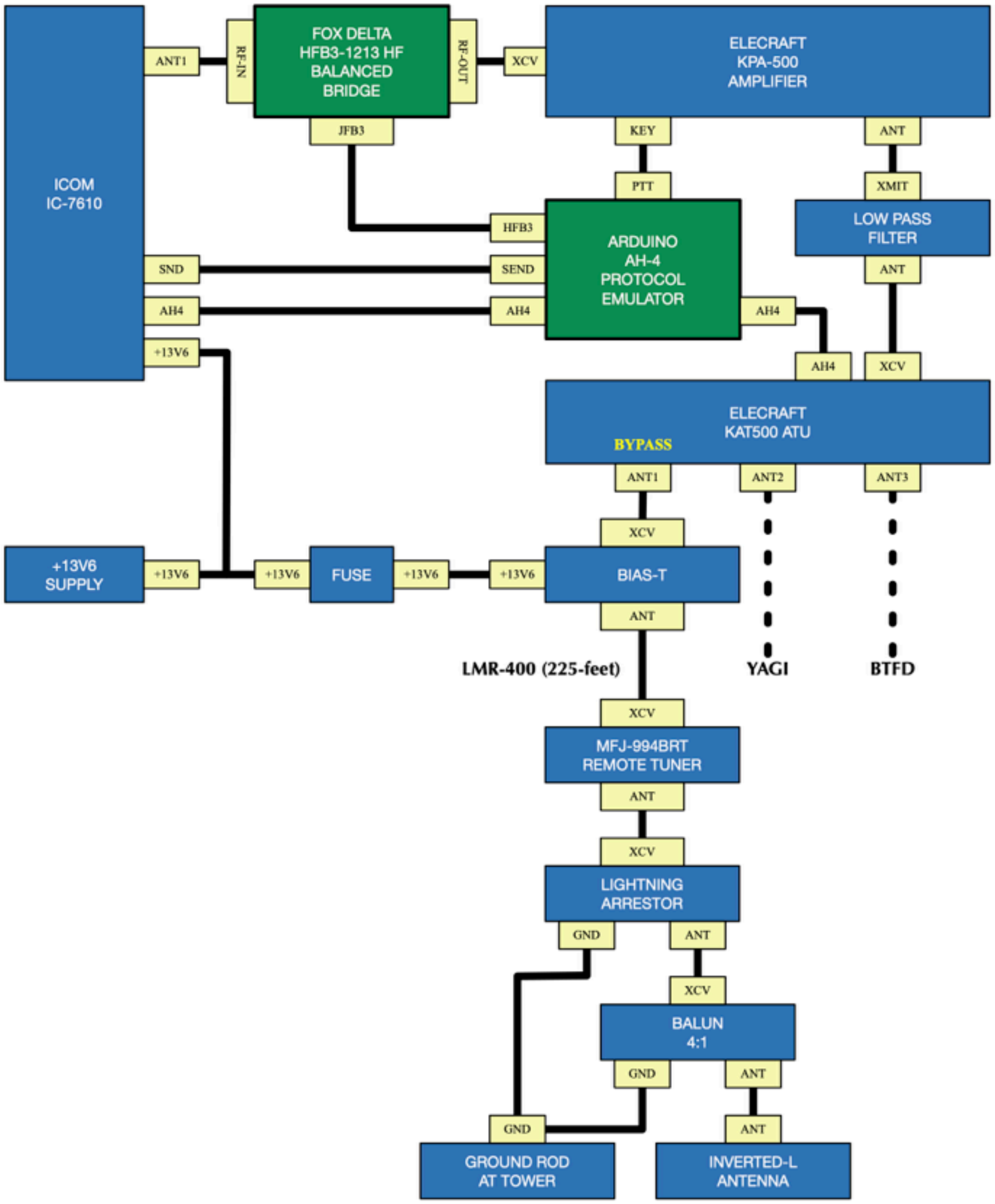
Click here to download source code.

The following block diagram shows haw the station is configured where only AH4 Emulation is required (ie. no repeat operation). Note that the Fox Delta HFB3 HF Balanced Bridge is placed between the transmitter and the amplifier, where the power level will not exceed 100-watts. This placement of the Fox Delta HFB3 is between the transceiver and the amplifier. The amplifier is bypassed (inhibited) during the tuning process by blocking the routing of the transceiver SEND singal to the amplifier PTT signal. This results in the transmission of a low power carrier, resulting from the AH4 KEY line assertion to the transceiver, during the tuning cycle and prevents damage to the auto-tuner by avoiding the auto-tune process at power levels that exceed the limits of the auto-tuner during the tuning sequence.



