EVLA Memo 156: Gain Distribution and Frequency Response of the T304 Input Stage

K. Morris, February 2012

Abstract

The RF (8 – 12GHz) printed circuit board (PCB) in the T304 provides gain, total power detection, adjustable attenuation, and phase compensation for the higher-order bits of the adjustable attenuator. Frequency-dependent effects from this circuit board tend to dominate the frequency response of the module.

This analysis seeks to identify whether (and to what extent) the variation in gain and frequency response observed in the T304 module affects the science results, and if so, how many and which circuit boards in the T304 require replacement in order to bring the variation within acceptable limits. The gain difference between the two types of circuit boards is being addressed by removing 7dB of excess attenuation from the lower-gain boards.

1 Introduction

When the T304 first went into production, circuit boards were procured in three batches of 40 each. The vendor Circuit Design Specialties (CDS) won the original competitive bid in 2007, and built the first two batches. The third batch triggered another competitive bid process, which this time was awarded to Trilogy Circuits. Upon testing the Trilogy Circuits PCBs, it was observed that the overall gain of a T304 built with these boards was on average 7dB higher than modules built with CDS boards, and that the roll-off seen across the input band was reduced. At this point (2009), however, 2/3 of the project total of PCBs had been built by the previous vendor, and neither budget nor schedule allowed for replacing those to match the now superior Trilogy PCBs.

EVLA Memo 154 gives a complete treatment of the problem of bandpass roll-off and its effects on EVLA science, although that memo dealt exclusively with the observing effects seen in the 8-bit (1 – 2GHz) digitizer path. The difference in gain and frequency response between the two PCB types extends to the 3-bit (2 – 4GHz) digitizer path as well, but is largely corrected by output attenuator and the Gain Slope Equalizer. The gain difference is nevertheless apparent in the difference in attenuator settings. Memo 154 introduced the convention of dividing the 8-12 GHz input band into four 1GHz bands (8-bit) in order to trace the frequency-dependent effects from the input to the output of the module. The same convention will be used in this analysis, and extended for the 3-bit signal path by partitioning the T304 input into two 2GHz bands, for the purpose of analyzing the 3-bit signal path. Each division is referred to as an “IF Window”, and associated with the L302 synthesizer frequency that tunes that window to the anti-aliasing filter band. These windows are defined in Tables 1 (8-bit) and 2 (3-bit).

Table 1: IF windows for the 8-bit (1 - 2GHz) path

Window	Intermediate Frequency (IF) (GHz)	2nd LO (L302) frequency (GHz)
1	8 - 9	11.024
2	9 - 10	12.048
3	10 - 11	13.072
4	11 - 12	14.096

Table 2: IF windows for the 3-bit (2 - 4GHz) path

Window	Intermediate Frequency (IF) (GHz)	2nd LO (L302) frequency (GHz)
1	8 - 10	12.048
2	10 - 12	14.096

These represent the regions of the T304 input band as they are used in observing. Certain receiver bands can be associated with certain windows. For example, L-band nearly always uses an L302 frequency close to 14GHz, owing to the low-frequency tuning limit of the L301. This tuning arrangement places L-band spectrum in IF window 4. The Ka-band receivers, when used with the 8-bit samplers, are forced to use an L302 frequency close to 13GHz due to filters located after the 1st LO tripler in the receiver, placing the 1GHz region of the Ka-band spectrum in IF window 3. Wideband receivers that use the 3-bit samplers will have some portion of the receiver band covered by Window 2, and will tend to require lower equalizer settings and require lower attenuator settings in order to reach gain flatness and total power targets. The L302 tunings used in the Maintenance scripts for each band in 8-bit observing are shown in Table 3.

Table 3: Maintenance script sky and 2nd LO frequencies, by receiver band, for the 8-bit path

Receiver band	Sky frequency MHz (AC,BD)	L302 frequency MHz (AC,BD)	T304 IF Window (AC,BD)
L	1512, 1512	13720, 13720	4, 4
S	2636, 2764	12596, 12724	2, 2
C	6000, 6000	12560, 12816	3, 3
X	8332, 8460	10892, 11020	1, 1
U	15502, 15452	12402, 12452	2, 2
K	22460, 22972	12612, 12100	2, 2
A	34008, 34136	12712, 12584	3, 3
Q	43190, 43408	12746, 12528	3, 3

2 Gain survey of the T304 module

T304 attenuator settings for a given observation tend to vary from module to module, but also vary from receiver band to receiver band. An attempt to quantify the variation in RF board (input stage) gain resulted in a measure of IF power distribution whose mean value changed with changing receiver band. The range of adjustment of the T304 attenuators should compensate for some variation in receiver output level, and intermediate IF module level. To ensure adequate adjustment headroom, the T304 input (RF) attenuator, which can be varied from 0 to 31dB in 1dB steps, should be set at 8dB when the total power detector reads the target value.

The distribution of T304 gain, for each receiver band, is shown in Appendix A. The widths of the distribution are defined by several factors:

1. The distribution of gain among components in each module
2. The variation in output power level of each of the receivers.
3. The variation in gain between the two types of circuit board

This survey was performed on January 5 - 6, 2012, with three antennas out of service on Jan 5, and one antenna out of service on Jan 6. The results are therefore underestimates. Additionally, the results for S, X, and Ku bands are limited by the number of installed EVLA receivers: 19 S-band, 14 X-band, and 17 Ku-band. The purpose of the survey was to try to identify those T304 modules most in need of RF PCB replacement by identifying those modules that accounted for the low-end tails of the gain distributions, independent of receiver band.

The target value for the RF total power detector was traditionally defined as -20dBm for all receiver bands. This was recently revised in the case of L and S bands to -27dBm and -24dBm, respectively, to compensate for the narrower bandwidths of these receivers.

The method:

1. At each receiver band, set all T304s to the Total Power (TPD) target for that band
2. Record the attenuator value required to achieve that target
3. Compute these quantities:
    a. Gain = attenuator setting + total power measurement.
    b. Gain threshold = default attenuator setting + target total power value
    c. Gain deficit = measured gain - gain threshold

Table 4 lists the results of the survey. The “deficit” column is the amount, in dB, by which the mean gain across all available T304s differs from the ideal threshold value. This represents the degree to which the receiver or IF power varies from one receiver band to another. The “threshold gain” places the input attenuator at its default value when the TPD target is achieved. A tolerance of +/- 2dB should be allowed. C-band receivers are set too low by about 6dB.

Similarly, Ka-band could each be adjusted up in level by 4dB, thereby reducing the number of T304s that are set to lower than their default attenuator values. Receiver bands with differences smaller than 2dB do not require correction outside the T304. The mean gain and gain threshold for each receiver band are shown in Figure 1.

The “worst-case deficit” column in Table 4 is difference between the mean gain and the left peak of each of the distributions shown in Appendix A. It is the maximum amount by which the first mixer stage is underdriven in those modules.

