Galactic Background Measurements with the LWDA Receive Chain

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Introduction

On May 24/25, 2006 a second field test was conducted on the full LWDA signal chain. The test was conducted at Palmetto State Park (PSP), approximately 65 miles south of Austin. The park is located in a valley, which provides a significant reduction in the ambient RF levels. Aaron Kerkhoff, Johnathan York, and David Munton participated in the overnight test.

Measurements were taken between approximately 8 pm (CDT), Wednesday May 24 and 9:00 am Thursday May 25th. We generally followed a test plan drafted by Aaron Kerkhoff. The primary goal of the test was to take a series of measurements that would allow us to observe the galactic background moving overhead during the night, and to also collect additional engineering data. We collected data from two antennas simultaneously during this period, with each antenna configured to provide only a single polarization. The signal chain included the following components.

- Two LWDA antennas.
- Two of the new Tele-Tech production version of the Hicks balun.
- Balun/antenna cables fabricated for LWDA.
- Heliax 50 Ω cable (30 m cable and a 60 m cable).
- Amplification stages (2 MiniCircuits ZKL-2R7 and 2 ARL gain stages).
- Digital receiver revision 3 (RX).
- Adder board.
- An enclosure to contain all digital electronics and amplification stages.
- Computers
- Spectrum analyzer (SPA)

Test Plan

The test plan that we prepared for the measurements is outlined in the following paragraphs.

1. Setup antennas, unroll coax. cables, setup SPA, laptops, electronics box, and power supply. Place antennas ~ 20m apart in the E-W direction; align dipoles used for measurement in N-S direction.

Re-check setup / RFI environment

2. Connect 180° combiner to one of the antennas, and connect the coax directly to SPA. Perform passive RFI survey with SPA over at least 0.01-2 GHz. Note any strong signals. Log SPA data with laptop.
3. Connect baluns to both antenna, coax. cables to electronics box, and electronics box to SPA. The COTS / 2-SGS receive chain (with full gain) should be connected

inside the electronics box. However, remove power from digital electronics inside box. On antenna #1, examine spectrum with SPA over the band of 0.01 – 2 GHz. Verify that proper LWDA passband appears with noise at approximately the correct level. Note any strong signals both in band and out of band. Log SPA data with laptop. It will likely be necessary to repeat this step with some attenuation applied to one of the SGS due to ambient RFI causing intermods / compression. Switch the antenna coax cables on the electronics box and repeat the steps above for antenna #2. Look for any differences between the two antennas.

4. Based upon measurements in 3., determine attenuation level to use for remaining measurements.
5. (optional) Repeat 3. with laptops turned off and visually note any differences in spectrum.
6. Apply power to digital electronics and startup RX and adder. Visually note any differences in spectrum on SPA from steps 3. or 5. Log SPA data with laptop. Verify that RX measurements are consistent with SPA measurements. Log RX measurements with laptop.

Calibrate receive chains

7. Connect noise source to balun of antenna #1. Using SPA, verify that measured noise is consistent with expected values over 50-100 MHz. Conduct video averaged measurements over 50-100 MHz band with SPA (logged to PC). Take short integration measurements with RX over 50-100 MHz band (say, 5 sec. integration over each 1.6 MHz band.) Verify that RX and SPA measurements for antenna #1 agree over 50-100 MHz band. Repeat previous steps for antenna #2. Verify that RX measurements for antennas #1 and #2 agree over the band.
8. Repeat 7. w/ noise source turned off (to give 290 K source.)

Conduct short duration sky noise measurements

9. Connect balun back to antenna. Conduct video averaged measurements over 50-100 MHz band with SPA (logged to PC). Take short integration measurements with RX over 50-100 MHz band (say, 5 sec. integration over each 1.6 MHz band.) Verify that RX measurements are consistent with SPA measurements over 50-100 MHz band. Verify that measurements agree with expected sky noise values.
10. Perform longer "stability test" (up to 16 min.) with RX at one or more "clean" bands. Verify that resulting stability agrees with expected sky noise stability for that time of day. It may be desirable to repeat this test every so often as the sky noise stability varies. NOTE: make sure all electronics have been on for at least 1 hour before running this test.

Conduct long duration sky noise measurements

11. Setup both SPA and RX to sweep between 50-100 MHz every 15 minutes for asclose to 24 hours as is possible. Each SPA sub-band measurement will be video averaged, while 5 sec. of integration will be used for each RX sub-band measurement.

Site Layout

Figure 1 shows the site layout. As in our previous test [1], we used the a CCC park pavilion, know as the Refectory, as a working area. We positioned one antenna (referred to as A1) at a fixed location (in the far left of Figure 1), which was close to the position used in our previous set of measurements at PSP. A1 was connected to the electronics by a 30m run of Heliax cable.

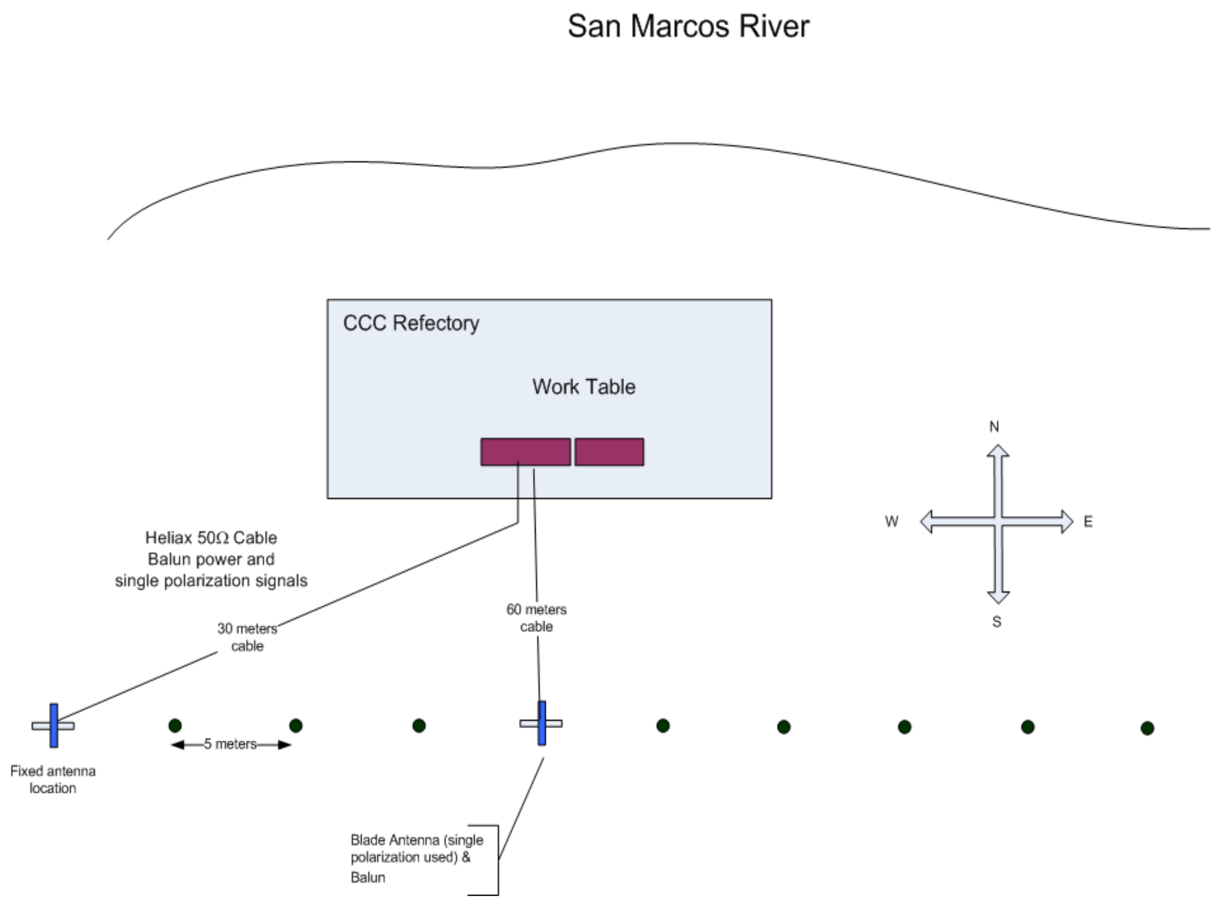

Figure 1. Measurement Configuration

We decided to modify the original test plan slightly by marking off, at 5 meter intervals, a series of 14 additional positions for the second antenna. This chain of positions was roughly aligned in an east-west direction. As shown above, the blade antennas were aligned so that one set of blades was parallel to the N-S axis, and data was collected from this pair of blades. A standard spot, 20 m east of A1, was chosen for the primary location of the second antenna (A2), which was connected to the electronics via a 60 m run of Heliax cable. Photos of the antenna locations are shown in Figure 2. The second photo looks east along the line of antenna locations from A1.