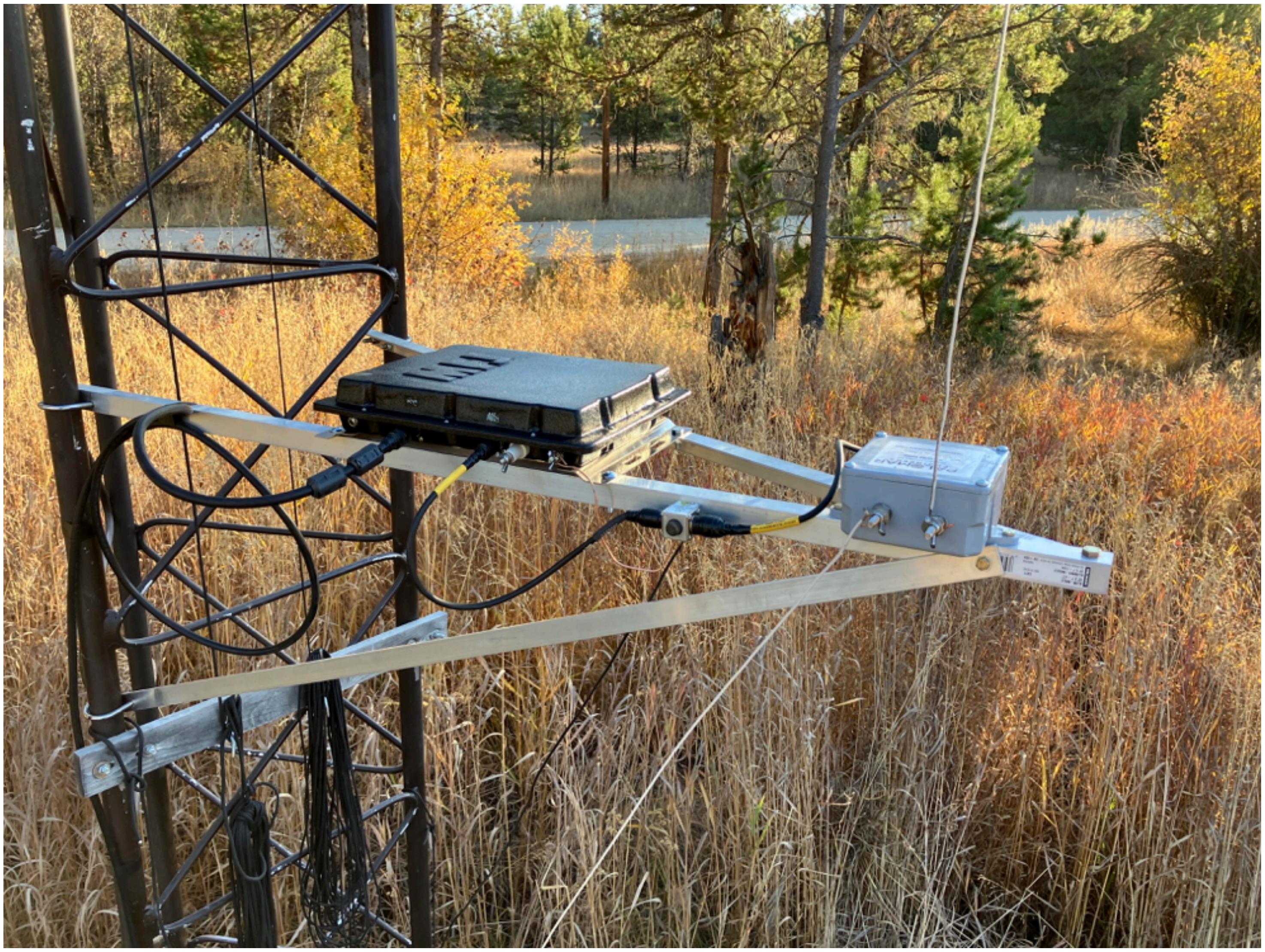
Under normal operation, a transmitter output level of 23-watts produces 500-watts output from the Elecraft KPA-500 amplifier. When tuning, in response to assertion of the AH4 KEY signal, the transmitter output level is approximately 10-watts.

The following block diagram shows haw the station is configured where both AH4 Emulation and AH4 repeat operation are required. Note that the Fox Delta HFB3 HF In this configuration, the station configuration would have the MFJ-994BRT on one KAT500 antenna port and that antenna port <u>must</u> be operated in the BYPASS mode. Note that it is not possible to force a specified antenna port to always be in BYPASS mode with the KAT500 Utility, so this must be managed by the radio operator.

