Design and Evaluation of a HELA–10 Based FEE with 3–State Switched Calibration

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1 Introduction

This report documents the design, testing, and demonstration of new front end electronics (FEE) for use in absolute flux measurements. The FEE implements a 3–state calibration system similar to that used by the Large aperture Experiment to detect the Dark Ages (LEDA) and Experiment to Detect the Global EoR Step (EDGES) [1, 2]. Table 1 provides a summary of all relevant specifications. The design files, made using ExpressPCB's free software, are available online[1].

The remainder of this report is organized as follows. Section 2 summarizes the the design of the FEE. Section 3 presents the laboratory testing of the FEE's RF characteristics. Section 4 demonstrates the calibration capabilities of the FEE under laboratory conditions. The FEE's development history is discussed in Appendix A.

2 Design

A block diagram of the FEE is shown in Fig. 1. Two Mini–Circuits Laboratories (MCL) HELA–10 amplifiers are used as a pre–amplifier and a line driver, and were selected for their exceptional linearity ratings [3–5]. The signal path is differential from the antenna terminal to the bias-T, at which point a balun converts the signal path to 50 Ω single-ended. A summary of the remaining blocks follows:

- Relays – Mechanical relays configured in a balanced arrangement provide the means of switching between the antenna and the calibration sources. Mechanical relays were selected over an IC switch because of their low loss and noise characteristics [6].
- CB & FM – Two series resonant LC notch filters designed to trap the strong signals from Citizen Band and FM radio at 26.5–27.5 and 88–107 MHz, respectively [7]. This block's response is shown in Fig. 2. The loss in the filters is small ($<$ 1 dB) and thus they have been placed before the preamplifier.
- 30–90 MHz – A second-order Butterworth filter establishes the bandpass of the entire interferometer [7]. The filter is absorptive (i.e. a diplexer) to prevent reflections between the two amplifiers from corrupting the desired signals. This block's response is also shown in Fig. 2.
- Noise Source – The calibrated noise source is a Mercury SM4 noise diode[2]. This block also includes a temperature data logger[3] to get an accurate measure of the ambient temperature in the calibration.
- Bias and Control – This block regulates the DC voltage to the levels required by the other blocks, as well as selecting the calibration state. Section 2.1 explains the operation of this block.

Table 2 shows a complete bill of materials for the FEE. The total cost includes the cost of the enclosures and temperature data loggers. The cost of an individual spare board is about $250.

[1] https://sites.google.com/a/vt.edu/rht/fluxmeas
[2] Previously Micronetics. http://rf.mrcy.com/RF_Components/Noise_Diodes.html
[3] http://www.onsetcomp.com/products/data-loggers/ua-001-08

RF Specifications	
Peak Gain	21 dB
3-dB Bandwidth	30-80 MHz
Noise Temperature	∼500 K
Input 1 dB Compression Point	+11 dBm*
Input Third Order Intercept	>+11 dBm
Input Second Order Intercept	+28 dBm
Input Impedance	150 Ω differential
Output Impedance	50 Ω single-ended
Power Consumption	
DC Voltage	12-22 V
DC Current	0.8 A
Mechanical Dimensions	
Board Dimensions	6.225in. W × 2.6in H
Enclosure Dimensions	7in. W × 5in. H ×3in. D

Table 1: Summary of the FEE's specifications.
*The input 1 dB compression point is about −18 dBm for the LWA FEE.

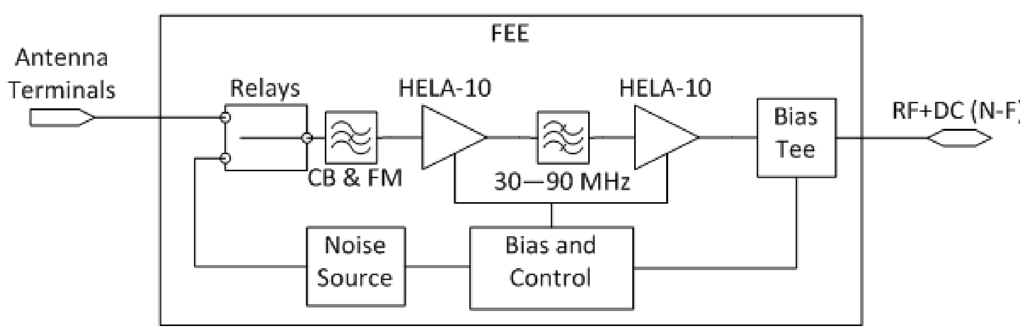

Figure 1: Block diagram of the FEE.