Figure 3 provides a view of the antenna top, and the short cable used to connect the balun to the antenna. Cables like these will be used at the LWDA site.

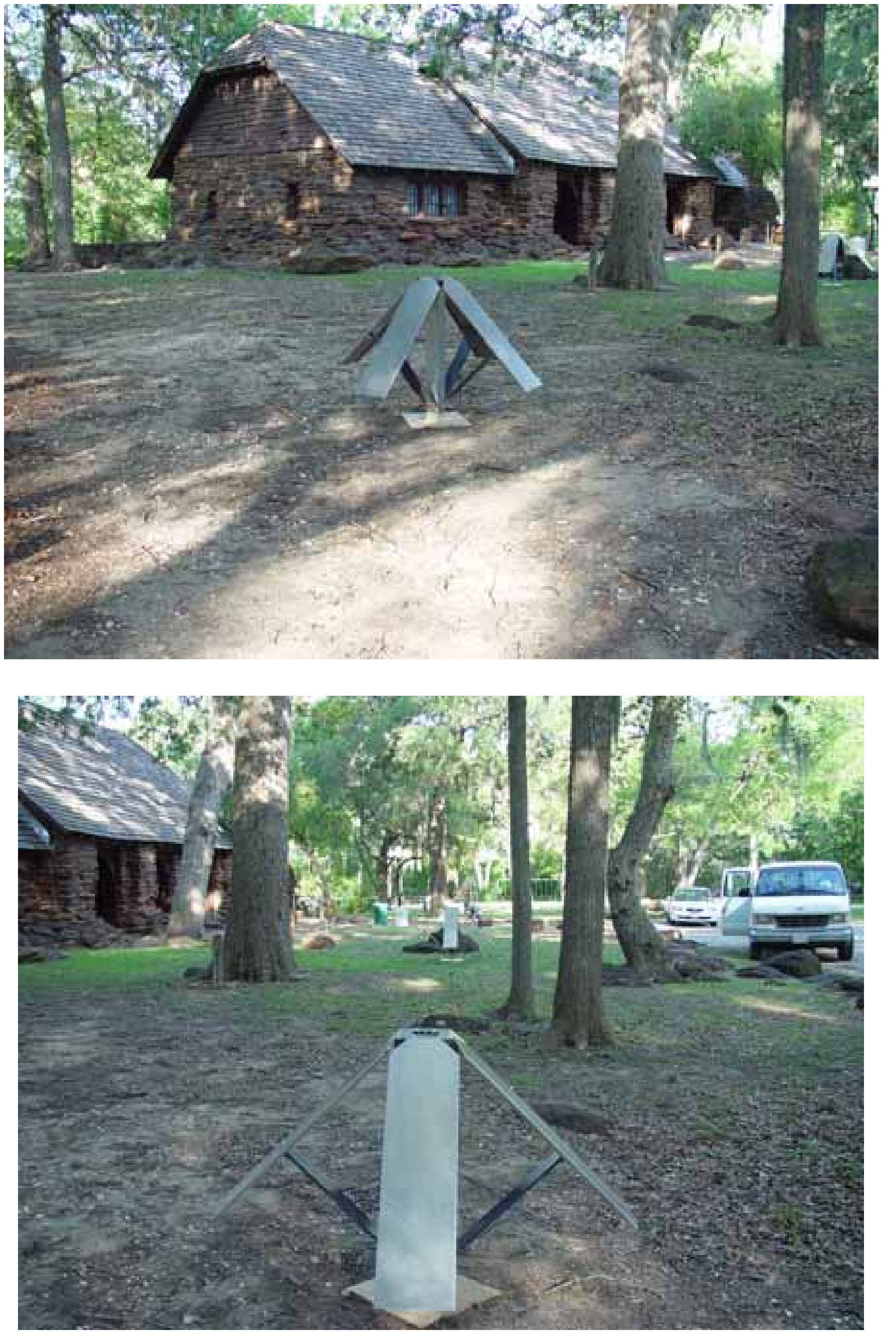

Figure 2. Photos showing the fixed and 20- meter antenna locations. The site that was used as a fixed location is occupied by the closest antenna in the photos.

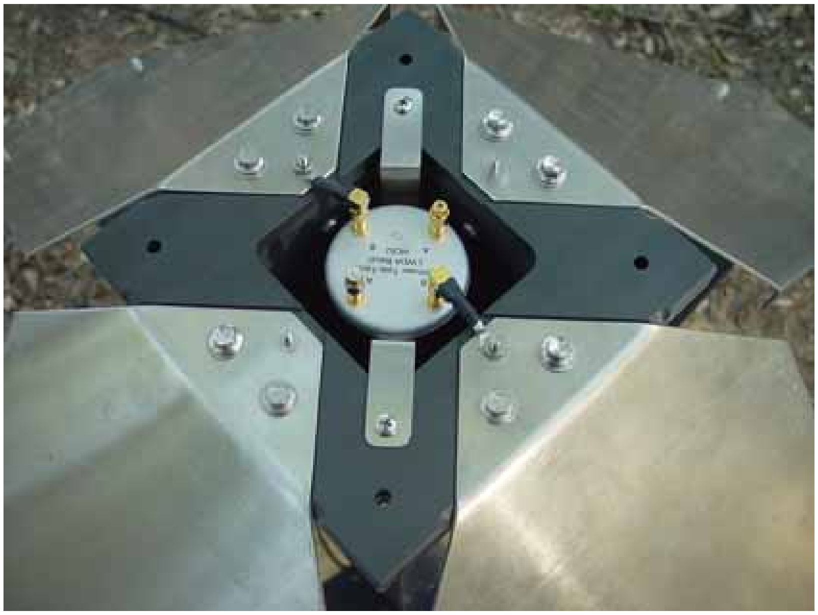

Figure 3. Top of antenna 1, showing the short cables antenna/balun cables.

Electronics Test Configuration

The figures below provide an outline of how the electronics were configured on the benchtop during the measurements. Figure 4 shows the overall configuration of electronics, while Figure 5 shows the configuration inside the digital electronics box.

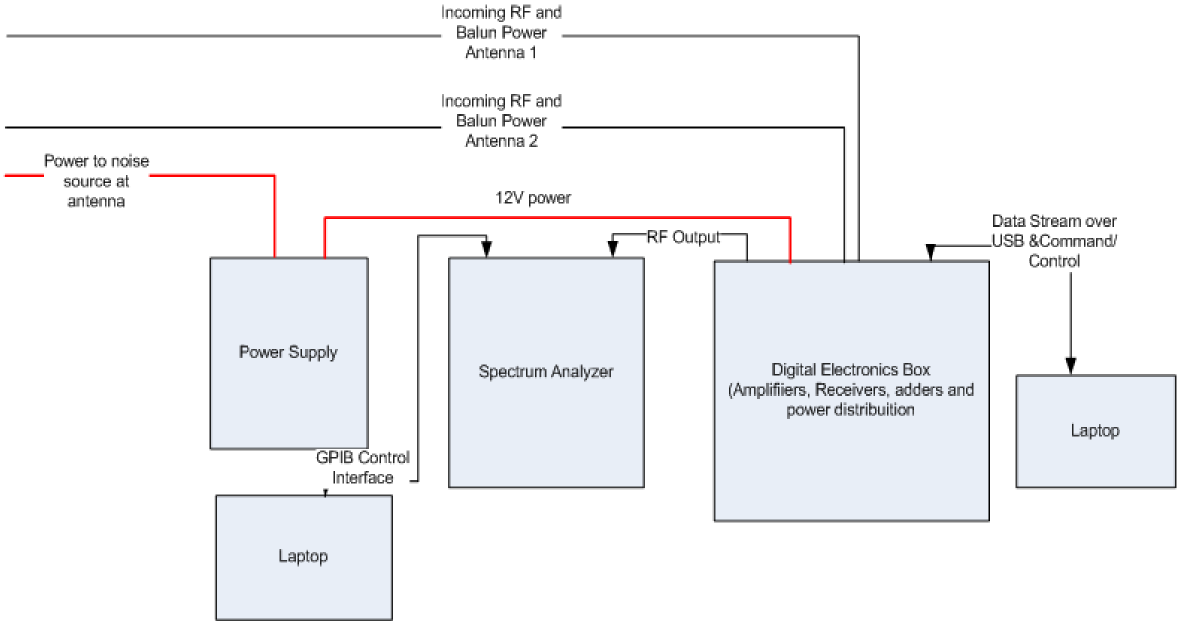

Figure 4. Configuration of the benchtop electronics.