Table 4: T304 RF total power target, gain, and threshold

Band	Gain threshold dB	Mean gain dB	Worst-case gain, dB	Mean deficit, dB	Worst-case deficit, dB
L	-19	-14	-24	+5	-10
S	-16	-18	-24	-2	-8
C	-12	-18	-28	-6	-10
X	-12	-16	-26	-4	-10
Ku	-12	-13	-26	-1	-13
K	-12	-12	-22	0	-10
Ka	-12	-14	-22	-2	-8
Q	-12	-10	-20	+2	-10

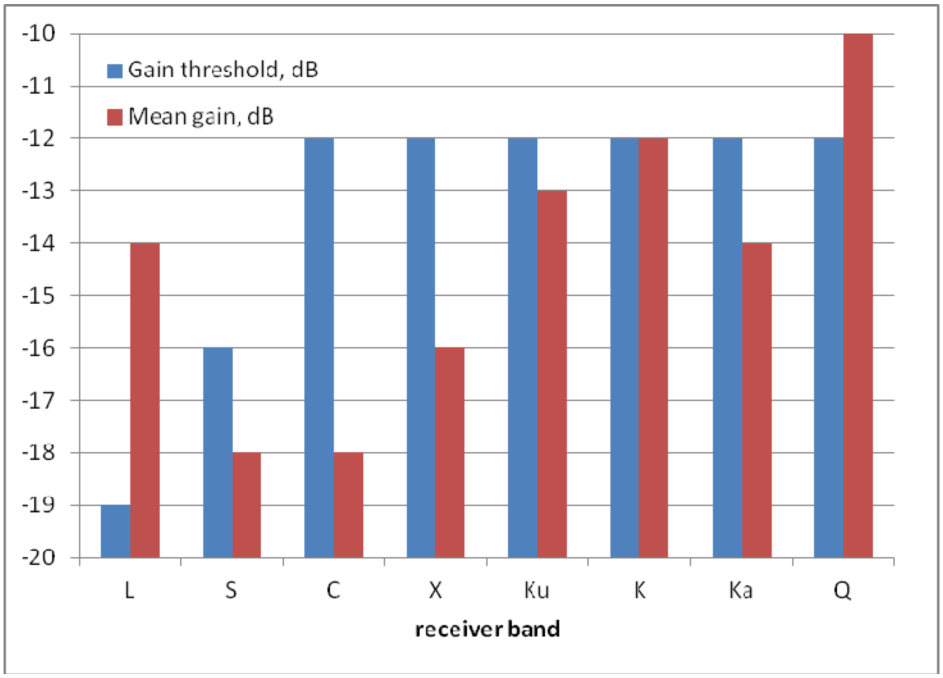


Figure 1: measured mean gain and calculated gain threshold of T304, by receiver band

3 Variation in response due to component tolerance

The individual electronic response of the components will cause even well-calibrated modules to exhibit variations in gain. Table 5 shows a list of RF board components and their min, max, and typical gains. Excluding the excess attenuation of the variable attenuator, which has a fixed minimum insertion loss that shows some tolerance, the PCB shows an expected total power gain of 9.6dB with a standard deviation of 2.1dB. The peak-to-peak variation, which would require all tolerances to align either high or low, and is extremely unlikely, is 12.2dB between minimum and maximum gain.

Table 5: Expected component gain and gain tolerance. A = fixed attenuator CPW = coplanar waveguide PD = power divider U = semiconductor device (amplifier, switch, or variable attenuator)

Part	Typical Gain, dB	Min Gain, dB	Max Gain, dB
U1	12.00	11	13
U3	12.00	11	13
U5	-4.25	-4.5	-4
U6	12.00	11	13
U7	-1.85	-2.1	-1.6
U9	-1.85	-2.1	-1.6
U10	-1.85	-2.1	-1.6
U11	-1.85	-2.1	-1.6
U15/19	12.00	11	13
PD1	-4.25	-4.5	-4
PD2	-4.25	-4.5	-4
A1	-1.00	-1	-1
A2	-1.00	-1	-1
A3	-1.00	-1	-1
A4	-1.00	-1	-1
A7/9	-2.00	-2	-2
A5/10	-10.00	-10	-10
PCB CPW	-0.79	-0.91	-0.66
PCB microstrip	-1.50	-1.7	-1.3
Total	**9.56**	**3.49**	**15.64**
Standard deviation, dB	**2.1**		
Peak-to-peak, dB	**12.2**		

4 Frequency-dependent loss & dependence on PCB type

From laboratory test data and on-antenna surveys of bandpass shapes, attenuator settings, and total power measurements, a trend has emerged in which the T304 modules that show the most loss at 8 – 12GHz are the same modules that show the most exaggerated roll-off across this band. These tend to be the CDS circuits boards, and as such, are candidates for replacement.

4.1 *Laboratory comparison of response by circuit board type*

Figure 2 shows the 1-2GHz output response of the T304, referred to the input band, for the four IF windows. Two modules' responses are shown for comparison: one (red trace) comprising entirely Trilogy PCBs, one (blue trace) entirely CDS PCBs. The total power has been normalized in order to enable comparison of the differential slopes for each IF window. This is reflected in the apparent increased noise floor for the CDS boards. The difference in the two noise floors, about 7dB, is the average difference in total gain, integrated across frequency, between the CDS and Trilogy boards. This gain difference is easily remedied through the removal of 7dB of excess attenuation from the CDS boards. The change in bandpass slope is a more troubling effect, and must be analyzed for its potential impact on science results. Figure 3 shows the differential bandpass response per IF window. In each case, the CDS board response is subtracted point-by-point from the Trilogy board response.

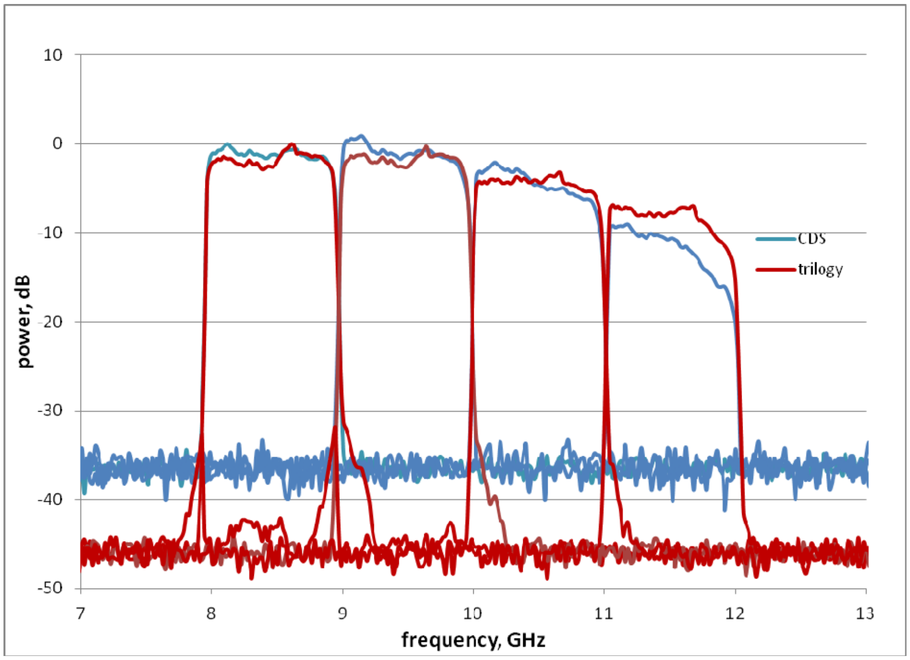


Figure 2: 1-2GHz output at four different LO tunings, by PCB vendor. The difference in the noise floor level (7dB) is the difference in gain between the two PCB types. Total power has been normalized for each tuning.