Part ID	MFG	MFG Part #	Unit Price	Quantity	Total Price
Relays	Panasonic	ARE13A12	$6.39	10	$63.90
J3-J5,J8	Sullins	PPTC021LFBN-RC	$0.26	50	$13.10
J6,J7	Linx	CONSMA001	$2.40	25	$60.00
Bias L	TDK	MLZ2012E4R7M	$0.09	50	$4.33
Diplexer/Notch Ls	Epcos	B82498F3180J	$0.70	20	$14.04
	Epcos	B82498F3680J	$0.70	20	$14.04
	Epcos	B82498F3820J	$0.70	20	$14.04
	Epcos	B82498F3101J	$0.70	20	$14.04
	Epcos	B82498F3151J	$0.70	20	$14.04
R1,R4,R6	SEI	RNCF0805BTC1K13	$0.55	20	$11.02
R11	SEI	RNCS0805BKE1K00	$0.52	10	$5.23
R16	SEI	RNCS0805BKE825R	$0.52	10	$5.23
R2,R5	SEI	RNCS0805BKE332R	$0.52	20	$10.46
R3	SEI	RNCS0805BKE75R0	$0.52	10	$5.23
R7-R10,R12-R15	SEI	RNCS0805BKE10K0	$0.32	50	$15.81
U3	TI	LM2940CSX-12/NOPB	$1.58	10	$15.78
U5	TI	LP339DR	$0.54	10	$5.42
Board-Enclosure Cable	Amphenol	135111-02-M0.25	$20.82	2	$41.64
Enclosure	LMB Heeger	J-882 PL/UNPD	$13.70	4	$54.80
4-40 Screws	B&F	PMS 440 0025 PH	$0.03	100	$2.98
4-40 Nuts	B&F	HNZ 440	$0.01	100	$1.49
1/4in x 2.5in Carriage Bolt			$0.20	20	$4.00
Bypass Caps	AVX	06035C104KAT2A	$0.04	100	$3.50
Diplexer/Notch Cs	AVX	08052U560GAT2A	$0.46	20	$9.20
	AVX	8052U680JAT2A	$0.35	20	$7.00
	AVX	08052U101JAT2A	$0.35	20	$7.00
	AVX	08052U131JAT2A	$0.35	20	$7.00
	AVX	08051U161JAT2A	$0.35	20	$7.00
U1,U2	Mini-Circuits	HELA-10	$15.95	10	$159.50
Impedance Transformers	Mini-Circuits	ADT3-1	$3.45	20	$69.00
	Mini-Circuits	ADT2-1	$3.45	20	$69.00
	Mini-Circuits	ADT1.5-1	$2.95	20	$59.00
ATTN3	Mini-Circuits	PAT-30	$2.95	20	$59.00
D1	Mercury	SM4	About 35		Requires Quote
Temperature Sensors	OnSet	BASE-U-1	$67.00	1	$67.00
	OnSet	BHW-PRO-CD	$99.00	1	$99.00
	OnSet	UA-001-08	$42.00	4	$168.00
PCB	ExpressPCB		$1.00	195	$195.00
			Totals		$1375.82

Table 2: Bill of materials for the FEE, including the enclosure, mechanical parts, and temperature sensors. The different sections, demarcated by the double lines, indicate parts procured from different distributors; from top to bottom, these distributors are Digikey, Lowe's, Mouser, Mini-Circuits, Mercury, OnSet, and ExpressPCB. Total cost is for 4 FEEs, and includes spare parts and parts bought at price breaks.

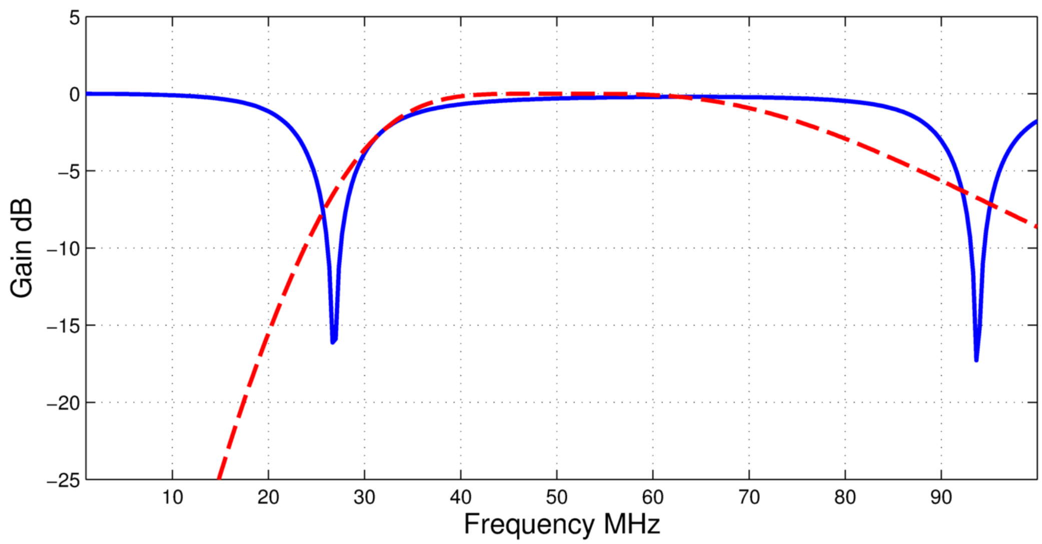

Figure 2: Modeled transfer functions of the (solid) CB & FM and (dashed) diplexer filters.

State	DC Bias	CPR1	CPR2	CPR3	Terminal Connection
1	16 V	High	Low	Low	Antenna
2	18 V	Low	High	Low	Noise Source – Off
3	20 V	Low	High	Low	Noise Source – On

Table 3: DC voltages on which the FEE changes its calibration state.

2.1 Board Design

Figures 3 and 4 show the RF chain and the Bias and Control sections of the FEE, respectively. Figure 5 shows the layout of the FEE. The FEE was fabricated using ExpressPCBs ProtoPro 4-Layer service. A fully populated FEE is shown in Fig. 6. The FEE draws 0.85 A of DC current in state 1 and 0.82 A in states 2 and 3, due predominately to the highly linear amplifiers. The heat generated by amplifiers is dissipated in the enclosure, the mechanical details of which are discussed in Section 2.2.

The calibration state is determined by the DC voltage level provided to the input of the FEE. Figure 7 shows a circuit diagram for the control system, explicitly showing the comparators, which are hidden in Fig. 4. CPR1 and CPR2 are always in opposite output states and set the state of the relays, while CPR3 sets the noise diode's bias. The transition voltages between the three different states are 17.2 and 19 V. Table 3 shows the specified DC bias voltages and their associated calibration state.