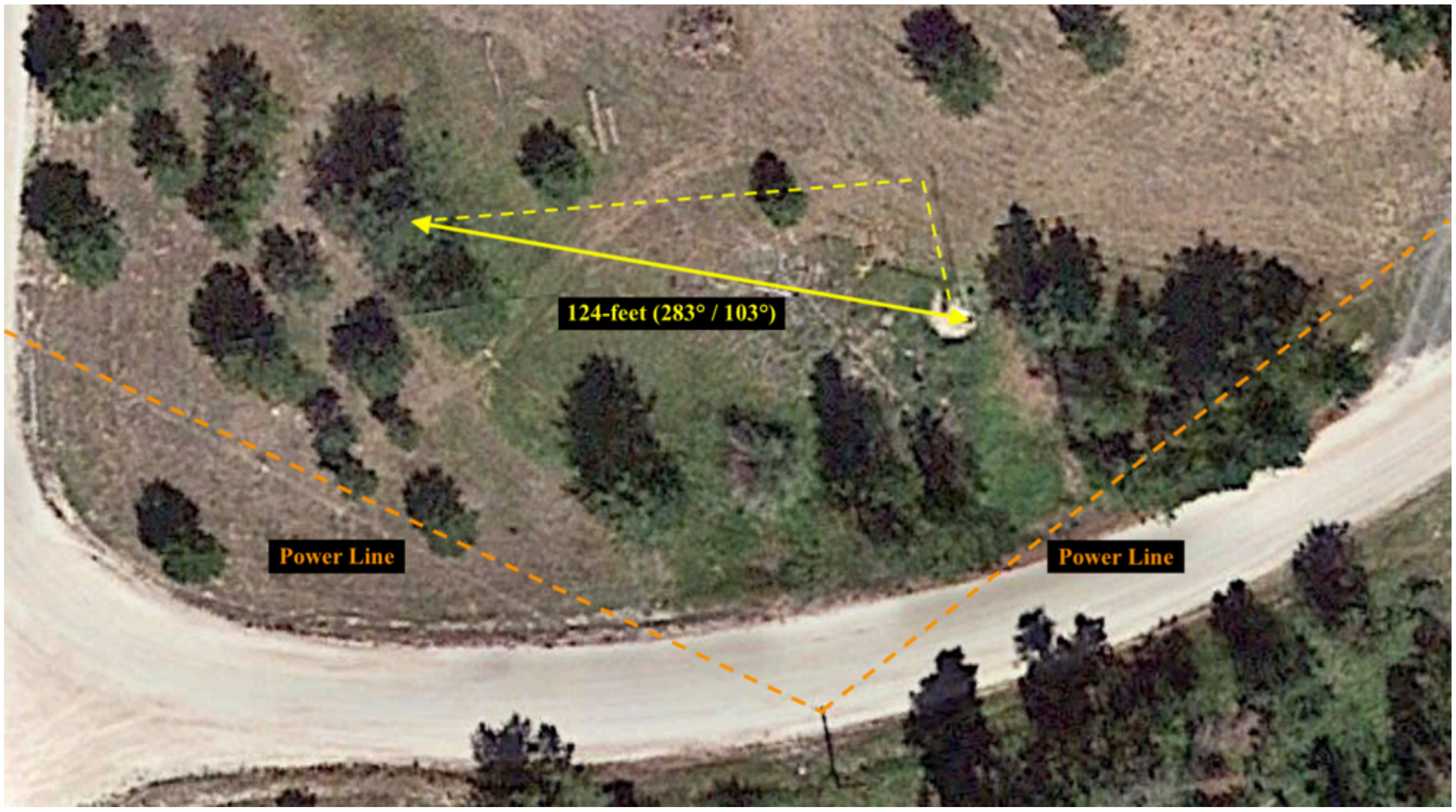


MFJ-994BRT Remote Auto-Tuner installed on tower stand-off with lightning arrestor and 4:1 balun. The total lenght of the stand-off arm is 4-feet, and is mounted approximately 6-feet above the ground to keep the installation above the normal snow depth. A ground rod is installed at the base of the tower.

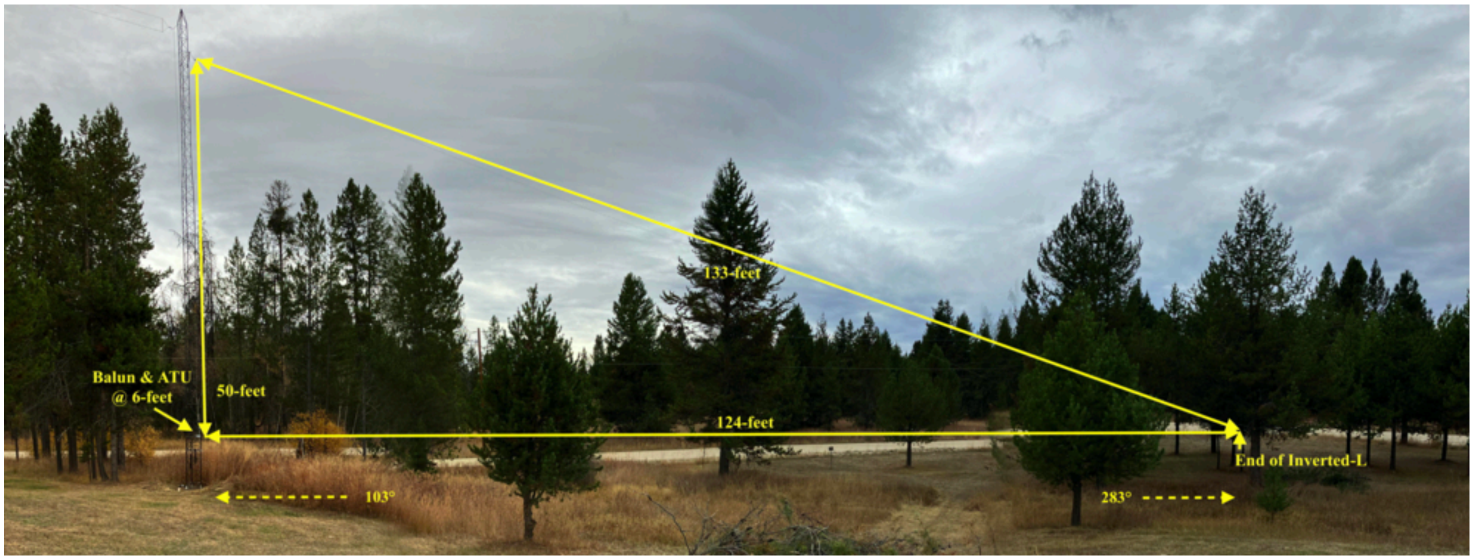
An identical stand-off is mounted at the 56-foot level of the 60-foot tower.



Arial view of Inverted-L antenna layout. The end of the Inverted-L that is opposite to the feed point is tied off to a tree that is 124-feet from the tower. There are no trees inside of the "L". The vertical segment of wire is 50-feet and the sloping portion is 130-feet long, for a total wire length of 180-feet.