Figure 4 shows the absolute passband slopes for IF Window 4 -- window 4 shows the largest slope of any of the four IF windows.. Best fit lines were determined between 11.04GHz and 11.98GHz, thereby avoiding the anti-aliasing filter transition bands.

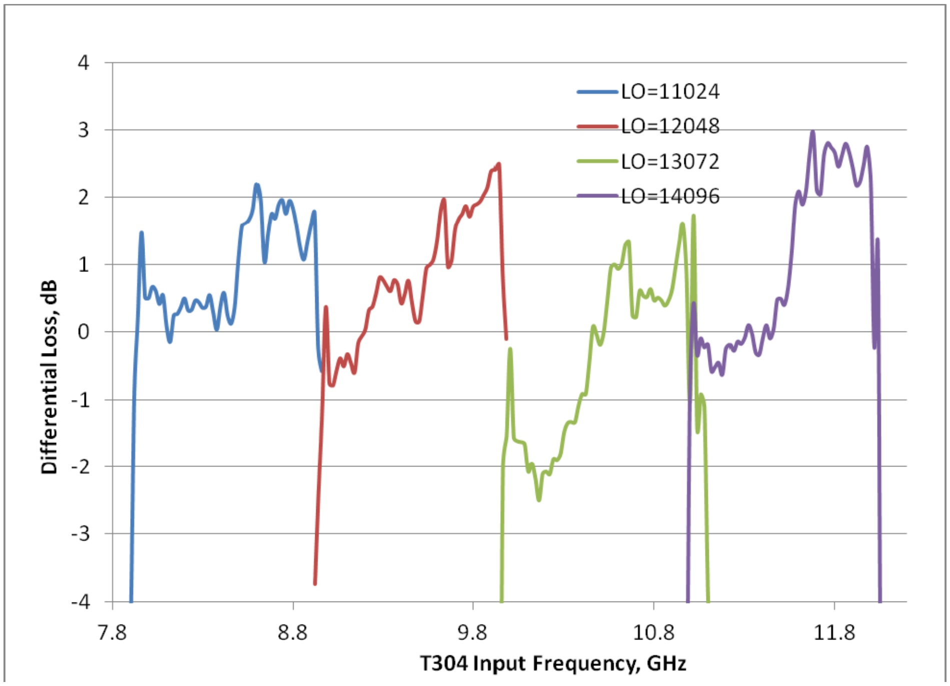


Figure 3: Differential bandpass response between Trilogy and CDS boards, 8-bit path.

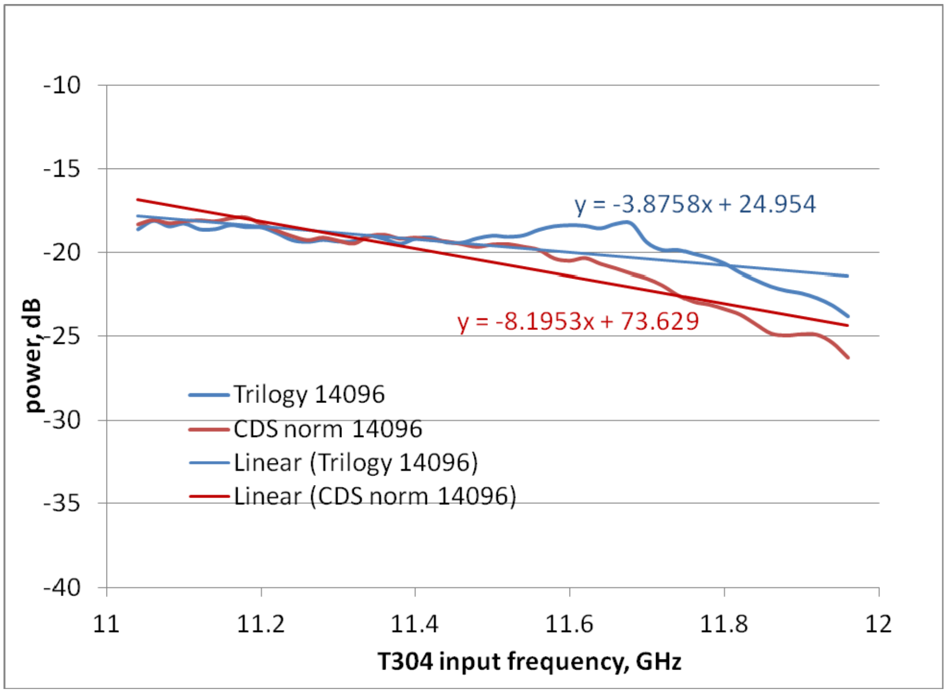


Figure 4: Passband slope of IF window 4 for the two circuit board types -- Trilogy in blue and CDS in red.

The CDS boards show an increased slope for any tuning of the L302, of between 2 and 4dB versus the Trilogy boards. For the worst-case 8-bit L302 tuning (IF window 4), CDS boards show a baseline spectral slope of 8dB, versus 4dB for the Trilogy boards. The worst-case 3-bit tuning results in a slope difference of 6dB between Trilogy and CDS boards, although this is removed by the gain slope equalizer. Equation 9 from EVLA Memo 83 predicts that the ratio of correlation coefficient from one end of the sloped passband to the other is

$$\frac{\rho_{\nu_h}}{\rho_{\nu_l}} = \frac{1+G-q(1-G)}{G[(1+G+q(1-G)]},$$

where G is the gain ratio between the two ends of the spectrum and q is a quantization factor based on the number of bits used in the representation of the signal. For b=3 bits, q = 0.96; for b = 8bits, q = 0.99. Given the worst-case slopes for the two boards, CDS boards will result in about 3% loss in signal-to-noise ratio (SNR) due to the sloped passband, while Trilogy boards will result in about 1% SNR loss.

4.2 On-antenna measurement of gain response across all modules

We can view the instantaneous spectra of the sampled data in the Deformatter. Figure 5shows spectra for all available antennas, for one sampled 8-bit IF (in this case, IF A) during a K-band observation. K-band uses T304 IF window 2, and is predicted to be relatively flat across the sampled passband.

This is confirmed by taking the standard deviation of the power across all antennas and plotting it versus frequency, as shown in Figure 6. The sharp rise at the right end of the plot is due to the shoulder effect as discussed in EVLA Memo 154. The response at the outer 20 – 50MHz of passband on both ends is dominated by filter cascade. Neglecting these two band-edge effects, the standard deviation of spectral response is fairly flat with frequency, about 1dB.

By contrast, Figure 7 shows a similar plot of spectra taken during a Ka-band observation. Ka-band uses IF window 3 (actually, intermediate to 3 and 4), and should show the most frequency dependence of gain variation. This is confirmed in the plot of standard deviation in Figure 8, where, again neglecting the band-edge effects, the standard deviation of spectral power rises from right to left (the spectral sense of the plot is inverted due to bandpass sampling in the digitizer).