2.2 Enclosure and Antenna Interface

The enclosure provides heat sinking and protection from the environmental for the FEE. The mechanical details of the enclosure are shown in Fig. 8, and a picture of the enclosure is shown in

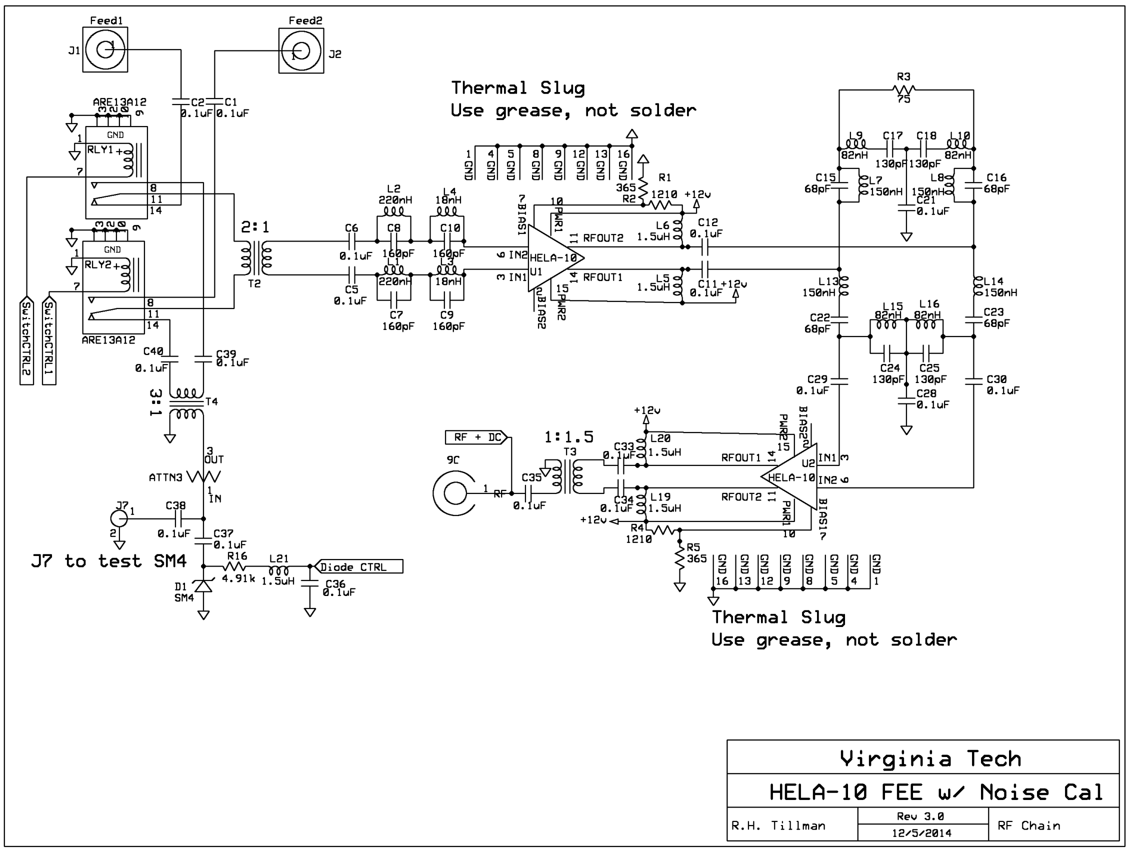

Figure 3: FEE's RF chain.