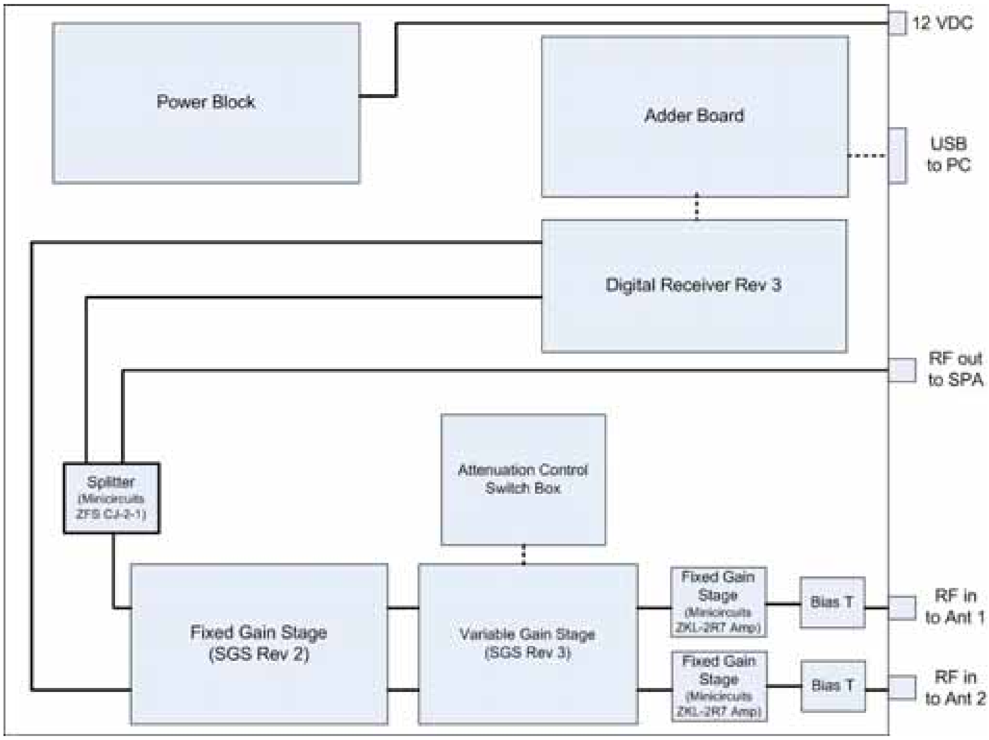

Figure 5. Configuration of the receive chain inside the shielded NEMA enclosure.

Laboratory Measurements of Receive Chain Components

Individual Component Measurements

Prior to field testing, each component in the test setup depicted in Figure 5 was tested individually to verify that it met vendor or designer specifications. These measurements included S-parameters (matching, gain / insertion loss, coupling, reverse isolation), effective noise temperature, linearity metrics, and power draw. All measurement results conformed to specifications except for the noise temperature of the production model dual-polarization active balun.

The noise temperature measurement of the balun was performed using a MiniCircuits ZFSCJ-2-1 180° combiner and an Agilent N8974A noise figure analyzer (NFA). The insertion loss of the combiner was carefully measured and was applied as a loss compensation in the NFA measurement. The measured input referenced noise temperature for both channels of the balun is shown in Figure 6. Note that the average measured temperature across 60 – 80 MHz, 320.1 K, is considerably higher than the value measured by R. Bradley, close to 250 K; it is assumed here that R. Bradley's measurements are accurate [2]. Averaging was employed on the NFA, using 200 samples to generate a noise temperature estimate at each frequency, so that the maximum variation between successive temperature estimates at any frequency was +/- 5 K. Given these results, we do not believe that the discrepancy is due to measurement noise.

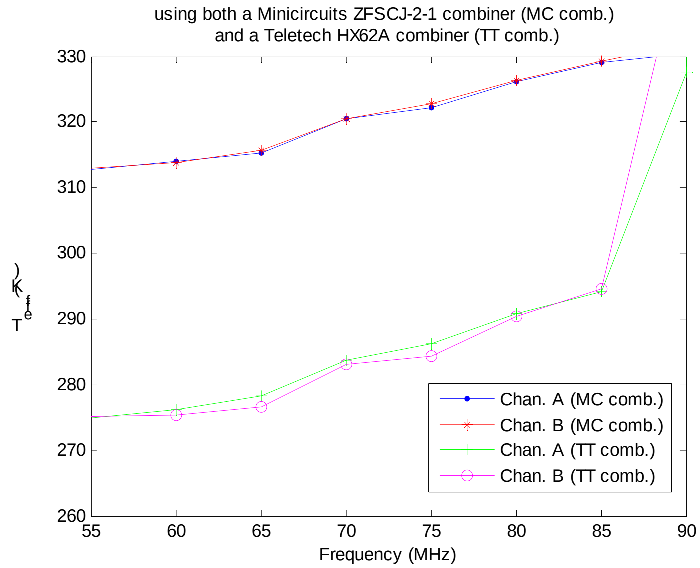

Figure 6. Measured effective noise temperature of final LWDA active balun design using either Minicircuits combiner (MC) or Teletech hybrid (TT) on input of balun. Note that FM interference has apparently leaked into the Teletech combiner measurements above 85 MHz.

We have repeated this measurement multiple times on the NFA with similar results. Furthermore, nearly identical results are achieved when the same test configuration is used to measure older, single polarization versions of the active balun. However, accurate noise temperature measurements have been made using the NFA on other active devices. Therefore, we believe that the discrepancy is due to some aspect of the configuration used to measure baluns noise temperature. We investigated whether the error might be due to additional insertion loss in the setup that was not accounted for in the NFA loss compensation. However, since the measured return loss of the combiner output ports and balun input ports were better than -20 dB and -12 dB, respectively, the mismatch loss should be << 0.1 dB. Phase imbalance between the two devices could also cause loss. However the phase imbalance of either the combiner or balun is expected to be better than 1° at LWDA frequencies. At this time it remains unclear to us why the NFA measured balun temperature is so much higher than R. Bradley's measurement.

Due to the significant bias noted in the original noise temperature measurements, we repeated the measurements using a different combining element prior to the balun. A bare Hick's balun circuit board was modified so that the SMA inputs could be connected directly to a Teletech HX62A hybrid via bus wire. The output of the hybrid was connected to another SMA connector; no other components on the board were populated. A picture of the hybrid board is shown in Figure 7. The hybrid board was measured on a network analyzer and found to have a return loss of better than -30 dB on all ports and an insertion loss of 0.25 dB (in addition to the nominal 3 dB loss) through each side of the hybrid. The balun was re-measured on the NFA using the hybrid board and the procedures described above. The measured system temperature of the balun using this setup is compared with that using the Minicircuits combiner in Figure 6. The average hybrid measured balun temperature between 60 to 80 MHz, 283 K, is much lower than that measured with the Minicircuits combiner, though it is still higher than expected for the balun. The high temperature noted above 85 MHz appears to be due to FM interference coupling into the measurement (perhaps through the unshielded hybrid board.) It has been noted that the balun temperature is somewhat sensitive to the bias voltage / current. For these measurements, the bias voltage used was 9 V. In lowering the voltage down to 8 V, the noise temperature dropped 4 to 5 K. This still leaves a significant discrepancy between our result and R. Bradley's result. It is believed that this error is due to some remaining flaw in the NFA test configuration rather than a flaw in the balun.