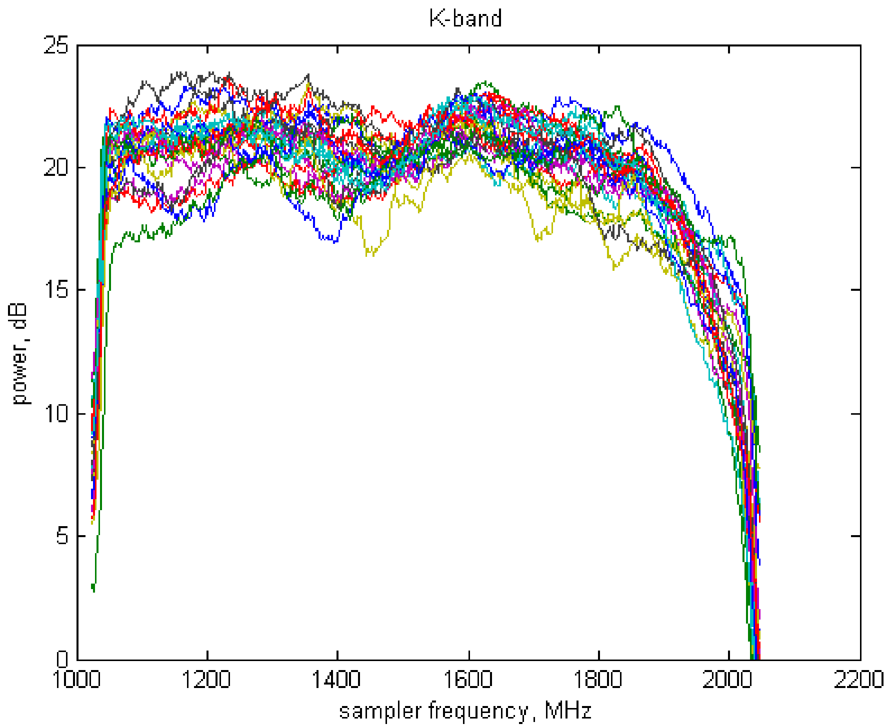


Figure 5: K-band spectra from deformatter. 2 averages, 512 spectral channels

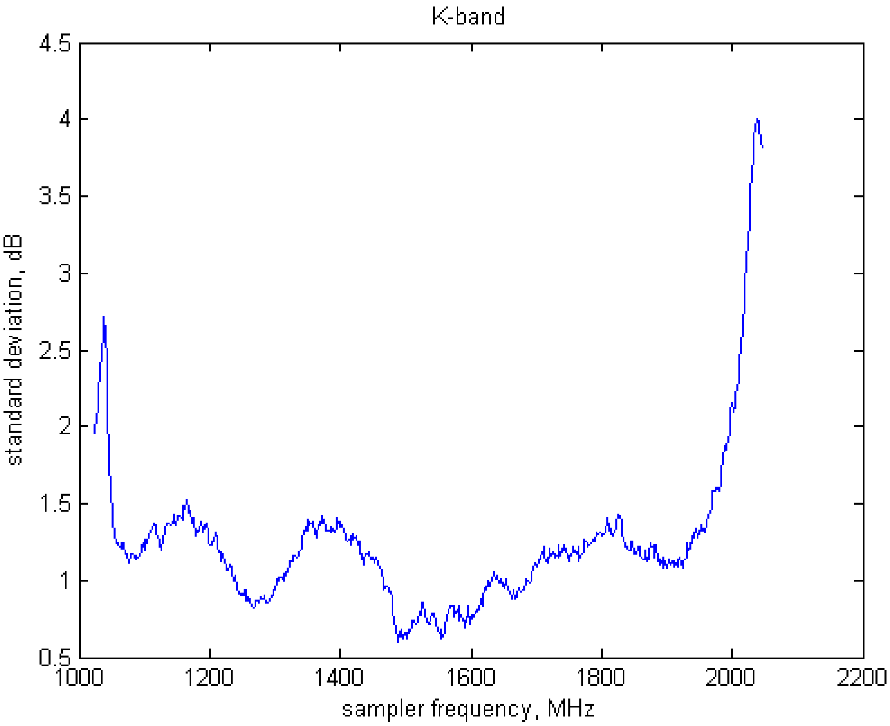


Figure 6: K-band spectral standard deviation.

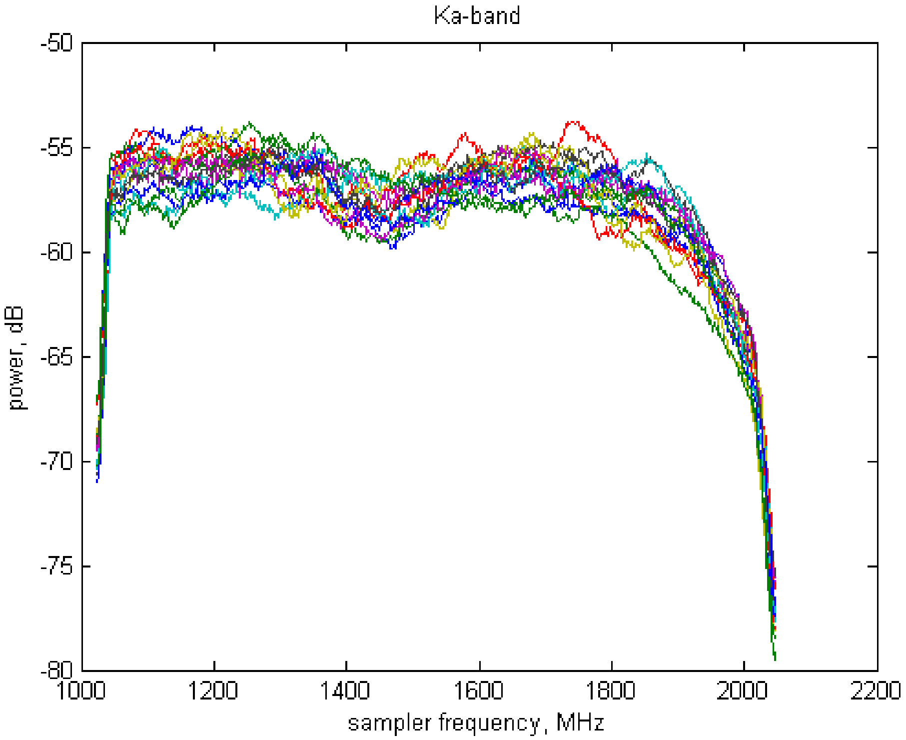


Figure 7: Ka-band spectra.