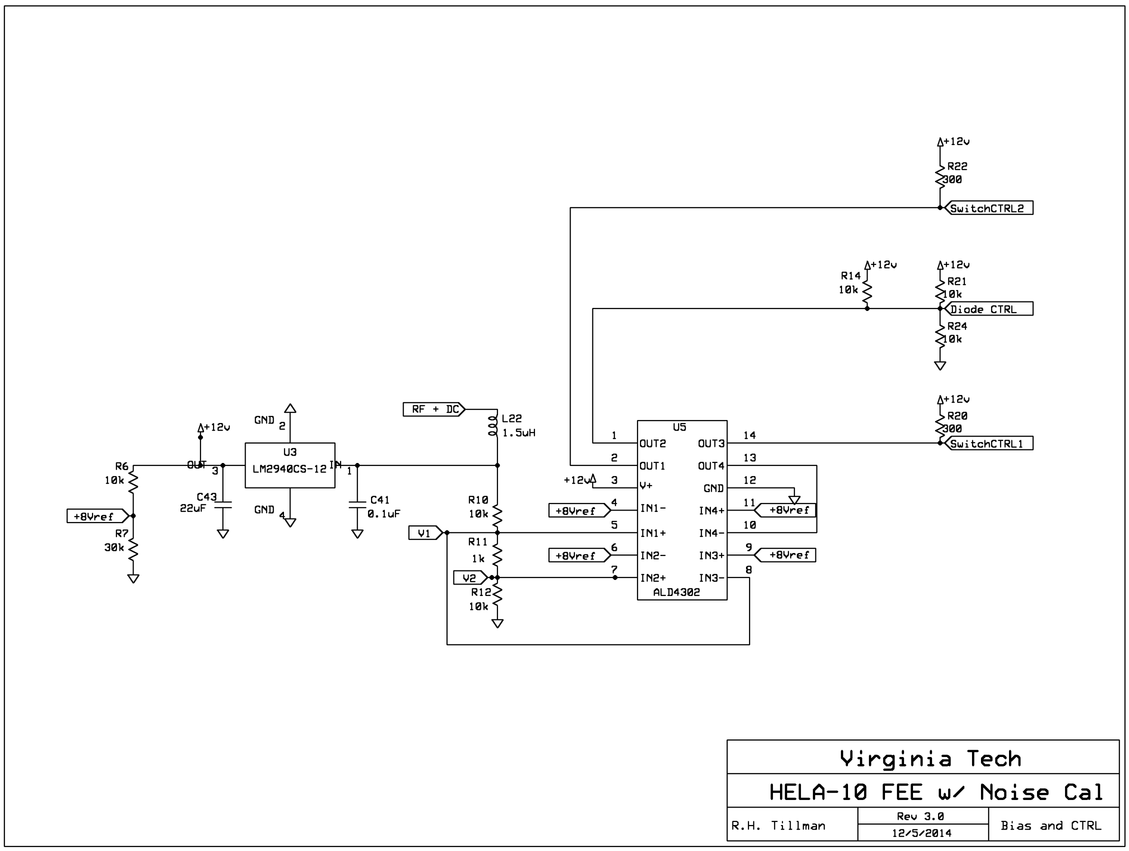

Figure 4: FEE's bias and control network.

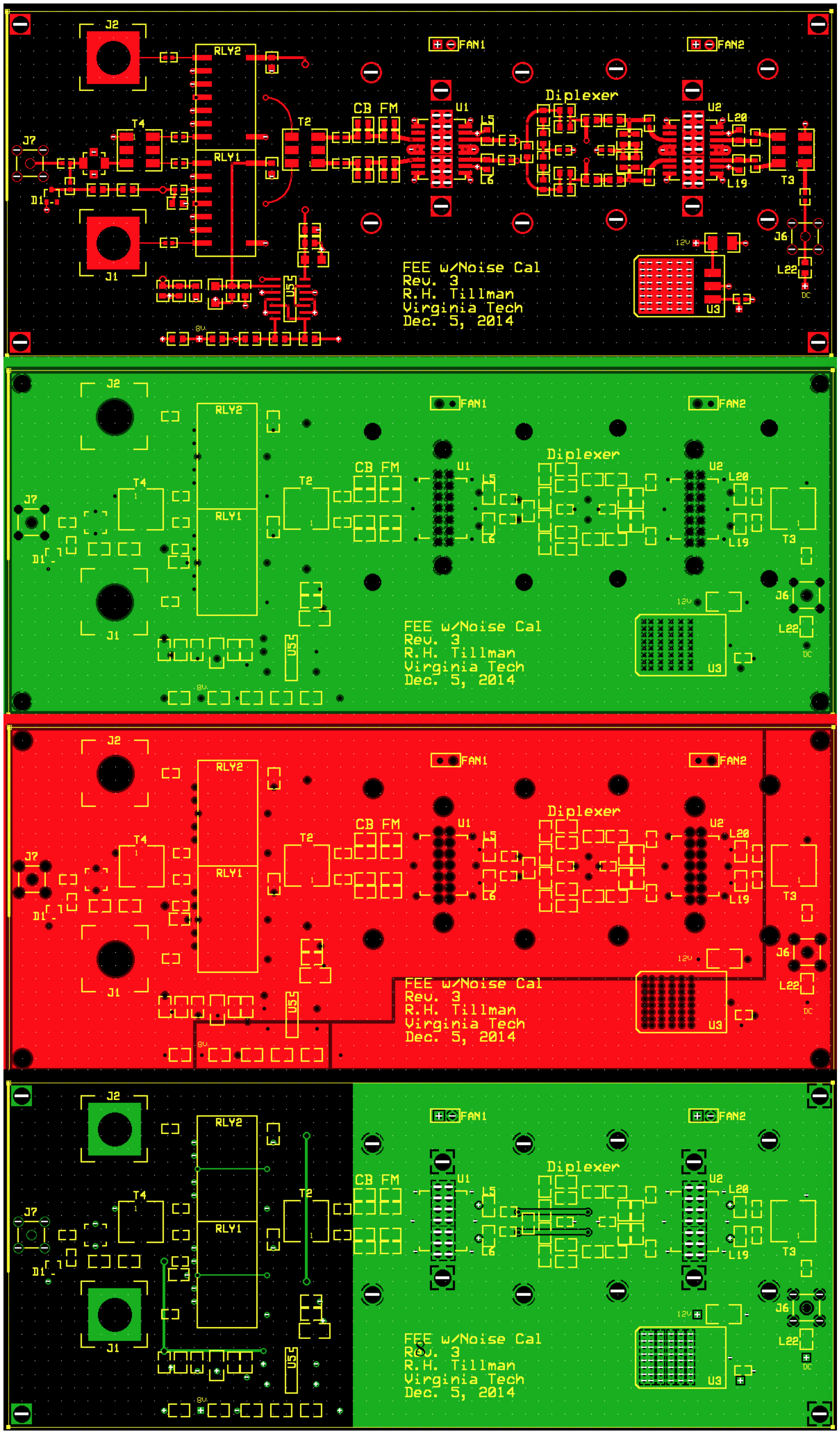

Figure 5: Layout of FEE. From top to bottom, the layers are Top Copper, Ground Plane, Power Plane, and Bottom Copper. The top silk screen layer is shown on all layers for reference.