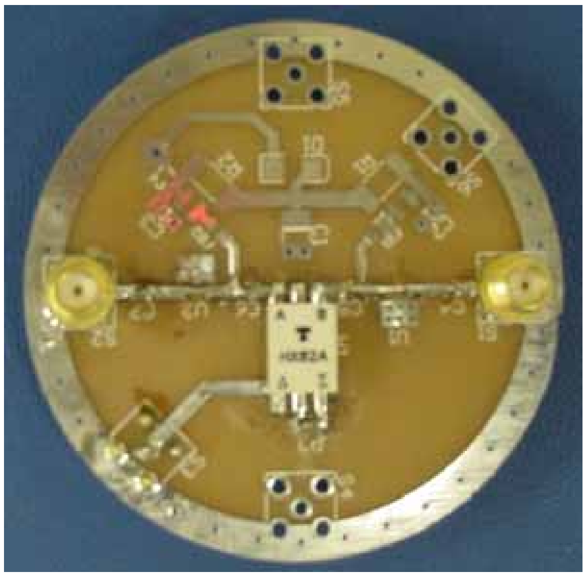

Figure 7. A modified Hick's balun board with direct connects between input connectors and Tele-Tech HX62A 180º hybrid.

Gain and System Temperature of Full Receive Chain

We used the NFA to measure the gain and system temperature of the entire receive chain setup to be used in field testing. This included a balun, a short N-type to SMA coaxial cable, a 30 m length of Heliax coaxial cable, and all of the receive chain components depicted in Figure 5. Note that the results provided here are for channel 1 (labeled "Ant 1") in Figure 5 so that the 2-way splitter at the output, just before the receiver is included in the measurement. The measurements were conducted using both the Minicircuits combiner and the hybrid board to interface the balun to the NFA. The same procedure as described before was used to conduct the NFA measurements.

The measured system gain and temperature of the setup for SGS attenuations of 0 dB and 21 dB are provided in Figures 8 and 9, respectively. The gain measured by the Minicircuits combiner and the hybrid board are nearly identical, and therefore, only the combiner measured gain is included in Figure 8. Both the combiner and hybrid measured system temperatures are included in Figure 9. Also included in these figures are the

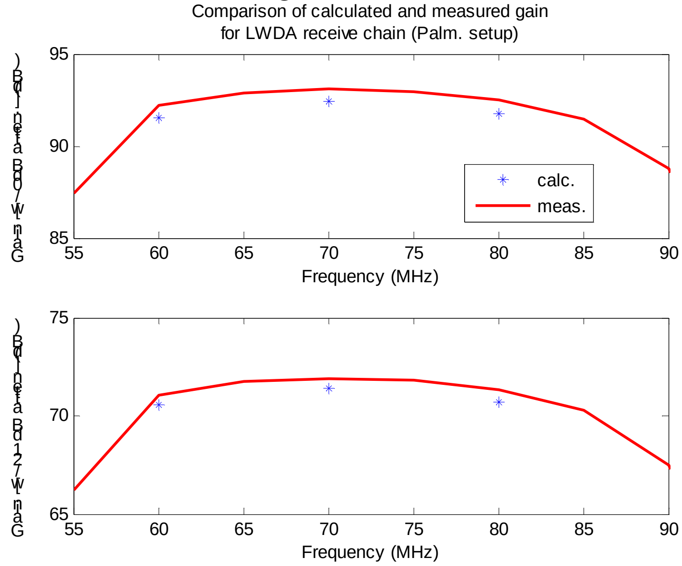

Figure 8. Comparison of measured and calculated system gain for receive chain (Chan. 1) used for field testing. SGS attenuation = 0 dB (top), SGS attenuation = 21 dB (bottom.)

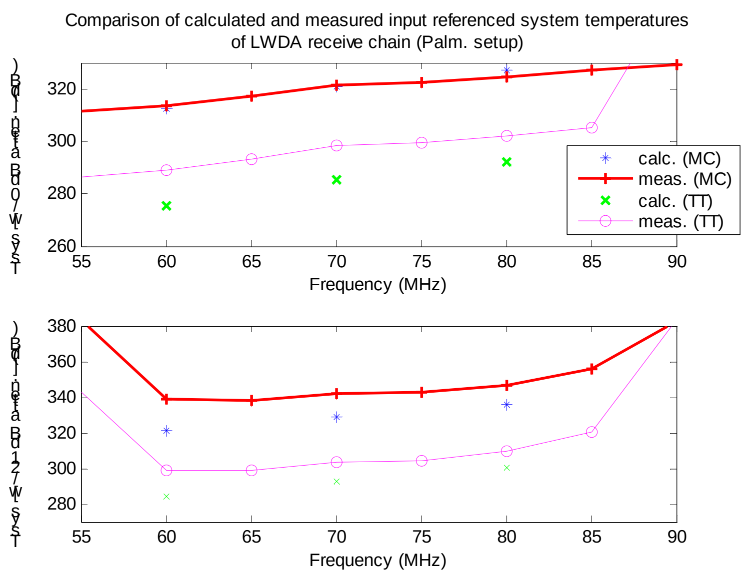

Figure 9. Comparison of measured and calculated system temperatures for receive chain (Chan. 1) used for field testing. SGS attenuation = 0 dB (top), SGS attenuation = 21 dB (bottom.) Results are shown for measurements with both the Minicircuits (MC) combiner and Teletech (TT) hybrid.

expected values of system gain and temperature at 60, 70, and 80 MHz. These values were calculated using gain and noise measurements of each individual component in the setup and cascaded analysis. Note that the NFA measurements of balun temperature given above in Figure 6 were used in this analysis. From Figure 8, it can be seen that the measured and expected values of system gain agree well at each frequency and for both

SGS attenuation levels tested. The maximum error between the measured and calculated values is 0.7 dB. This indicates that cascading the components of the receive chain has not introduced any unexpected losses. The calculated and measured receive chain temperatures for an SGS attenuation of 0 dB and using the Minicircuits combiner agree extremely well (when the NFA measured balun temperature is assumed in the calculation), as is evident in Figure 9; the maximum error is less than 5 K at all frequencies. However the 21 dB attenuation measurement using the combiner and the hybrid measurements for both attenuations are typically ~ 10 K higher than expected. Despite this discrepancy, NFA measured noise temperatures for the full receive chain are generally consistent with the NFA measured noise temperature for the balun alone. This indicates that the components in the receive are not contributing additional noise when they are cascaded, which suggests the receive chain is functioning properly. Though not shown here, similar results were achieved for channel 2 in the test setup. As expected, the system gain was roughly 3.7 dB higher since a splitter was not included at the output of that channel.

For reference, the calculated receive chain system temperature using the expected temperature of the balun, 253 K, at 70 MHz and for 0 dB and 21 dB SGS attenuations is 256.3 K and 264.1 K, respectively.

Linearity Metrics for Full Receive Chain

Measurements were made to determine the intermodulation distortion and harmonic distortion performance of the full receive chain. For OIP3 / OIP2 measurements, tones were placed at 73.9 and 74.1 MHz. For HD3 / HD2 measurements a tone was placed at 74.1 MHz. The intermodulation product and harmonic powers were measured for a number of output tone powers between -7 dBm and +8 dBm. The measured second and third order intercept and harmonic distortion levels for channel 1 of the receive chain for a tone output power of +5 dBm are given in Table 1 for SGS attenuations of 0 and 21 dB. The expected OIP3 due to the receive chain derived from cascaded analysis is included for comparison. Note the calculated OIP3 values are 3.7 dB lower than the designed receive chain due to the signal splitter placed at the output of the test setup used for these measurements. The measured OIP3 for 0 dB attenuation agrees well with calculation. It is not clear why the measured OIP3 increased when SGS attenuation was increased – it should decrease somewhat as the calculations indicate. The measured OIP2 is extremely high (we didn't originally measure the OIP2 of the SGS – so we'll need to do this to see it agrees with this result.) The HD2 and HD3 values are approximately 5 dB higher than were measured for the SGS alone for this output tone power. However, the values are still reasonable.

Table 1. Linearity metrics for channel 1 of full receive chain for different SGS attenuations. Note that calculated OIP3 values are 3.7 dB lower than for designed receive chain due to splitter placed at output of the test setup for these measurements.

SGS atten. (dB)	Meas. OIP3 (dBm)	Calc. OIP3 (dBm)	Meas. OIP2 (dBm)	Meas. HD3 (dBc)	Meas. HD2 (dBc)
0	+37.6	36.3	+73.1	-55.8	-73.7
21	+42.3	34.5	+73.3	-57.5	-73.5

Radiometric Stability of Full Receive Chain

A test was performed to determine the radiometric stability of the receive chain. The setup consisted of a HP346B calibrated noise source connected to the full receive chain with 21 dB of attenuation on the SGS. RX measurements were logged continuously for 12 hours. The data set was reduced to determine the variance of total power measurements for each of a number of different integration lengths ranging from 50 ms to roughly 2.8 hours. The results of this test are plotted in Figure 10 along with the expected reduction in power estimate variance with increasing integration length. As can be seen, the RX power estimate variance appears to decrease steadily until an integration length of at least 100 s. This indicates that the receive chain is radiometrically stable at the single minute time scale, as desired.