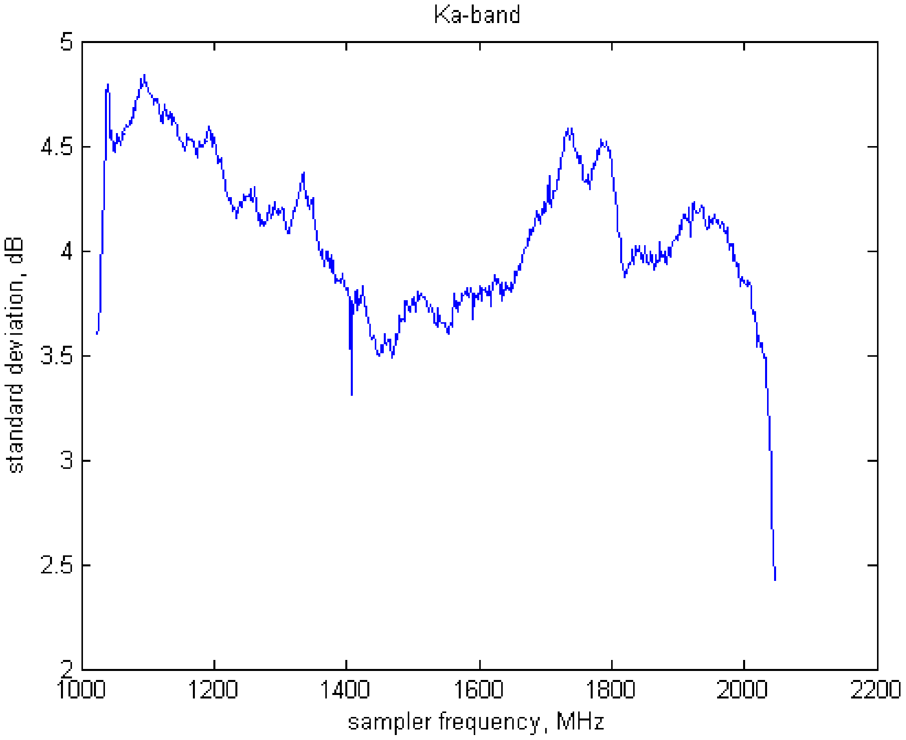


Figure 8: Ka-band spectral standard deviation.

4.3 Exception for 3-bit signal path

Unlike the 8-bit path, the 3-bit path allows slope equalization (see EVLA Memo 80: *A Gain Slope Correction Scheme for the EVLA Receiver System* by R. Hayward, M. Morgan and K. Saini). The gain slope equalizer adjusts the slope of the 2-4GHz passband in increments of 2.4dB +/- 0.5dB. There are 16 possible settings, 0 through 15, for a total of 36dB, +/- 4dB, of slope adjustment range.

Figure 9 shows the two IF windows for the 3-bit path, for each PCB type. In each case, the gain slope equalizer was set so that the passband was maximally flat (slope ~ 0dB). For the 1st IF window, both Trilogy and CDS boards required an equalizer setting of 10. For the 2nd IF window, the Trilogy board required a setting of 8, or 4dB increased slope, while the CDS board required a setting of 7, or 6dB increased slope.

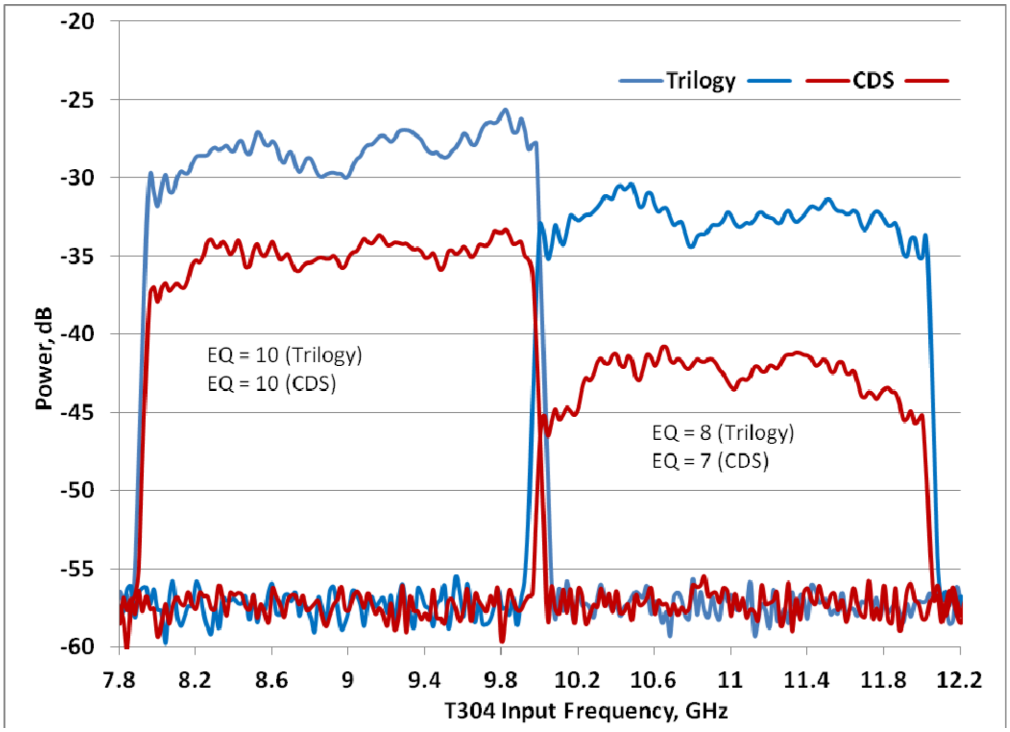


Figure 9:2-4GHz output for each of two IF windows, by PCB vendor. Each equalizer step represents approximately 2dB of slope across the 2GHz-wide band. A difference in EQ setting of 3 would therefore be a difference of slope of 6dB across 2GHz.

5 Physical differences between Trilogy and CDS boards

Chip Scott performed a visual inspection of circuit boards from the two PCB suppliers – Circuit Design Specialties and Trilogy Circuits. [Scott, September 2011]. The goal was to identify visually-qualitative indications that one PCB was different from the other. Chip Scott also recommends certain design practices for future PCB development at the design frequency of 8 – 12GHz. The phrase “good board” denotes the Trilogy Circuits board while “bad board” denotes the CDS board. The report can be divided into three sections:

1. Visible differences in construction between the two board types
2. Recommended further tests to perform, and
3. Design recommendations for future revisions.

Visible differences

These are the set of visible differences which could explain both increased loss in general and increased lowpass response in particular. Chip Scott summarizes the results:

1. RF Dielectric material is much whiter on the good board versus bad. Bad board appears slightly burned or etched.
2. Possible counterfeit material?
3. Via configuration significantly different in the two designs. Much denser and smaller on the good board (.007” good, .015” bad).
4. Larger vias appear to be tougher to solder to slugs on the back of the RF IC packages. Fewer appear to be soldered.
5. Via construction on the bad board is poor. Raised rings around the periphery of the vias are unexplainable.

Regarding the use of counterfeit high-frequency board laminate, I have requested that Rogers Corporation, the manufacturer of the raw laminate material, perform an analysis of the two circuit board substrates to determine whether the material is the same and, if not, what the differences are. As of this writing, no representative of Rogers Corporation has returned my request for analysis.

Figures 11 and 12 show the placement of board vias in the coplanar waveguide sections of the board. Figure 11 is the CAD design artwork from which both boards were nominally fabricated. The sparsity of vias in the CDS board (Figure 12, top) compared to the Trilogy board (Figure 12, bottom) and the design file, could account for both increased loss overall and increased lowpass frequency response observed in the CDS boards. This cannot be remedied without refabricating.