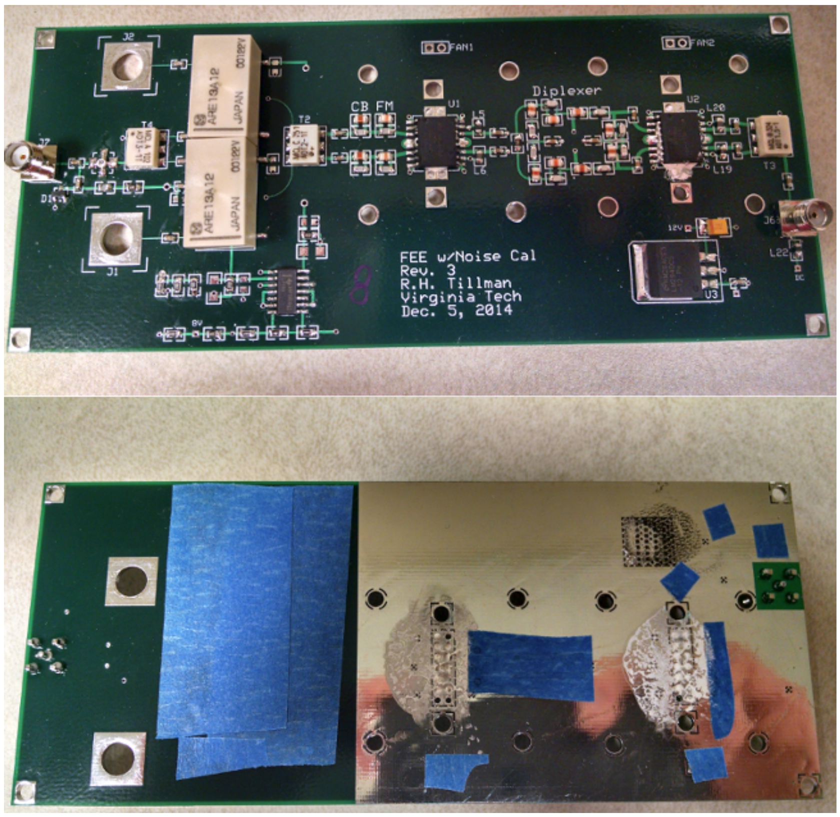

Figure 6: FEE after population. The painter's tape on the bottom layer prevents traces and vias carrying signal and power do not become shorted to ground through contact with the enclosure.

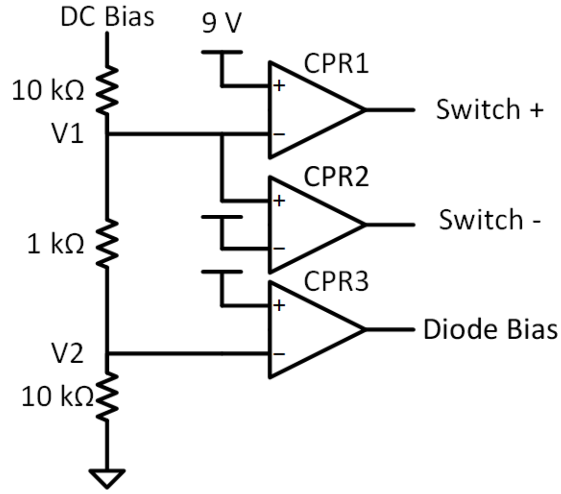

Figure 7: Circuit diagram of the control system.

Fig. 9. Figure 10 shows the temperature measured near the noise diode as a function of time after first powering the FEE. It takes roughly one hour for temperature to be within 1% of its final value, but the total temperature change is less than 10% between initial power-on and final stability.

Figure 11 shows a FEE integrated with a dipole antenna. The FEE interfaces with the antenna through 0.25in. diameter, 1.25in long galvanized carriage bolts. The antenna terminals are spaced 1.5in. apart.

3 Testing

This section presents the characterization of the FEE's RF chain, consisting of the amplifiers, filters, and balun components. Measurements were made of the FEE's gain, linearity, and noise characteristics.

Figure 12 shows the FEE's measured and expected gain, G_{FE}, for the six functional FEEs[4]. The passband reasonably matches the expected form, but with a couple differences. The notches differ from expected, but within the bounds of the Monte Carlo simulation in [7]. The high frequency deviation was also seen in initial prototypes, and is attributed to parasitics in the filter components.

Figure 13 summarizes the linearity measurements made of the FEE. Measurement of the 1 dB compression point (P_{1dB}) was made at 50 MHz, and is +11 dBm input referenced. The expected P_{1dB} for two cascaded HELA–10 amplifiers is only +6 dB, and the difference is attributed to the insertion loss of the passive components. Measurement of the input second order intercept point (IIP2) was made at 35 MHz to ensure the second harmonic at 70 MHz was within the passband. The extrapolations of the linear and second order responses are also shown in Fig. 13, and IIP2 is about +28 dBm. Finally, the input third order intercept point (IIP3) was measured with two signals at 29.7 and 30.3 MHz, dictated by the available signal generator. The measured IIP3 is

[4]Four are of the third revision, two are of the second. See the appendix for details on the differences.

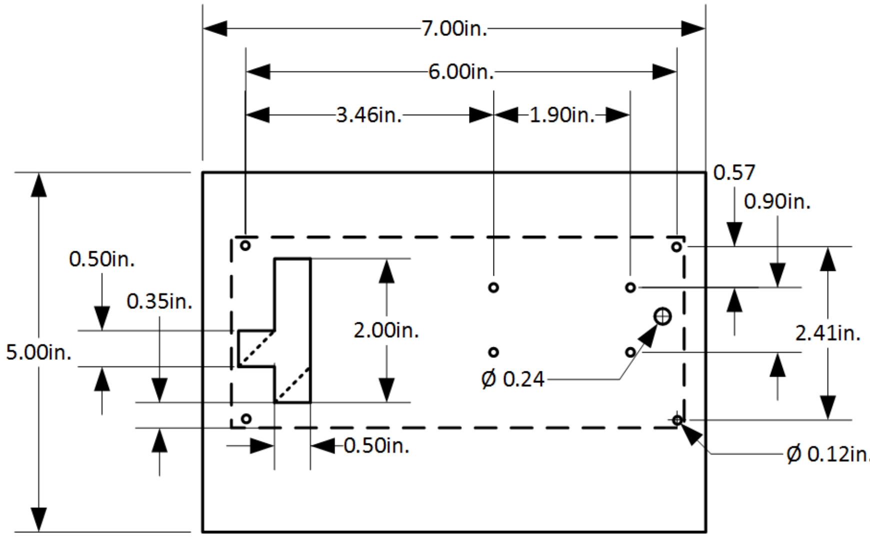

Figure 8: Diagram for the enclosure, showing the holes and cutouts for the FEE. The FEE's location is shown by the dashed line.