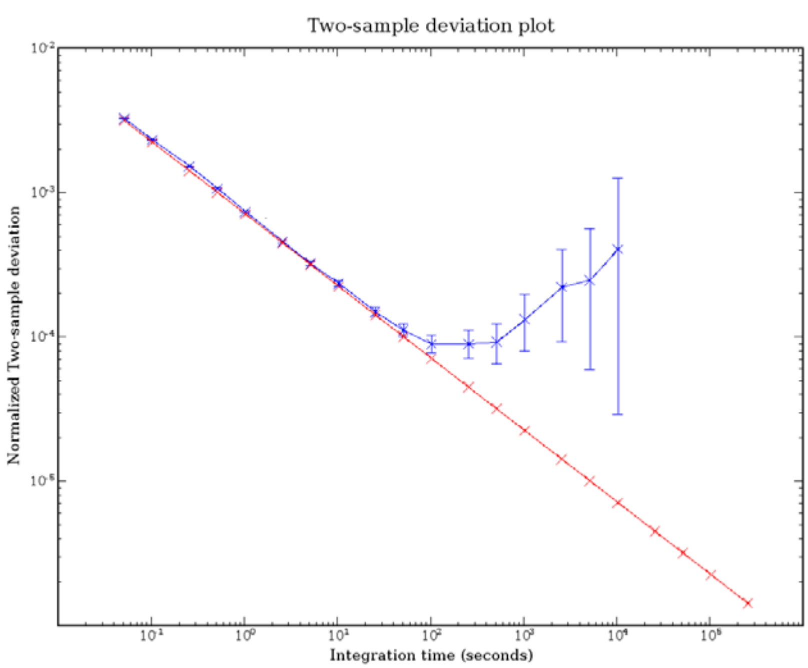

Figure 10. Measured variance of LWDA receiver total power measurements when connected to broadband noise source with 21 dB of attenuation on the SGS.

Passive Survey Results

As indicated in test plan above, field measurements began by performing a passive survey of the RFI environment. To perform these measurements, the A1 blade antenna was connected to 180° combiner, which was connected directly to the spectrum analyzer (SPA) via a 30 m coaxial cable. The measured power at the SPA between 0 – 2 GHz was logged by laptop. The results of this measurement between 0 to 300 MHz are shown in Figure 11. Here, the measurement band ("in band") is considered to be 50 to 100 MHz. As can be seen, the typical ambient RFI levels at PSP are relatively low. The peak out of band interferer occurs in the FM band, at 106.3 MHz, with a received power of -59.3 dBm. Other relatively strong out of band interferers occur at 152.7 MHz (P = -66.3 dBm), 162.7 MHz (-71.2 dBm), and a number of HF frequencies (> -80 dBm.) There were no signals at frequencies above 300 MHz, with a received power > - 85 dBm. The strongest in band signal occurs at 67.2 MHz with a power of -77 dBm. There are a few more in band signals (notably 55.3, 71.7, and 77.2 MHz), but the powers of these signals are all < -88 dBm. The power levels agree well with measurements taken at PSP on 4/20/06.

In the next measurement, the blade dipole was connected to the balun, which was connected through the coaxial cable and full receive chain to the spectrum analyzer. In this measurement, all analog components were powered, but digital electronics (receiver and adder) were not. The SGS attenuation was initially set to 0 dB. However, in this configuration, a high number of very high power spikes appeared in the measurement band. This was likely due to the last gain stage and / or SPA generating intermodulation products due to very high input powers. Since the measured gain of the full receive chain = 92.4 dB at 70 MHz, the peak in band RFI would be as high as +15.4 dBm. This power is above full-scale on the receiver ADC, and clearly much higher than is needed to perform measurements. Therefore, the SGS attenuation was increased to 21 dB to lower the received power to a more reasonable level; 21 dB is the maximum available attenuation in the setup used for these tests.

The measured power at the SPA between 0 – 2 GHz with the full receive chain powered and with 21 dB of attenuation set on the SGS was logged to a laptop. The digital electronics remained off in this measurement. The measured spectrum between 50 to 100 MHz is shown in Figure 12. The expected passband due to SGS bandpass filters is apparent between 55 to 90 MHz. The same strong in band signals are present in this figure as are in Figure 11 with a peak power of approximately 0 dBm. Between these strong signals, however, are a number of relatively quiet bands. Although it is not shown in Figure 12, no signals appear in the spectrum outside of 50-100 MHz except for some signals near 10 MHz with a power of -70 dBm and some signals between 200-225 MHz with powers of up to -66 dBm.

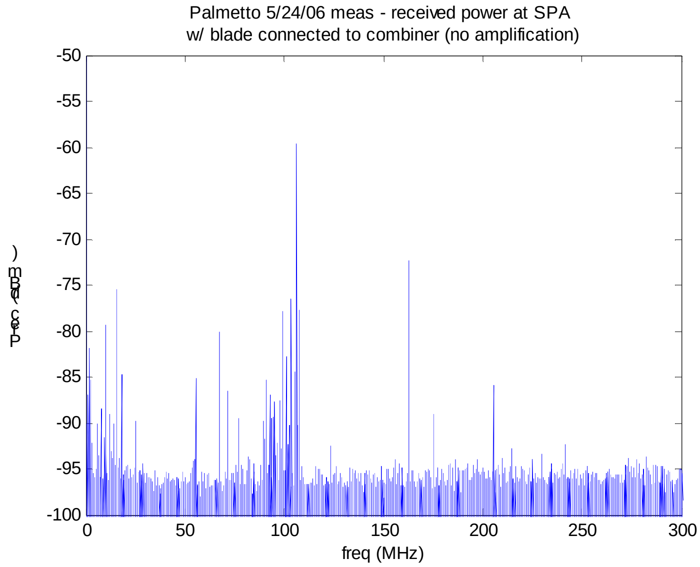

Figure 11. Measured power at spectrum analyzer when connected directly to blade antenna. Add ~ 2.1 dB to result to reference measurement to antenna terminals.

The last measurement was repeated after turning on and configuring the receiver and adder boards in order to determine if any radiation from these boards was being coupled into the measurements. The results from this measurement are compared to measurements with the digital electronics turned off in Figure 12. There is no noticeable difference in the spectrum between 50 to 100 MHz between these two measurements. Additionally, there is no noise increase at frequencies above 100 MHz due to the digital electronics. Therefore, it appears that radiation from the digital electronics is not coupling into the measurements (or at least, it is not apparent for very short integration lengths.)

From these preliminary measurements it was determined that the equipment was performing properly and that it should be possible to conduct sky noise measurements using the receiver without causing self-interference. Since 21 dB SGS attenuation provided reasonable peak RFI levels while not causing significant intermodulation products, this attenuation level was used for all subsequent measurements.

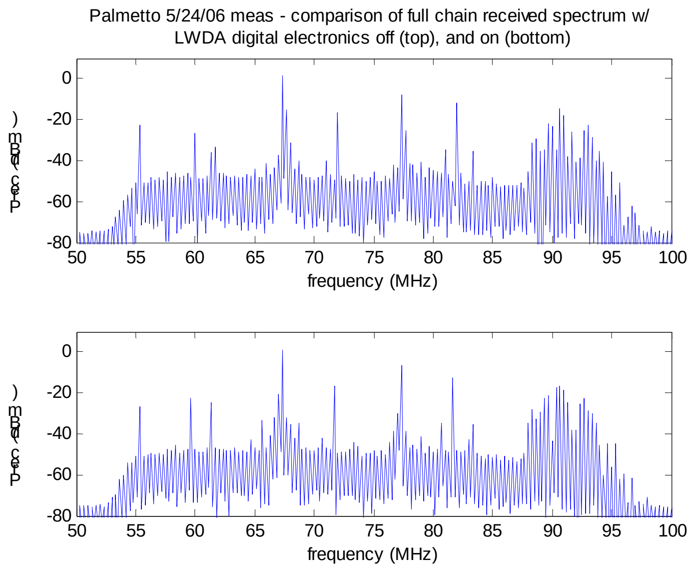

Figure 12. Measured power at spectrum analyzer when connected through full receive chain (Chan. 1) with 21 dB applied to SGS. LWDA digital electronics off (top) and on (bottom.)