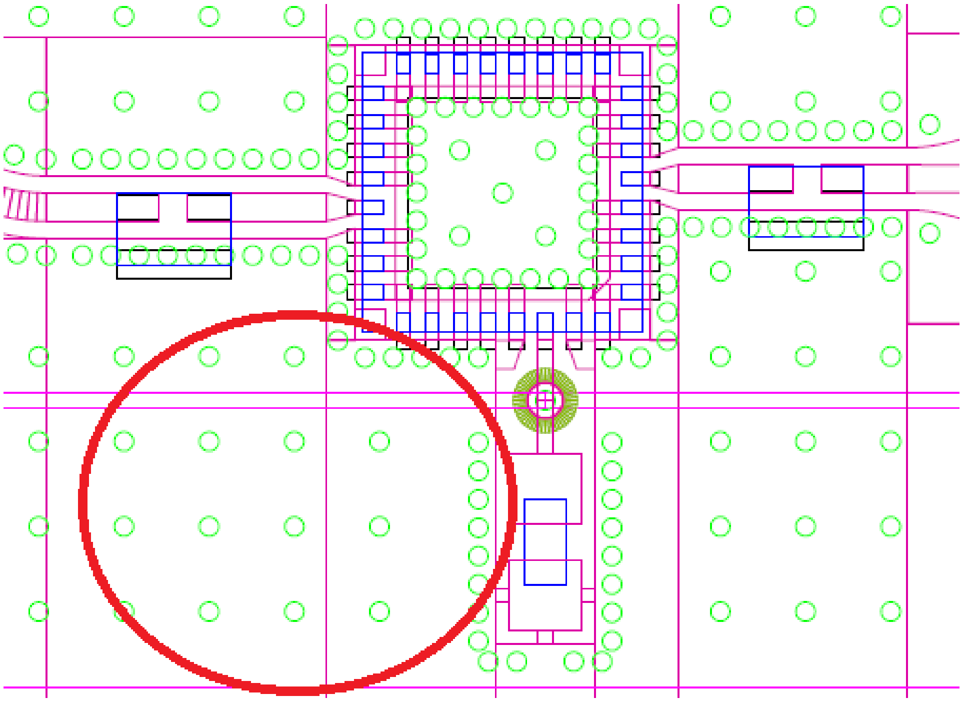


Figure 11: CAD drawing of circuit board fabrication file. Note the region in the red oval. The via density and placement of the Trilogy board matches the design drawing, while those of the CDS board do not.

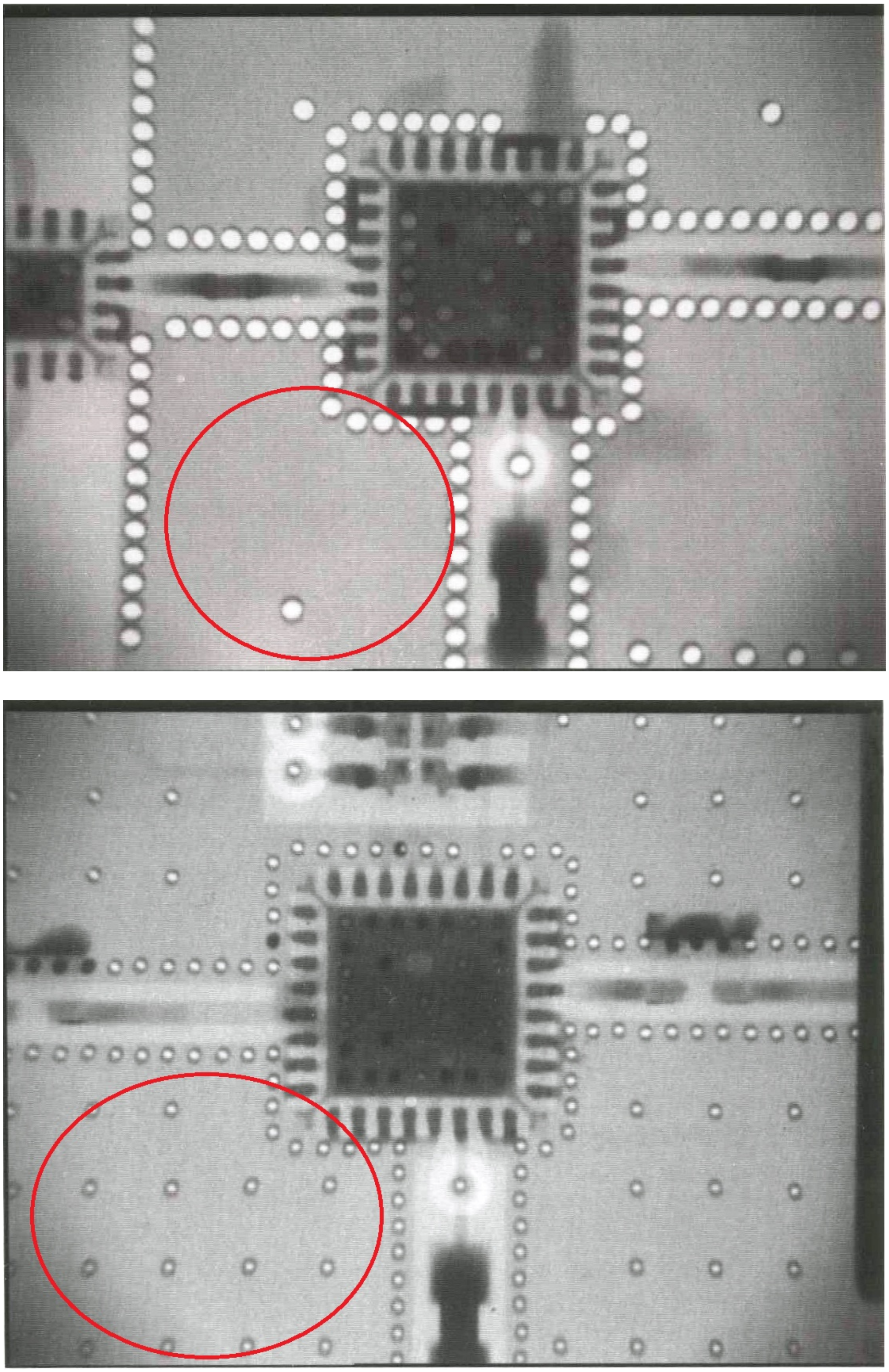


Figure 5: X-ray images of the two types of circuits board -- CDS (top) and Trilogy (bottom). Note the density of the board vias (white circles) in the region in the red oval.

Recommended test: Probe Test

Continuous wave (CW) tones were measured with a coaxial probe at two different input frequencies – 9.344GHz and 11.904GHz, with a tone power of -33.8dBm, along the signal path of the RF board. The RF attenuator was set to 5dB for all tests. The input signal source power varied by +/- 0.1dB between the two frequencies. The results of the gain probe test are shown in Figure 13. The measured gain at each point in the signal path tracks within a couple dB the theoretical gain for that stage, though there is no clear "culprit" – the loss of gain with frequency appears to be distributed throughout the circuit, rather than concentrated in one or more particular components.