Figure 9: FEE in an enclosure.

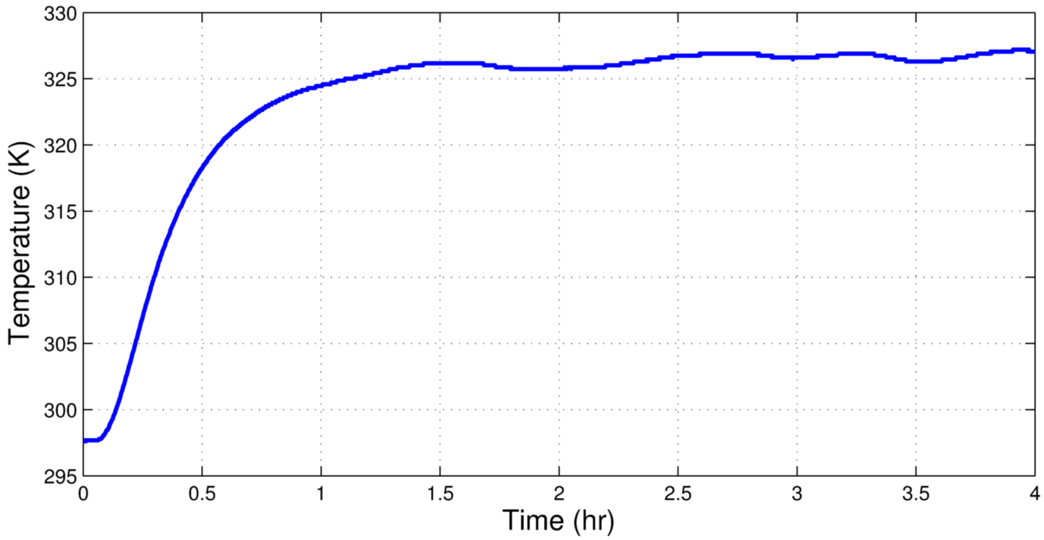

Figure 10: Demonstration of thermal stability.

Figure 11: FEE integrated with the dipole antenna. Note: an older revision of the FEE is pictured (see appendix) but the interface has not changed.

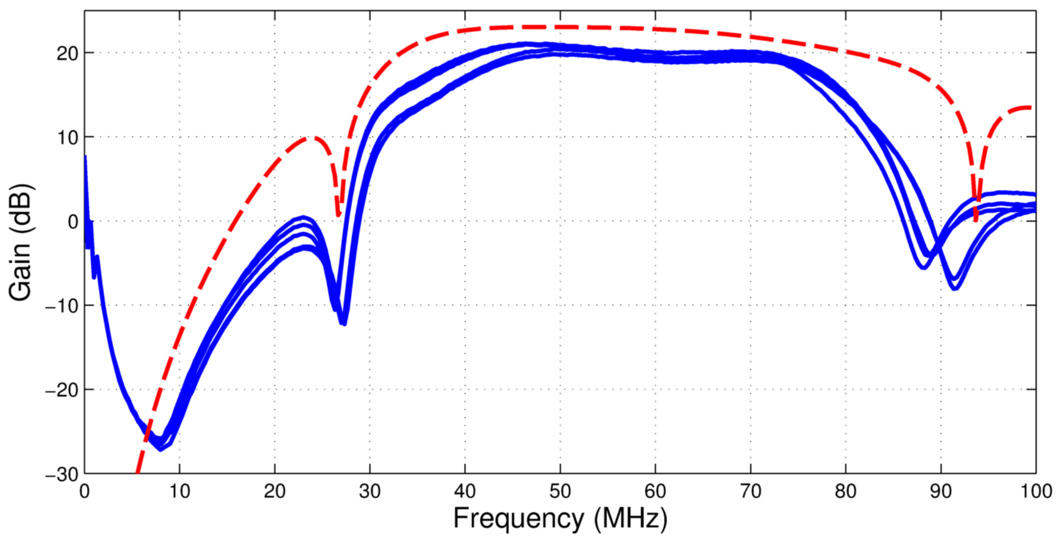

Figure 12: Measured (solid) and expected (dashed) G_{FE}.

+12 dBm, however the third harmonic levels measured increase less than a cubic term, so this is more of a lower limit on the IIP3.

Figure 14 shows the FEE's measured and expected noise temperature, T_{FE}, again for the six functional FEEs. The measurement was made by connecting a matched load to the antenna terminals and measuring the output power spectral density (PSD). The results are consistent with the expected T_{FE} derived from analysis using datasheet values.