Noise Source Measurement Results / Calibration Procedure

As indicated in the test plan, the next step was to perform measurements using the full receive chain (balun, cable, electronics box) with a calibrated noise source connected in place of the antenna. A 180° combiner was used to couple a HP 346B noise source to the balun at the A1 antenna. Between 60-80 MHz, the excess noise ratio (ENR) of the noise source is approximately 15.45 dB which corresponds to a hot temperature, $T_H = 10462$ K. It is assumed that when the noise source is turned off, its cold temperature is $T_C = 290$ K. Measurements were taken using both the receiver (RX) and the SPA between 50 to 100 MHz with the noise source turned on. The measurement settings used with the spectrum analyzer and receiver are provided in Tables 2 and 3 respectively.

The total power measurements from both devices are shown in Figure 13; the results have been adjusted so that they are referenced to a common noise measurement bandwidth, 10 kHz. In addition to the averaging performed during the measurement, the SPA data has been average over frequency at 500 kHz intervals in order to further reduce measurement noise. Also included for comparison is the expected power using this test setup at 60, 70, and 80 MHz. A balun temperature of $T_b = 253$ K, and the measured system gain (from NFA measurements) were used to generate this result. The use of $T_b = 253$ K agrees with SPA measurements slightly better than the use of the NFA measured $T_b = 320$ K, though the total power corresponding to the two conditions only differs by ~ 0.2 dB. All three results agree relatively well. The difference between the SPA measurement and expected values varies between 0.3 dB and 0.7 dB. The envelope of the RX frequency response is somewhat different than the SPA over the measurement band. This may be due to unmodeled mismatch at the input of the RX (likely due to the transformer used.)

Table 2. Settings used on spectrum analyzer during noise source / sky measurements.

Setting	Value
Measurement frequency range	50.0– 100.0 MHz
Sub-sweep span	5 MHz
Number of sub-sweeps	10
Number of points per sub-sweep	600
Resolution bandwidth	10 kHz
Detection mode	Sample
Display mode	Linear units
Reference level	0.5 mV
Video averaging	50 Samples

Table 3. Settings used on LWDA receiver during noise source / sky measurements.

Setting	Value
Measurement frequency range	50.2 – 98.2 MHz
Sub-sweep span (after discarding tails of frequency response)	1.6 MHz
Number of sub-sweeps	30
Number of bins per sub-sweep (after discarding tails of frequency response)	80
Bin size	~19.5 kHz
Integration length	> 400 frames = .02 sec[1]

Additionally, a 1.0 to 1.5 dB ripple is evident in the RX data. This ripple is expected, and is due to the particular digital filter designs implemented in the RX DSP. It is desired to derive a calibration to remove these effects so that accurate sky noise measurements can be made with the RX.

To calibrate RX measurements, it is first necessary to estimate system gain, G_{sys}, and system temperature, T_{sys} of the test setup in situ. Therefore, another measurement with the same setup was taken with the noise source turned off. The measurements with the noise source on and off were combined through the Y-factor method to generate G_{sys}, and T_{sys} estimates. Estimates of system gain and noise temperature as a function of frequency generated using RX data are shown in Figure 14. Also included are NFA measured values for comparison. The RX and NFA estimates of system gain agree well at all frequencies. The 1.0 – 1.5 dB ripple due to the RX filter response is evident in the RX gain estimate as expected. The two system noise estimates differ significantly. The

[1] In measurements taken earlier in the evening, total power was calculated using 400 frames of data, which corresponds to an integration length of 0.02 sec. Later in the evening a 20,000 frame average was used, which corresponds to an integration length of 1.0 sec.

mean RX estimated system noise temperature is much closer to the expected temperature for this test setup, 265 K. This suggests that the earlier noted discrepancy between expected and NFA measured noise temperature values is due to some problem in the

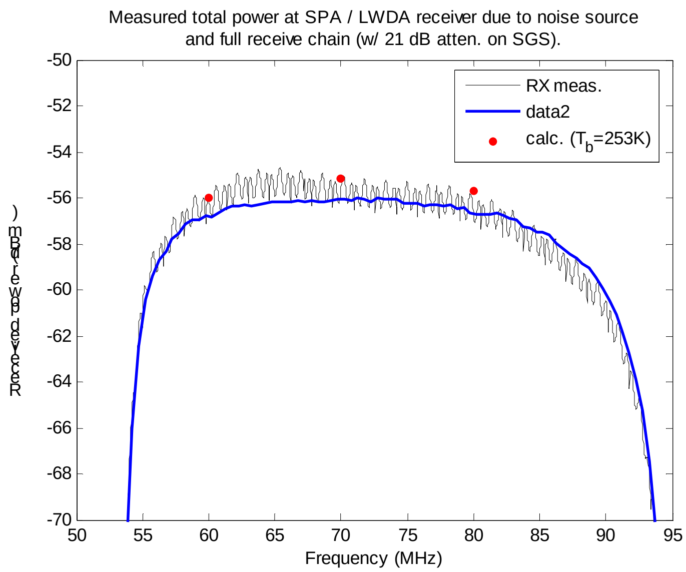

Figure 13. Spectrum analyzer and LWDA receiver total power measurements of calibrated noise source connected to full receive chain.

NFA test setup, rather than some flaw in the balun. There is an unexpected ripple in the receiver estimated system temperature with a maximum peak to peak variation of 30 K between 60-80 MHz. This does not seem to agree with R. Bradley's measurement result, which indicated that the balun is relatively flat (variation of < 10 K) over the 60-80 MHz band. It was first thought that this ripple could be due to noise contributed by the ADC and DSP chain, which could bias the Y-factor estimate of temperature. However, for the current setup the system noise contribution (referenced to input of the balun) due to these elements should only be approximately 4 K. Further study will be required to determine the cause of the ripple. Though not shown here, the same noise source measurements were performed on the second antenna, and similar performance was noted.

The estimates of G_{sys} and T_{sys} can then be used to correct sky measurements to improve measurement accuracy. The total power measured at the receiver can be expressed as

$$P_m = P_{sky} + P_{sys}$$

where P_m is the total power RX measurement, P_{sky} is the power corresponding to the noise temperature of the Galactic background reference to the receiver, and P_{sys} is the power due to system noise referenced to the receiver input. Using $P_{sys} = T_{sys} G_{sys}$, the following expression is used to determine the temperature due to the Galactic background referenced to the antenna terminals

$$T_{sky} = \frac{P_m - T_{sys} G_{sys}}{kBG_{sys}}$$

where k is Boltzmann's constant and B is the measurement bandwidth.

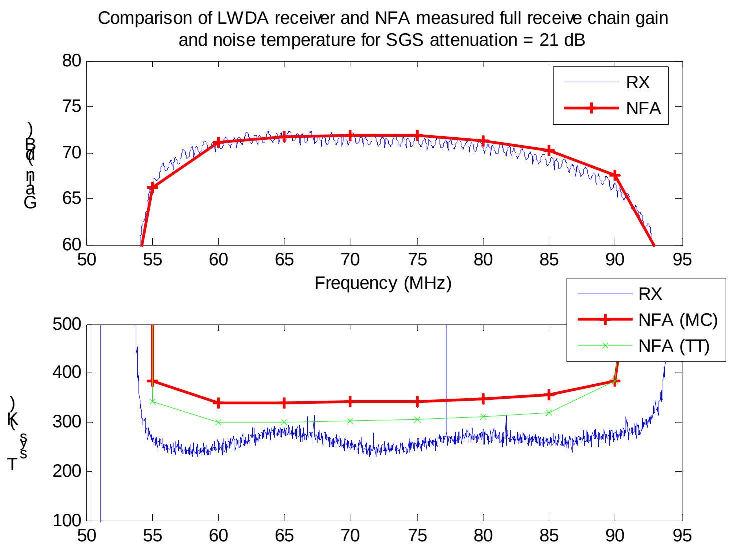

Figure 14. Comparison of LWDA receiver (chan. 1) and noise figure analyzer measurements of the system gain and temperature of the full LWDA receive chain with SGS attenuation = 21 dB.