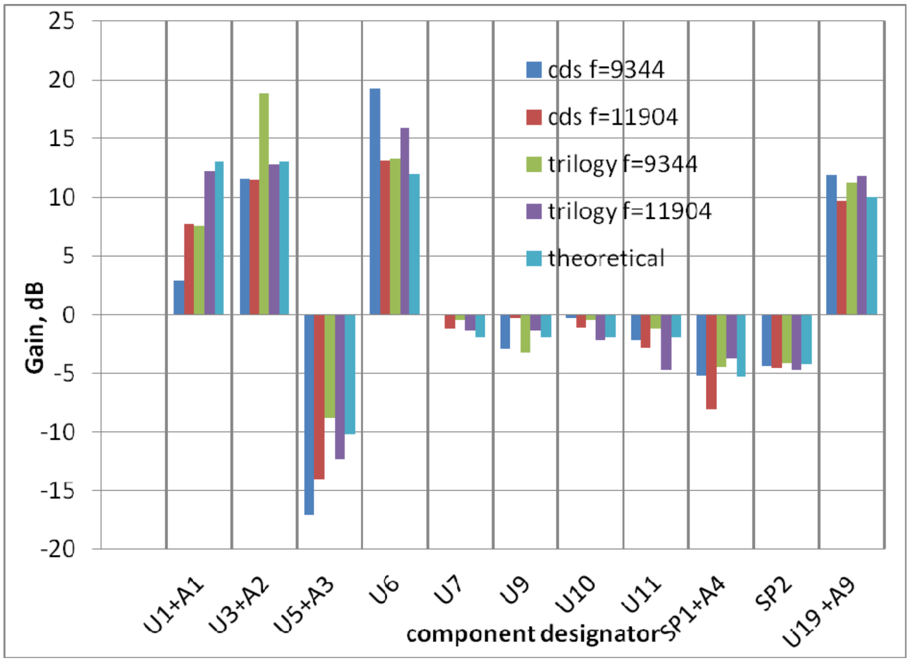


Figure 6: Gain of RF board, at major gain stages, measured with coaxial probe and spectrum analyzer. Theoretical gain is shown in cyan for comparison.

Future design recommendations

There is presently no plan or mandate to redesign the RF board. These recommendations should be considered if a future plan calls for redesign of the circuit board.

1. Future reference: for 1 dB pad use a single series 6 ohm resistor (the shunt resistor is so large as to appear as an open circuit). The return loss is better than 20 dB.

2. The attenuators work better upside down (according to the data sheet).

3. X-rays show incomplete soldering of backside metal slug of the ICs for both boards.

4. The DC blocks (100pF) appear to be different between the two designs. Since there are something like nine in the path they are a potential suspect.

6 Conclusions

The gross gain difference between the two types of circuit boards is being minimized in the laboratory during the retrofit process. The mean gain difference of 7dB between the two board types is being addressed by removing 7dB of excess attenuation from the modules with CDS boards. This still leaves the excess lowpass gain roll-off as a system issue.

The instrumental sensitivity loss due to passband slope is approximately 3% for the CDS boards and 1% for the Trilogy boards. Replacing CDS boards with new Trilogy boards may result in a slight improvement in sensitivity in the 3rd and 4th IF windows of the signal path during 8-bit observations.

There are 5 to 10 T304 modules which, even with 0dB of attenuation at the input, fail to meet the total power targets. In each case, however, the output attenuator has the necessary adjustment range to provide adequate power to the digitizers. Additionally, there are 25 – 30 T304 modules that cannot meet the “gain threshold” as defined in Section 2. Again, the output stage of each of these T304s still has sufficient adjustment range to ensure that the digitizers are properly driven. However, these 30 to 40 modules are underdriving the first mixer stage by as much as 13dB. These modules must compensate for the reduced power at the output stage, and in doing so, contribute excess self-noise to the digitized signal, compared to a properly performing T304.

7 Acknowledgements

Chip Scott lent his expertise to the comparison of the two circuit board types and provided some great engineering assistance. Ken Sowinski provided essential access to and operation of the array. Donna Field is the go-to person for all details of T304 operation.