Tower, tower-stand-offs and Inverted-L antenna.



The board supports two operating modes. In the first operating mode, MODE A / EMULATION, the AH4 ATU Emulator will provide handshanking with the AH4 protocol interface with the transceiver, using the Fox Delta HFB3-1213 HF Balance Bridge for VSWR measurement in support of the MFJ-994BRT Remote Tuner. In the second operating mode, MODE B / REPEAT, the AH4 ATU Emulator will repeat the AHR protocol signals between the transceiver and a secondary tuner that is attached to the AH4 ATU Emulator to enable the secondary tuner to provide antenna selection and antenna matching for antennas that are directly attached to the secondary tuner and are not connected through the MFJ-994BRT Remote Tuner.

- **MODE A - EMULATION - Auto-Tuning Initiated Manually**

  Select the antenna port on the KAT500 auto-tuner that has the MFJ-994BRT connected to it, and place the KAT500 auto-tuner into BYPASS mode.

  The Icom IC-7610 **MENU ▸ SET ▸ FUNCTION ▸ TUNER ▸ PTT START** should be set to **OFF**.

  In manually invoked tuning, the TUNE button on the AH4 Protocol Emulator is pressed to cause the AH4 Protocol Emulator to issue a request to the Icom transceiver to initiate an auto-tuning sequence. This request is made by asserting the AH4 KEY signal to the transceiver. Keying of an amplifier will be inhibited during the auto-tuning sequence. Once the auto-tune sequence has completed, keying of the amplifier will be enabled if a valid and stable VSWR resulted from the auto-tuning sequence. If a value and stable VSWR was not achieved, the amplifier will remain bypassed and subsequent transmissions will not key the amplifier.

- **MODE A - EMULATION - Auto-Tuning Initiated from Transceiver**

  Select the antenna port on the KAT500 auto-tuner that has the MFJ-994BRT connected to it, and place the KAT500 auto-tuner into BYPASS mode.

  The Icom IC-7610 **MENU ▸ SET ▸ FUNCTION ▸ TUNER ▸ PTT START** should be set to **ON**.

  Tuning from the transceiver is best achieved by setting up the transceiver to automatically iniitate an auto-tuning sequence on the first key-down event after the transceiver frequency has been changed.

- **MODE B - REPEAT - Auto-Tuning Initiated Manually**

  Select the antenna port on the KAT500 auto-tuner that has an antenna other than the MFJ-994BRT connected to it, and place the KAT500 auto-tuner into MANUAL or AUTO mode.

  The Icom IC-7610 **MENU ▸ SET ▸ FUNCTION ▸ TUNER ▸ PTT START** should be set to **OFF**.

  In mode B, the AH4 Protocol Emulator will pass the amplifier key line through so that it is controlled by another auto-tuner, such as the an Elecracft KAT500 auto-tuner. The AH4 Protocol Emulator will simply repeat the START signal from the transceiver to the KAT500, and repeat the KEY signal from the KAT500 to the transceiver. Manual tuning is initiated by pressing the TUNE button on the KAT500.

- **MODE B - REPEAT - Auto-Tuning Initiated from Transceiver**

  Select the antenna port on the KAT500 auto-tuner that has an antenna other than the MFJ-994BRT connected to it, and place the KAT500 auto-tuner into MANUAL or AUTO mode.

  The Icom IC-7610 **MENU ▸ SET ▸ FUNCTION ▸ TUNER ▸ PTT START** should be set to **ON**.

  Operation is identical to MODE A Auto-Tuning Initiated from Transceiver, but because the AH4 Protocol Emulator is simply repeating the AH4 protocol signals between the transceiver and the KAT500 auto-tuner, the KAT500 will perform the handshaking with the transceiver instead of the AH4 Protocol Emulator.

***NOTE:** Switching from MODE A / EMULATION to MODE B / REPEAT will remove any amplifier lock-out. Switching back from MODE B / REPEAT to MODE A / EMULATION will not restore the amplifier lock-out until an auto-tune sequence is started.*

# Chapter 14 - TESTING & EVALUATION

This section provides an evaluation of the performance of the AH4 Protocol Emulator. An evaluation of the MFJ-994BRT Remote Auto-Tuner is not provided. In all cases, a tuning solution has previously been resolved and the tuning parameters have been stored in memory within the MFJ-994BRT Remote Auto-Tuner. This means that all applications of a tuning solution with the AH4 Protocol Emulator will draw tuning coefficients from memory, resulting in a very rapid tuning solution.

- **MODE A / EMULATION - Auto-Tuning Initiated from Transceiver**

  The transceiver has been set to initiate an auto-tuning sequence upon first transmission after moving frequency (ie. the Tuner section of the Function page has the "PTT Start" parameter set to "ON").

  - With the transceiver powered down, the AH4 Emulator waits until the transceiver powers up before responding to any signal or tune switch input.
  - After powering up the transceiver, and if the transceiver has not moved from the last used frequency where transmission occurs, the transceiver does not initiate an auto-tune sequence. This is as expected.
  - After moving frequency, of a magnitude that the transceiver deams appropriate for an auto-tune sequence to be initiated, the auto-tune sequence initiates upon key-down. The AH4 Emulator is properly handshaking the AH4 interface signals. The longest observed tuning sequence, when migrating across {160m, 80m, 75m, 40m and 30m}, was just under 4.3 seconds and resulted in an average VSWR of 1.7:1, with a range of 0.0 when the AH4 protocol terminated with the negation of the KEY signal to the transceiver. The shortest auto-tuning sequence was observed to consume 675 milliseconds.