4 Calibration Demonstration

This section describes and demonstrates the FEE's calibration procedure. The output PSDs in each calibration state are:

$$P_{ant} = kG_{FE}((1 - |\Gamma_{ant}|^2)T_{ant} + T_{FE}) \tag{1a}$$

$$P_L = kG_{FE}(T_{amb} + T_{FE}) \tag{1b}$$

$$P_{cal} = kG_{FE}(T_{amb} + T_{cal} + T_{FE}) \tag{1c}$$

where P_{ant}, P_L, and P_{cal} are the PSDs when the switch is connected to the antenna, cold noise source, and hot noise source, respectively, k is Boltzmann's constant, T_{ant} is the antenna temperature, T_{amb} is the ambient temperature, and T_{cal} is the noise source's excess noise temperature. The factor $1-|\Gamma|^2$ is commonly referred to as the impedance mismatch efficiency (IME). The calibrated temperature, T_{3p}, comes from subtracting (1a) and (1c) from (1b) and dividing, and is independent of G_{FE} and T_{FE}:

$$T_{3p} = \frac{1}{(1 - |\Gamma_{ant}|^2)} \left(T_{cal} \frac{P_{ant} - P_L}{P_{cal} - P_L} + T_{amb} \right) \tag{2}$$

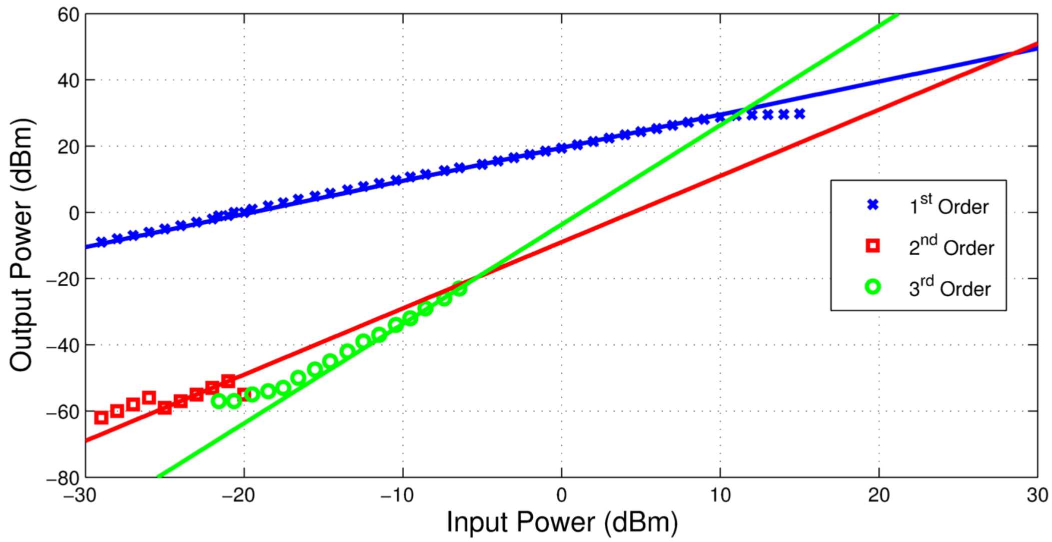

Figure 13: Summary of linearity measurements made of the FEE.

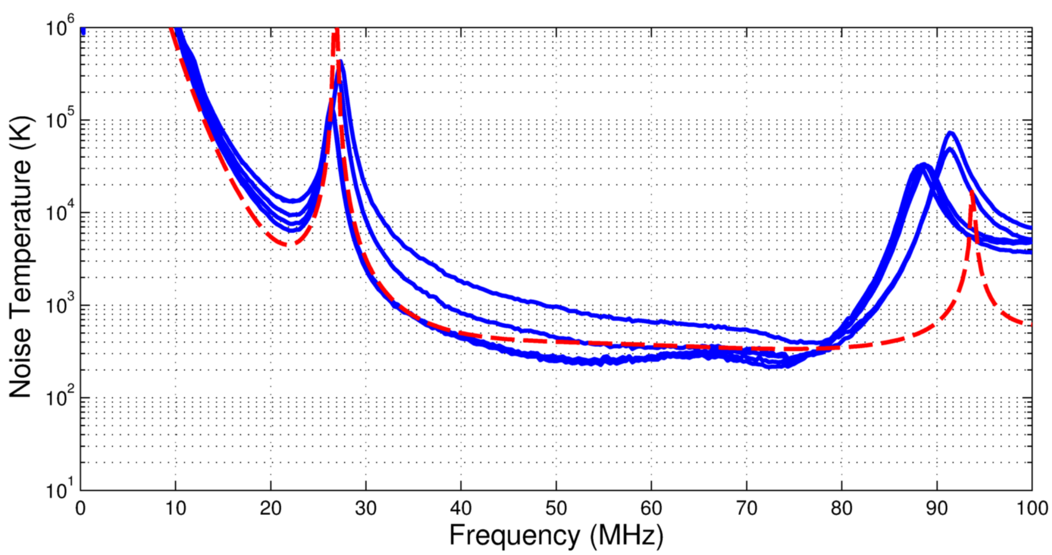

Figure 14: Measured (solid) and expected (dashed) T_{FE}.