Single Antenna Sky Noise Measurement Results

After noise source measurements were complete, the antenna elements on both antennas were reconnected to the baluns in order to perform sky noise measurements. Again the full receive chain with 21 dB of attenuation applied to the SGS was used. Measurements by the RX of both antennas were logged roughly every 5 minutes. Measurements of antenna A1 were also logged on the SPA every 15 minutes. The same settings as described in Tables 2 and 3 were used on the RX and SPA in sky measurements. These measurements were taken continuously over night between roughly 10 pm and 9 am CDT. The procedure described above, and the G_{sys} and T_{sys} estimates derived from noise source measurements were used to correct RX total power measurements in order to estimate sky noise at the antenna terminals. Data was not logged on the SPA when the noise source was connected and turned off. Therefore, the expected system temperature, 265 K, was used in conjunction with the SPA measurements with the noise source turned on to estimate system gain for those measurements. Then the same procedure was used to estimate the sky noise at the antenna terminals, as measured by the SPA. Only measurements from antenna A1 are discussed in this section.

It should be noted that due to limited time, no attempt was made to perform filtering of transient interference in the sky measurement results presented below.

Measured Sky Noise Spectra

The sky noise temperature spectra on antenna A1 referenced to the antenna terminals measured by both the RX and SPA at roughly 13:45 LST is shown in Figure 15. This time is approximately two hours after the observed sky noise minimum. Also included in this plot is the expected sky noise at the antenna terminals calculated using NEC simulation of a 2.0 m blade operating over an "average" lossy earth ($\varepsilon = 13$, σ=.005 S/m) and Cane's expression. As can be seen, the lower envelopes of the measurements agree well with each other and simulation, both in magnitude and frequency trend across the entire measurement band. Though there are a number of in band interferers, there are three bands centered about 63.0, 73.4, and 85.0 MHz that are relatively free from interference. Therefore further analysis of measurement data is focused in these three bands.

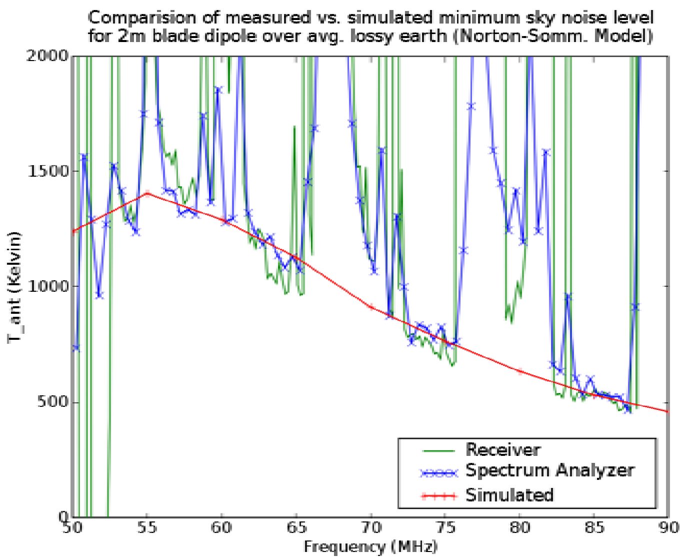

Figure 15. Comparison of RX and SPA measurements and simulation of sky noise temperature at terminals of 2.0 blade dipole operating over a lossy ground.

Time Variation of Measured Sky Noise

The RX and SPA measured sky noise temperature in each of the three clean bands is plotted as a function of time in Figure 16. In addition, a simulation of the expected sky noise diurnal variation for a 2.0 m blade dipole operating over a lossy ground at 74.0 MHz is included. This simulation was generated by ARL using sky map data provided E. Polisensky (NRL) and NEC simulation of the blade dipole response. It should be noted that no fitting has been applied in this graph – that is, the plotted results are the absolute values directly from measurement or simulation. As can be seen, RX and SPA data agree well in both amplitude and trend over each of the measurement bands. The SPA data is noisier than the RX data since much fewer data samples were used to form SPA average power estimates than RX estimates. The offsets in amplitudes between the bands are simply due to the expected sky noise amplitude variation with frequency as noted in Figure 15. It should be noted that there is an approximately 300 K offset between the simulated and measured trend at 74 MHz. Further study will be necessary to determine the cause of this offset.

To better compare the time trends, the measured RX data at 73.4 MHz was scaled by a constant that best fit it to the simulated data. Measurements at other frequencies were adjusted by this constant and another constant corresponding to the difference in simulated antenna losses (mismatch and ground losses) between the frequencies. These results are shown in Figure 17. The scaled measurements all agree extremely well with one another. The trend of the fitted measurements agrees well with simulation, though there is a small unexplained shift in time between the two. It appears that there was increased noise due to interference between 17:00 and 20:00 LST as the measurements deviate somewhat from simulation during that time.

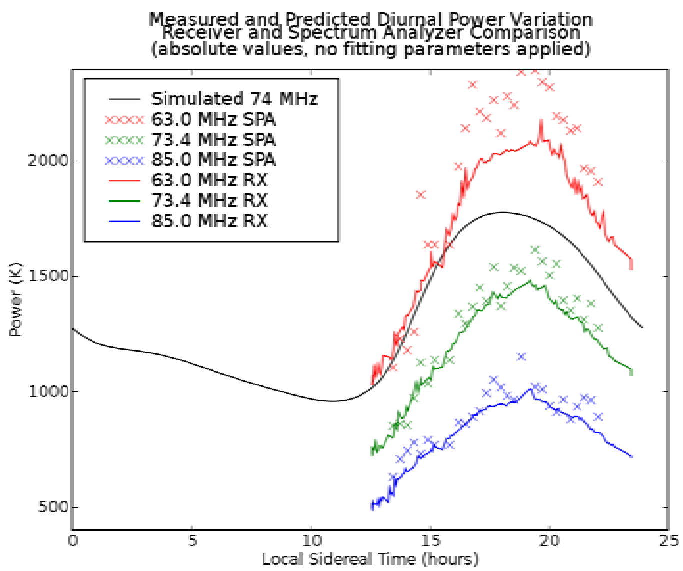

Figure 16. RX and SPA measurement and simulation of temporal variation of sky noise temperature at antenna terminals. All quantities are absolute measured or simulated values; no fitting was applied.

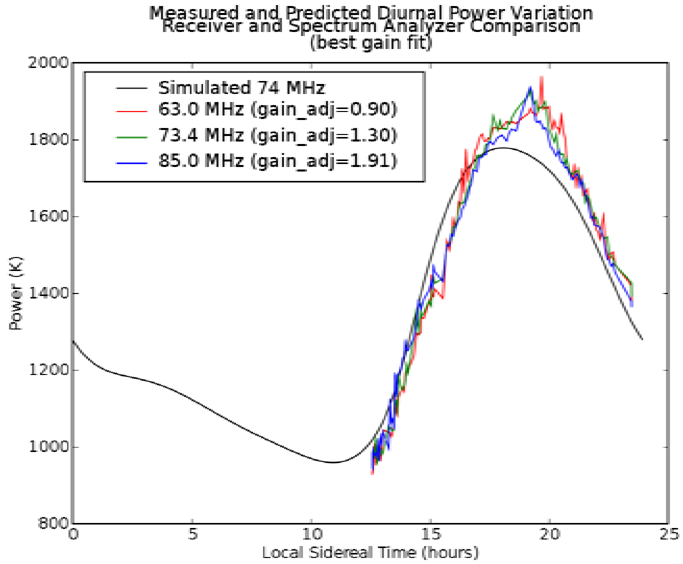

Figure 17. RX measurement and simulation of temporal variation of sky noise temperature at antenna terminals; data fitted to compare temporal trends.

Measured Sky Noise Stability

Extended length measurements were taken in each clean band in order to verify that the system stability was sky noise limited. However, it has been determined that reasonable stability can be attained only if rigorous filtering of transient interference is performed. We are still in the process of reviewing potential filtering methods, and therefore, we do not have a result for this data set at the current time.

Two Antenna Sky Noise Measurements Results

During this trip we also collected several sets of two-antenna data sets for later processing. In one data set, we left one antenna stationary at the western most edge of the collecting area, while the other was sequentially positioned along a roughly east-west line at 5m intervals from 5-65m. At each position, data was collected at three relatively RFI clean bands of centered at 63.0, 73.4, and 85.0 MHz. The other dataset consisted of positioning the second antenna 20m roughly west of the first antenna, and collecting data at 5 minute intervals over a 2.5 hour period.

At the conclusion of the measurements, a phase calibration measurement was taken by disconnecting the two antenna cables from the baluns, and connecting a noise source through a splitter to each cable.

The magnitude of the correlation for the 20m east-west baseline plotted against local sidereal time is given in Figure 18. This is an initial result supporting no definite conclusions. The remaining two antenna data will be processed at a later date.