    Further, it was observed that the Elecraft KPA500 amplifier is in bypass mode and is not being keyed during the auto-tune sequence. Amplifier keying does occur after the auto-tuning sequence has successfully completed.
  - Note that with the antenna configuration, there is some variation in VSWR measurement at the VSWR sample rate while in the auto-tuning sequence. This is where the longest tuning sequences occur, but the measurement seems to always settle to within the specifications set by the software *(ie. VSWR MIN is greater than or equal to 92% of VSWR MAX, the average measured VSWR across eight samples is less than or equal to ( MAX VSWR + MIN VSWR ) / 2, and the MAX VSWR is <= 2.0:1)*.
  - Powering down the transceiver does place the AH4 Emulator into a state where it waits for the transcieiver to be powered-on.
  - The AH4 Protocol Emulator functions properly with remote operation using SDR-Control, by Marcus Roskosch, and the AH4 Emulator performs flawlessly in this environment.

  Operation of the AH4 Emulator in EMULATION mode appears to be functioning correctly.

- **MODE A / EMULATION - Auto-Tuning Initiated from AH4 Protocol Emulator**

  The ability of the transceiver to initiate an auto-tuning sequence upon first transmission after moving frequency has been disabled for this test (ie. the Tuner section of the Function page has the "PTT Start" parameter set to "OFF"). Auto-tuning sequences were initiated manually, after a frequency change, by pressing the TUNE button on the AH4 Protocol Emulator.

  - With the transceiver powered down, the AH4 Emulator waits until the transceiver powers up before responding to any signal or tune switch input.
  - After powering up the transceiver, depressing the TUNE button does initiate an auto-

tune sequence.

  - The AH4 Emulator is properly handshaking the AH4 interface signals. The longest observed tuning sequence, without moving bands, was just over 5.5 seconds and resulted in an average VSWR of 1.7:1, with a range of 0.0 when the AH4 protocol terminated with the negation of the KEY signal to the transceiver. The shortest auto-tuning sequence was observed to consume 790 milliseconds.

    Further, it was observed that the Elecraft KPA500 amplifier is in bypass mode and is not being keyed during the auto-tune sequence. Amplifier keying does occur after the auto-tuning sequence has successfully completed.

  - Powering down the transceiver does place the AH4 Emulator into a state where it waits for the transcieiver to be powered-on.

- **MODE A / EMULATION - Auto-Tuning Initiated from ION2G as a prefix operation to an ALE Call**

  The ability of the transceiver to initiate an auto-tuning sequence upon first transmission after moving frequency has been disabled for this test (ie. the Tuner section of the Function page has the "PTT Start" parameter set to "OFF"). Auto-tuning sequences were initiated by a short tuning tone that is transmitted by the ION2G software as a prefix operation to an ALE Call.

  It should be noted that the ION2G software sends the prefix tuning tone at the same amplitude as an ALE Call. This means that the KPA-500 amplifier will have a short transmission at full-power, with the incorrect tuning parameters applied at the MFJ-994BRT Remote Auto-Tuner. This is followed by a short pause with no transmission, where the MFJ-994BRT will then apply the tuning parameters from memory, and then a resumption of transmission at full-power to initiate the ALE Call.

  The ION2G prefix tuning tone duration was set to 700 milliseconds, with a non-keyed gap following the tuning tone with a 100 millisecond duration.

  - A calling sequence was issued with ION2G and the AH4 Emulator was observed to perform an auto-tuning sequence on each channel as the calling sequence progressed across the scan group.

  - Longer auto-tuning sequences (ie. longer than expected when the auto-tuning parameters are pulled from the auto-tuner memory) were observed on some of the calling channels. During some of the longer auto-tuning sequences, the measured average VSWR across eight samples was slightly higher than the calculated mid-point between the MAX VSWR and the MIN VSWR, and it is this measurement that is holding off the completion of the auto-tuning sequence. This appears to occur as a one-time event on each channel and was likely due to a tuning solution not being stored in the tuner memory for the channel. Once the long tuning sequence completed, returning to the channel did initiate an auto-tuning sequence, but the duration of the tuning cycle was much shorter.

- **MODE B / REPEAT - Invoking Manual Tune on the Elecraft KAT500**
    - User interaction points toward REPEAT mode not satisfying requiriments, and in part, this is due to the Elecraft KAT-500 not remembering and applying the BYPASS mode when switching back to antenna 1 (ie. the Inverted-L / MFJ-994BRT). When switching to the Yagi, the user switches to repeat mode, changes the IC-7610 to an appropriate frequency, and keys-down. The Elecraft KAT-500 will detect the frequency and apply the appropriate antenna selection that is based on the profile stored in the KAT-500 and take the KAT-500 out of bypass mode. Auto-tuning then occurs and completes normally. The radio is now ready to use on the Yagi, but this is a one-way trip. When returning to a frequency that is appropriate for antenna 1 (ie. the MFJ-994BRT) and keying down initiates an auto-tuning sequence. The KAT-500 will select antenna 1, but will not place the KAT-500 auto-tuner into bypass mode. Because the KAT-500 is not in bypass mode, neither auto-tuner is guaranteed to solve the tuning problem.