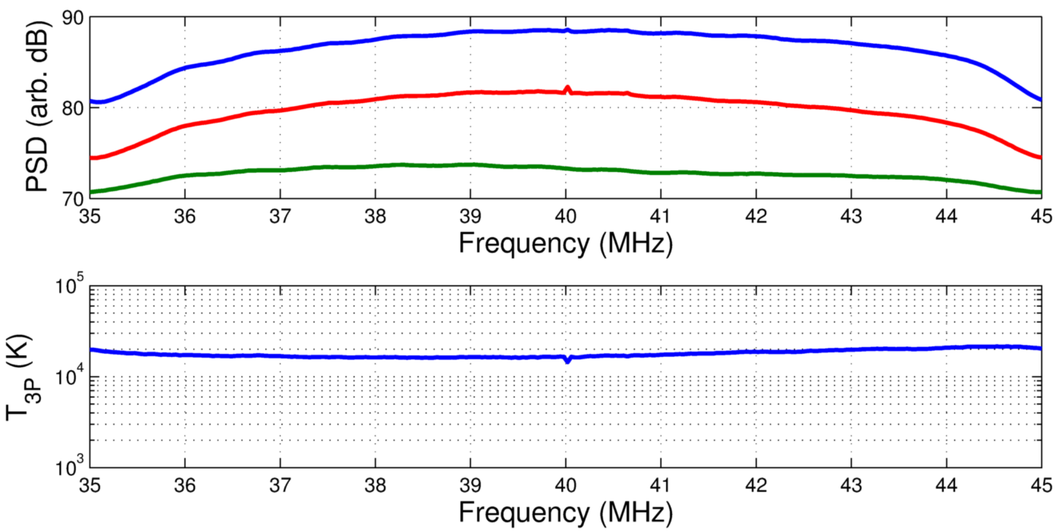

Figure 15: (top) Measured power in the three switch states, expressed in dB of the USRP's counts. From top to bottom these starts are the "antenna" (N-Gen), hot noise source, and cold noise source. (bottom) Calibrated noise temperature. RBW=39 kHz, 77 ms integration.

Accurate calibration by (2) requires *a priori* knowledge of T_{cal}. The resistor used to bias the noise diode was modified from the datasheet recommendations so as to increase T_{cal}. Lab measurements found the diode's noise temperature to be about 3×10^6 K, with a peak variance of 2×10^5 K [8].

For a quick lab demo, an Elecraft N-Gen noise source, attenuated by 20 dB was connected to the FEE's antenna terminals. From the (rough) excess noise ratio of 35 dB provided, the expected input temperature should be around 10,000 K. The measurement was made with the entire receiver chain that will be deployed to the field, including the cable, analog receiver, and USRP.

Figure 15 shows the measured powers at each switch state, and the calibrated noise temperature. The rough estimate of 10,000 K appears to be valid. A rigorous error model for the system is currently being developed, which will include a more careful evaluation of the FEE's calibration.

A FEE History

The current FEE is in its third iteration; the first version of the FEE prototyped the RF receiver and 3-state calibration system, the second version improved on thermal stability, and the current version improved on the reliability of the 3-state switched calibration as well as further improved thermal stability.

The first version of the FEE is shown in Fig. 16. The primary issue with this version was an explicit lack of thermal stability. A few minor layout and component selection errors were found during population and initial testing. These errors are summarized below, along with the fixes that were implemented:

- The pads of the first diplexer component were connected together. The trace was scratched out with an x-acto knife.

- R10 was not connected to the DC bias plane. The connection was made externally using spent solder wick.
- The ground pads of the attenuator were not connected to ground. The connection was made externally using spent solder wick.
- The diode D2 was not rated for the high current draw. It was replaced by another inductor identical to L22 that can.
- The originally selected comparator, TI's LM339ADR, was unable to drive the $\sim 200\ \Omega$ input impedance of the mechanical relays due to current limitations. It was replaced by an Advanced Linear Devices' ALD4302SBL.

The second version of the FEE, pictured in Fig. 17, had significantly better thermal characteristics, predominantly owing to a pair of fans cooling each amplifier[5]. A parasitic capacitance caused by the large ground screen beneath the antenna terminals led to instability in the antenna state, however this was fixed by drilling out the metalization on the antenna terminals. Additionally layout error switched the control signals going to the relays, which was corrected using single-strand wire as pictured.

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[5] The final FEE version does not use fans since heat sinking is provided by the enclosure.

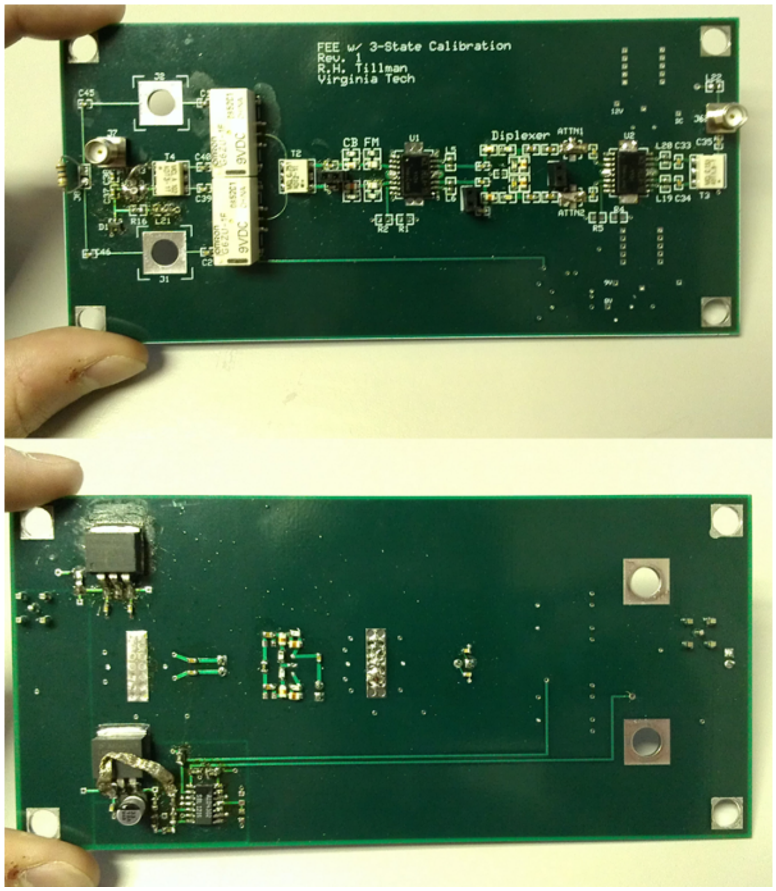

Figure 16: Top and bottom of the first version of the FEE.

Figure 17: Top and bottom of the second version of the FEE.