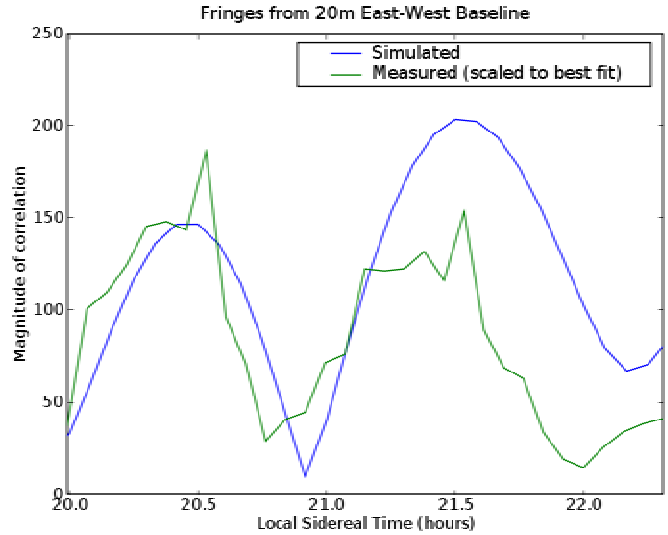

Figure 18. Magnitude of the correlation between two blade antennas spaced 20 m apart as a function of time.

Self-Induced RFI

While analyzing the data, we noticed the presence of a small broadband signal that was present intermittently with a period of 5 seconds. The anomalous T=5s signal is broadband, and appears as uniform white noise across the entire 1.6 Mhz collection band in bands centered at 63.0, 73.4, and 85.0 MHz. The relative magnitude suggests that the effective received signal intensity is approximately 200-300K. The magnitude and temporal characteristics of this signal are such that it would be undetectable through spectrum analyzer measurements alone.

Upon further investigation, the T=5s second signal appears to be related to hard disk activity in the notebook PC used to collect the data. The notebook PC was running a Linux 2.6 kernel, with the "dirty_writeback_centisecs" virtual memory parameter set to 500 centiseconds. The parameter causes the kernel to begin writing any modified ("dirty") data to disk once every 5 seconds. It would seem that the presence of the signal corresponds to the computer writing captured data to the harddisk.

Further insight came from analyzing data taken for the radiometric stability tests. During this particular test, one collection channel was disconnected from the antenna terminals and connected to a noise source, while the other collection channel remained connected to the antenna. The data shows that the anomalous signal was present in the channel connected to the antenna, but absent from the channel connected to the noise source. This suggests that the signal was introduced to the system through the antenna, rather than coupled locally. Figure 19 shows the data from the noise source, while Figure 20 shows the data from the antenna. These two datasets were taken simultaneously.

The detection of this signal emphasizes the importance of shielding any electronic equipment used near the LWDA, in particular, it should raise concerns about the use of notebook computers on-site. Fortunately the data supports the conclusion that this RFI is coupled through the antenna, and is not the result of any flaw in the LWDA components.

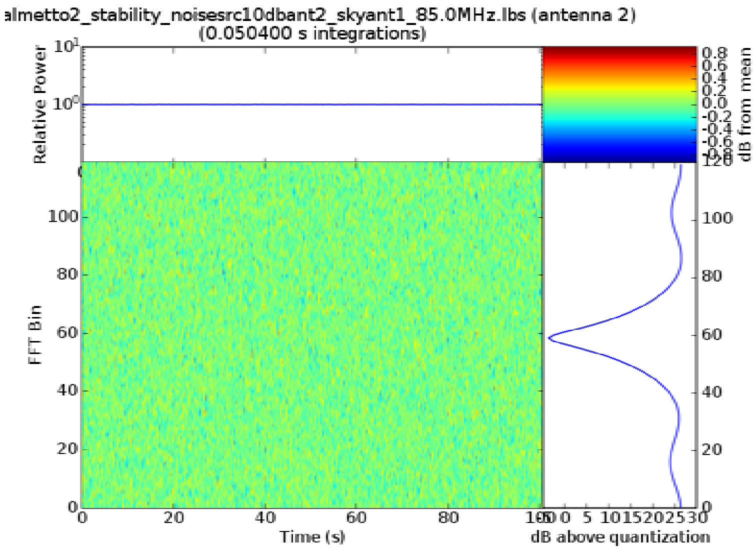

Figure 19. Spectrogram of data from receiver channel connected through receive chain to broadband noise source.

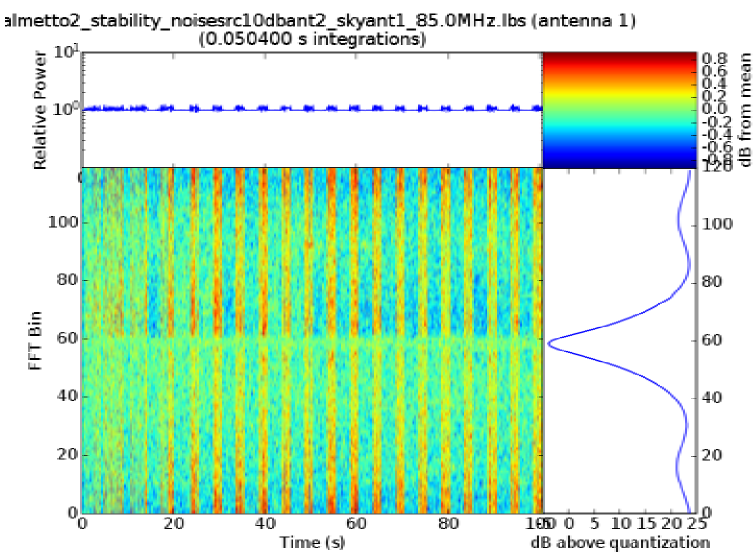

Figure 20. Spectrogram of data from receiver channel connected through receive chain to antenna.

Conclusions

Lab measurements performed on individual components in the LWDA receive chain largely agree with expectation. The lone exception was the noise temperature of the Hicks balun; two sets of measurements using a noise figure analyzer produced average balun temperature estimates between 60 to 80 MHz of 320 K and 283 K, which are significantly higher than the expected 250 K. R. Bradley has independently verified that the balun temperature is within 10 K of 250 K over this frequency range. Furthermore, a system noise estimate derived from LWDA receiver measurements of a calibrated broadband noise source connected to the full receive chain agrees very well with the expected value of the balun. Therefore it appears that the discrepancy noted in the NFA measurements are due to some problem with the test setup used in those measurements and not the balun. The measured system temperature of the full receive chain, however, is consistent the balun temperature measurements. Measurements of gain and linearity metrics of the full receive chain agree well with expected values. Extended receiver measurements using a broadband noise source indicate that the receive chain is radiometrically stable to the single minute time scale.

Sky noise measurements were conducted over a single night at Palmetto State Park using the full receive chain and two 2.0 m blade antennas. The spectra measured between 50 to 100 MHz by an LWDA receiver and a spectrum analyzer connected to a blade antenna through the receive chain agreed well with one another and with the expected galactic background noise spectra for that time of night (derived from Cane’s expression.) From these measurements, three bands relatively free from interference were found. Periodic total power measurements were taken in these bands by both the receiver and spectrum analyzer throughout a 11 hour period. The spectrum analyzer and receiver measurements over this period agree well. Both measurements closely follow the expected diurnal variation of galactic background. There is, however, an amplitude bias between the simulated and measured sky noise results. Some work will be required to understand the cuase of this bias.

Although measurements were taken with two antennas during the field test, we have not had much time to process these measurements together. An initial result was presented for the correlation between two antennas separated by a fixed baseline. The measurement appears to roughly agree with the simulated correlation trend with time. It was also demonstrated how interference due to the data collection laptop during these tests was coupled through the antenna into the measurements. This indicates that care must be taken to shield all electronics equipment used in astronomical measurements.

Based upon the results of this testing, we believe that all of the components of the receive chain, namely the antenna, balun, gain stages, receiver, and adder, are functioning properly both independently and together as a system. Furthermore, it was demonstrated that basic astronomical measurements can be made using the system. Therefore, we feel that the receive chain design is acceptable for use in the LWDA, and attention should now be focused on purchasing all remaining equipment in order to construct, test, and field a system at the VLA.

References

[1] J. York, A Kerkhoff, D. Munton, J. Copeland, Informal LWDA Notes from April 24, 2006.

[2] R. Bradley and C.R. Parashare, Evaluation of the NRL LWA Active Balun Prototype (Rev.A), 02/05. LWA Memo Series 19.