      The best option here is to force the KAT-500 auto-tuner to memorize the tuning solutions for the planned frequencies of operation, and then leave the AH4 Emulator in emulation mode. Then manually manage the bypass mode on the KAT-500 auto-tuner.

      This is less than ideal.

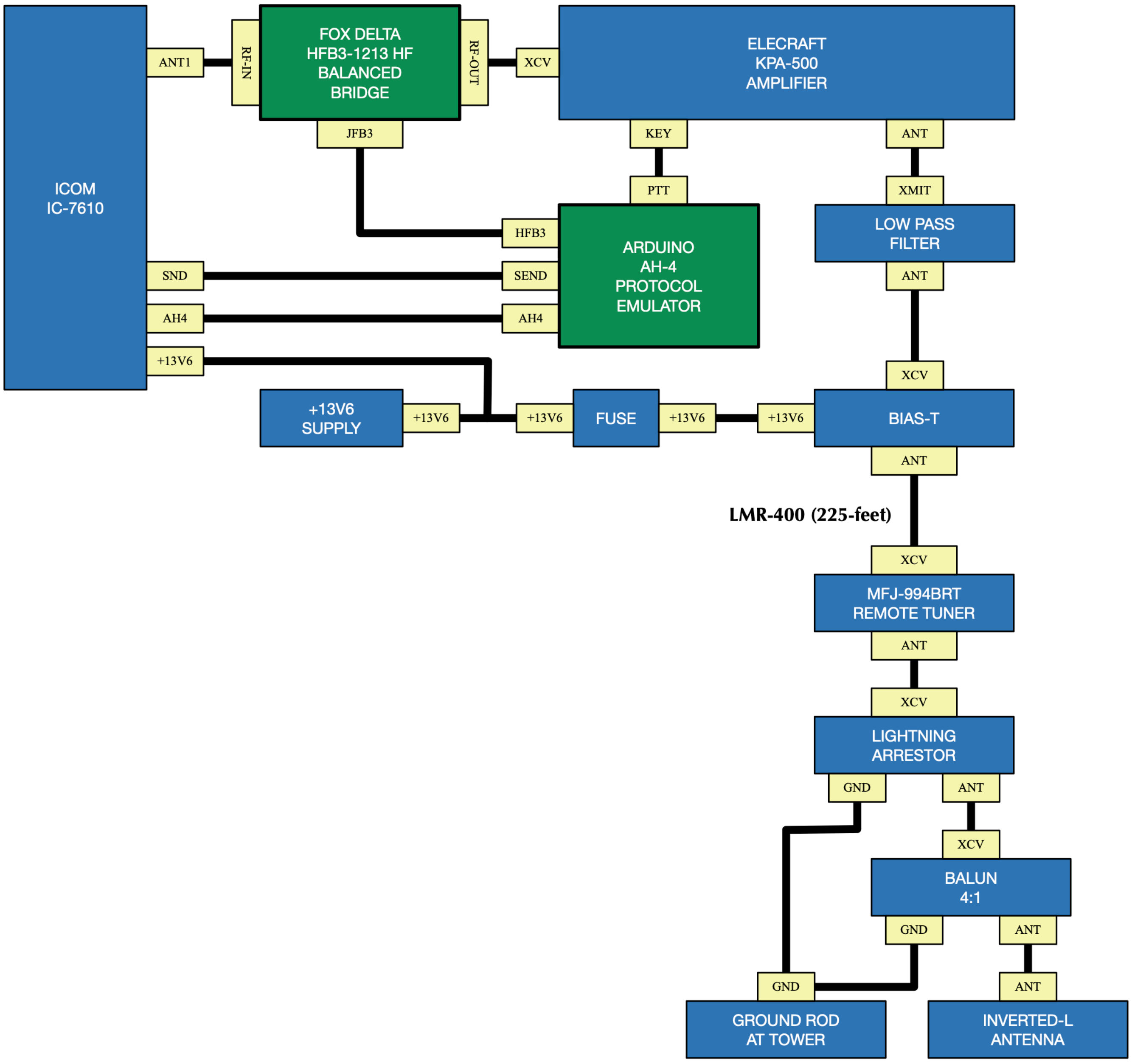
# Chapter 15 - CONCLUSIONS

The goals of simplifying the auto-tuning and amplifier sequencing have been achieved when operating with the antenna selection routing RF to the MFJ-994BRT / Inverted-L antenna. For this configuration, operation is as simple as setting up the radio to auto-tune on key-down. After moving frequency, key the transceiver and wait for the auto-tune cycle to complete. After the auto-tune cycle has completed, normal operation is available.

The goals of simplifying the auto-tuning and amplifier sequencing where reliance on the KAT-500 auto-tuner antenna selection to route RF to other antenna ports on the KAT-500 have not been achieved. The inability of the KAT-500 to remember and apply the BYPASS mode, based on antenna selection, is the largest hurdle to be overcome. The only viable configuration where reliance on the KAT-500 auto-tuner antenna selection is necessary is where the other antenna ports (ie. ports other than the port supporting the MFJ-994BRT / Inverted-L) are able to operate in bypass mode with no KAT-500 tuning being required.

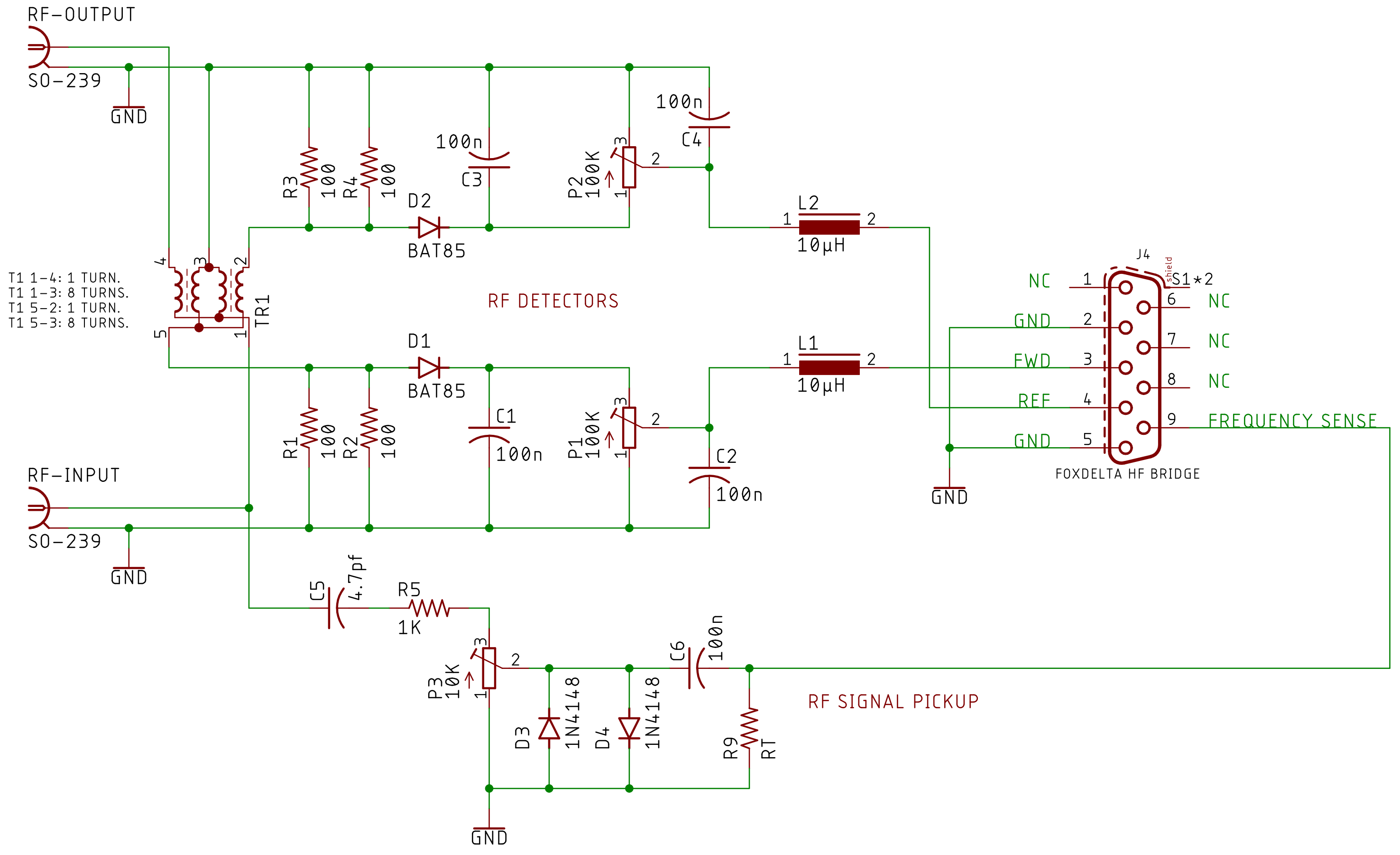
Although this project achieves all of the goals where operation is confined to the MFJ-994BRT / Inverted-L antenna, this project is not successful in achieving full frequency agility, at a high power level, across a multiple antenna configuration.

The configuration where this project succeeds is as follows:



The above configuration may simply omit the Emulate / Repeat switch.

*73, Ray Montagne (W7CIA)*



| | |
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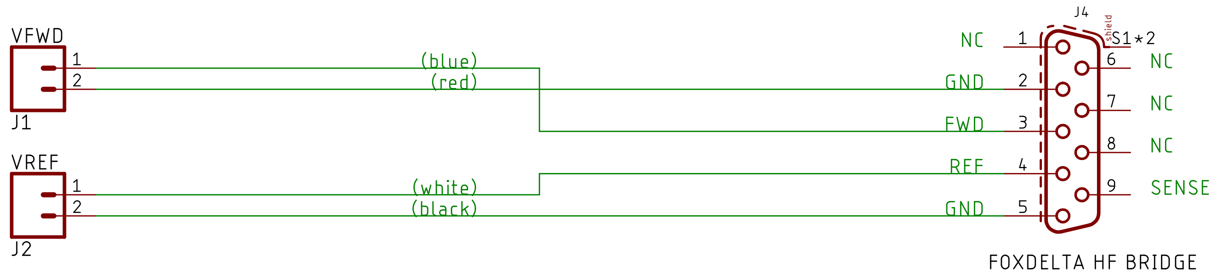
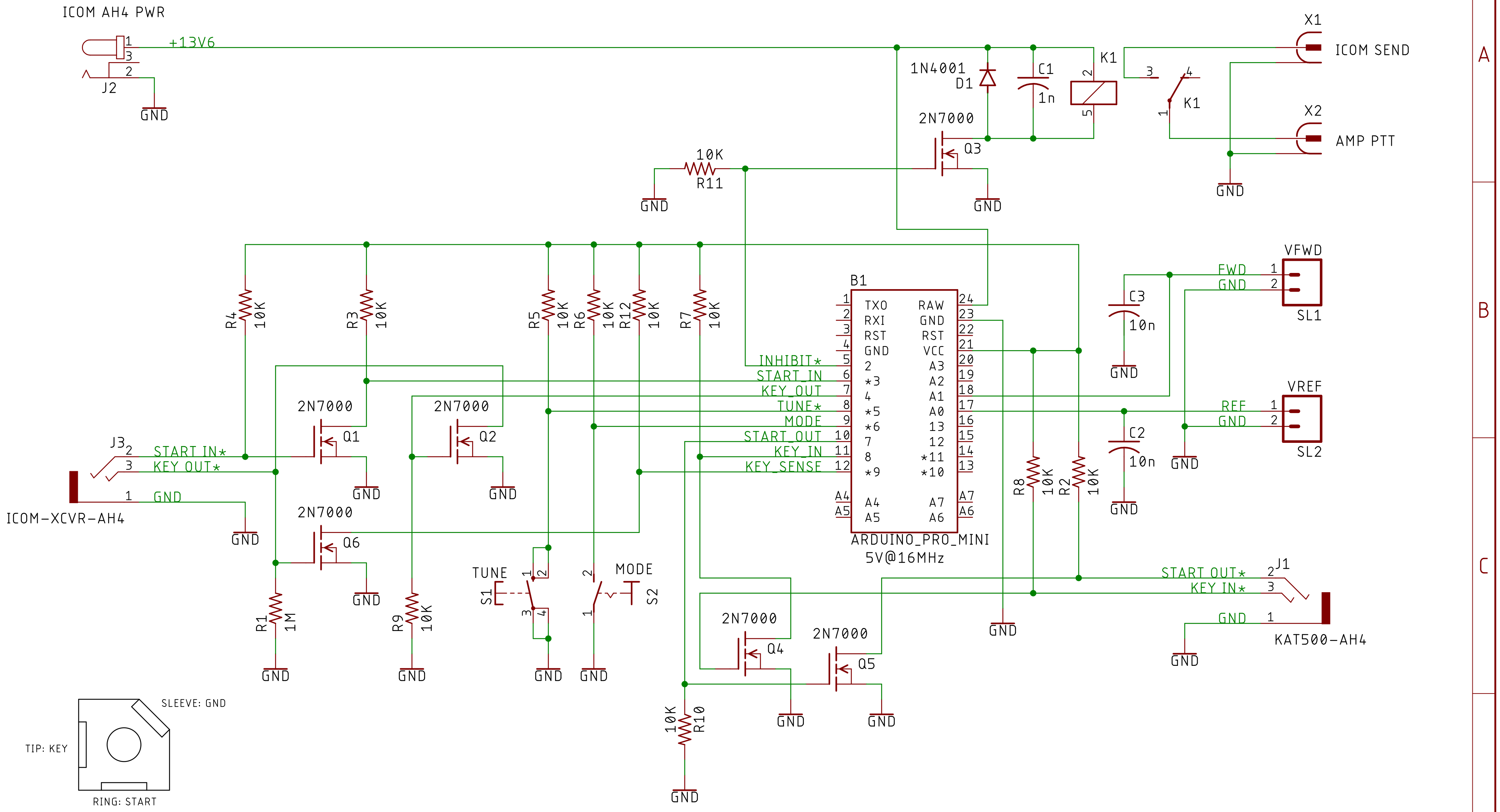
| | Sheet: 1/1 |



| | |
|---|---|
| Icom AH4 ATU Protocol Emulator | v2.1 Cable |
| For use with MFJ-994BRT Remote Antenna Tuner | |
| | 11/19/22 6:52 AM |
| | Sheet: 1/1 |



FOR USE WITH ICOM IC-7610, OR ANY ICOM TRANSCEIVER USING THE ICOM AH-4 AUTO-TUNER PROTOCOL, THE ELECRAFT KPA-500 POWER AMPLIFIER, THE MFJ-994BRT REMOTE AUTO-TUNER AND FOXDELTA HF BALANCED BRIDGE.

IF AN ELECRAFT KAT500 IS USED TO TUNE OTHER ANTENNAS, AND USES ONE ANTENNA PORT TO ROUTE RF TO THE MFJ-994BRT, THE MODE SWITCH CAN BE USED TO PASS THROUGH THE AH4 PROTOCOL SIGNALS WHEN THE ANTENNA PORT FOR THE MFJ-994BRT IS NOT SELECTED. NOTE THAT WHEN THE ANTENNA PORT FOR THE MFJ-994BRT IS SELECTED, THE KAT500 SHOULD BE PLACED INTO BYPASS MODE TO ALLOW THE EXTERNAL MFJ-994BRT TO PROPERLY PERFORM THE TUNING OPERATIONS. MODE A SHOULD BE USED WHEN THE MFJ-994BRT ANTENNA PORT IS SELECTED ON THE KAT500. FOR ALL OTHER KAT500 ANTENNA PORT SELECTIONS, MODE B SHOULD BE USED.

| | |
|---|---|
| Icom AH4 ATU Protocol Emulator | v2.3 |
| For use with MFJ-994BRT<br>Remote Antenna Tuner | 11/25/22 3:36 PM |
| | Sheet: 1/1 |