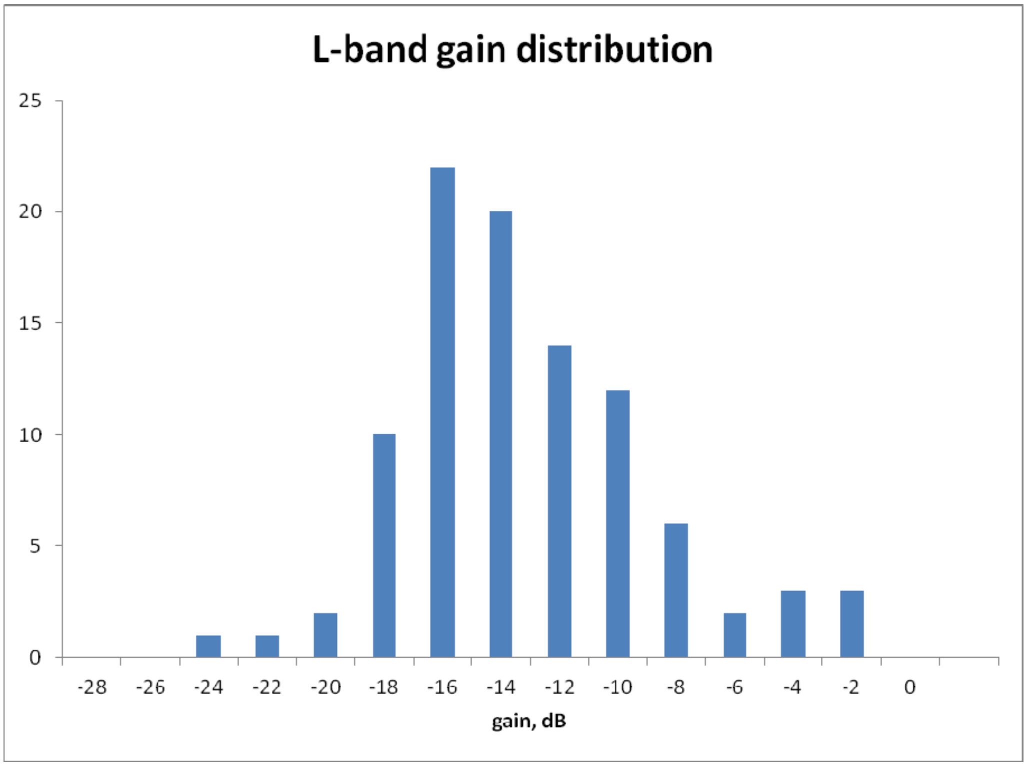
8 References

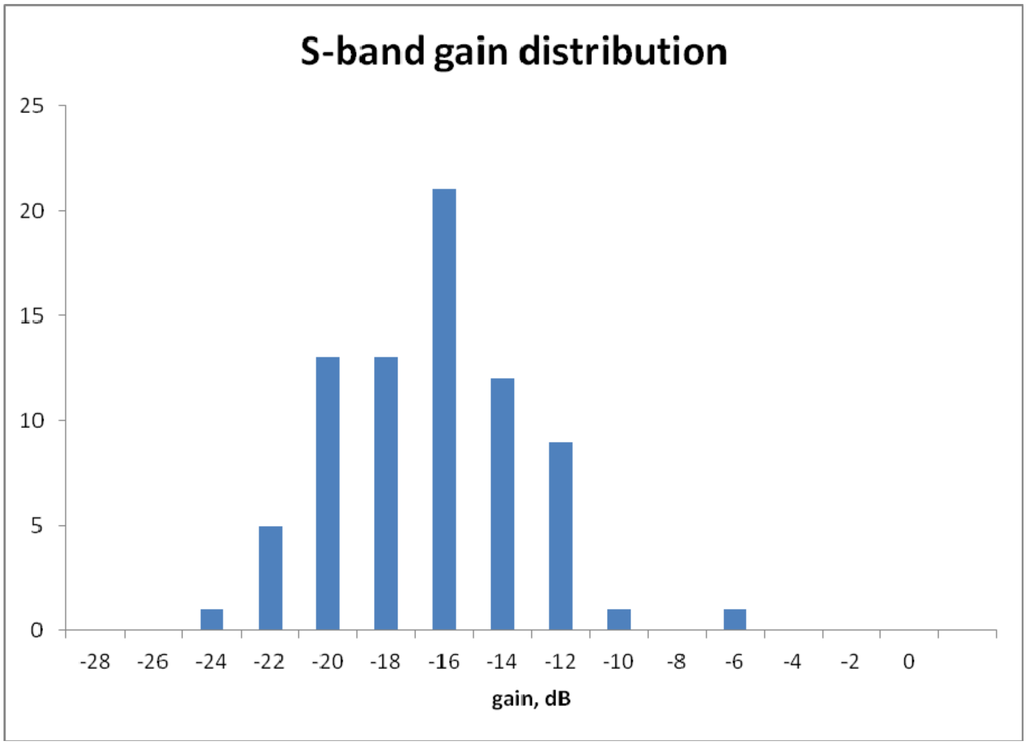
EVLA Memo 80: A Gain Slope Correction Scheme for the EVLA Receiver System R. Hayward, M. Morgan and K. Saini, 07/13/2004

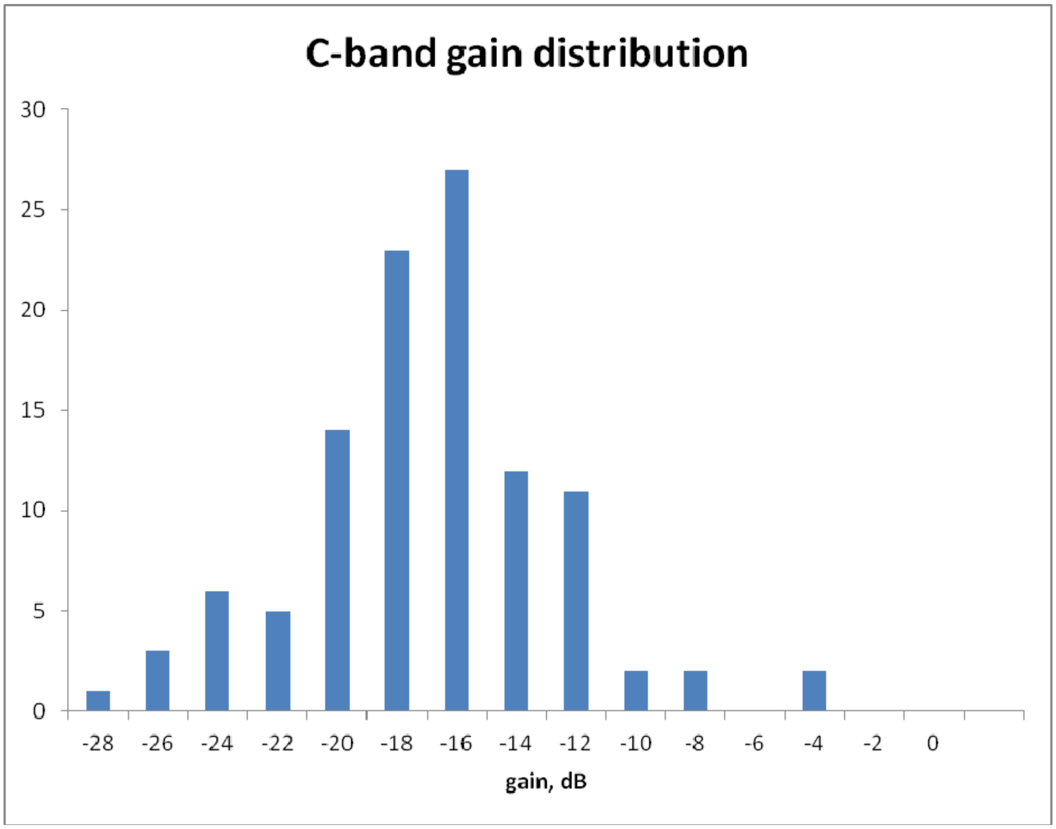
EVLA Memo 83: Quantization Loss for a Sloped Passband, Brent Carlson and Rick Perley, 2004

EVLA Memo 154: Characterization of the EVLA 1-2 GHz Intermediate Frequency Passband Keith Morris and Emmanuel Momjian (NRAO), 10/12/2011

Appendix A: T304 Gain distribution by receiver band






C-band gain distribution
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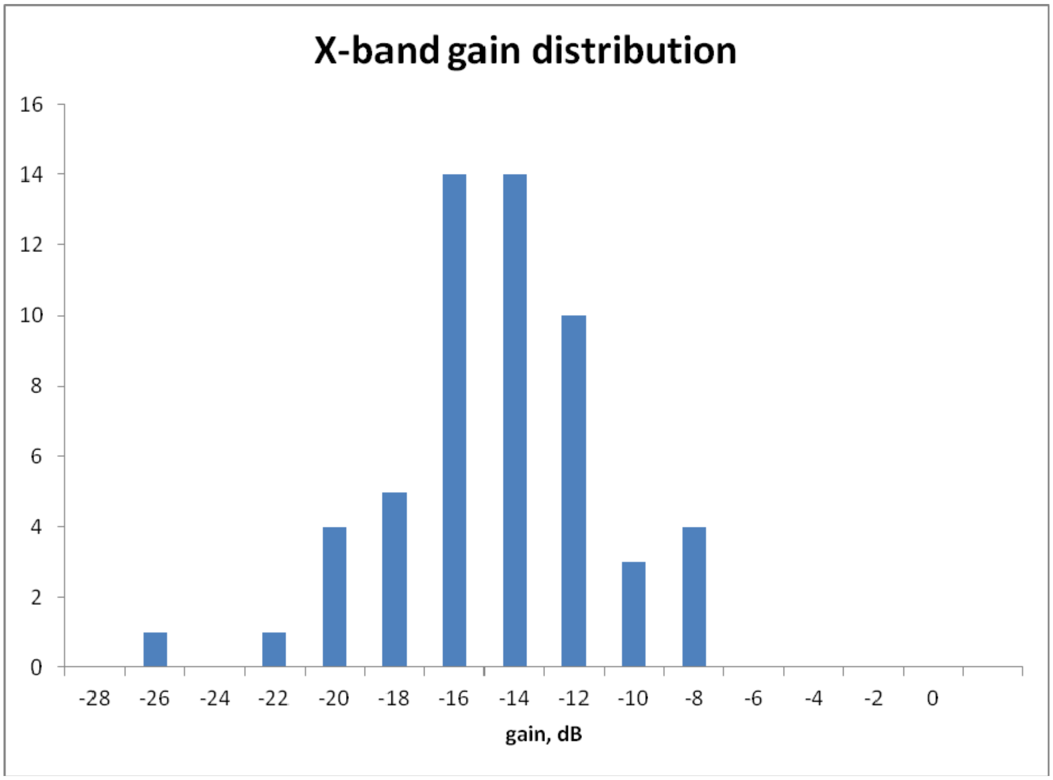
X-band gain distribution
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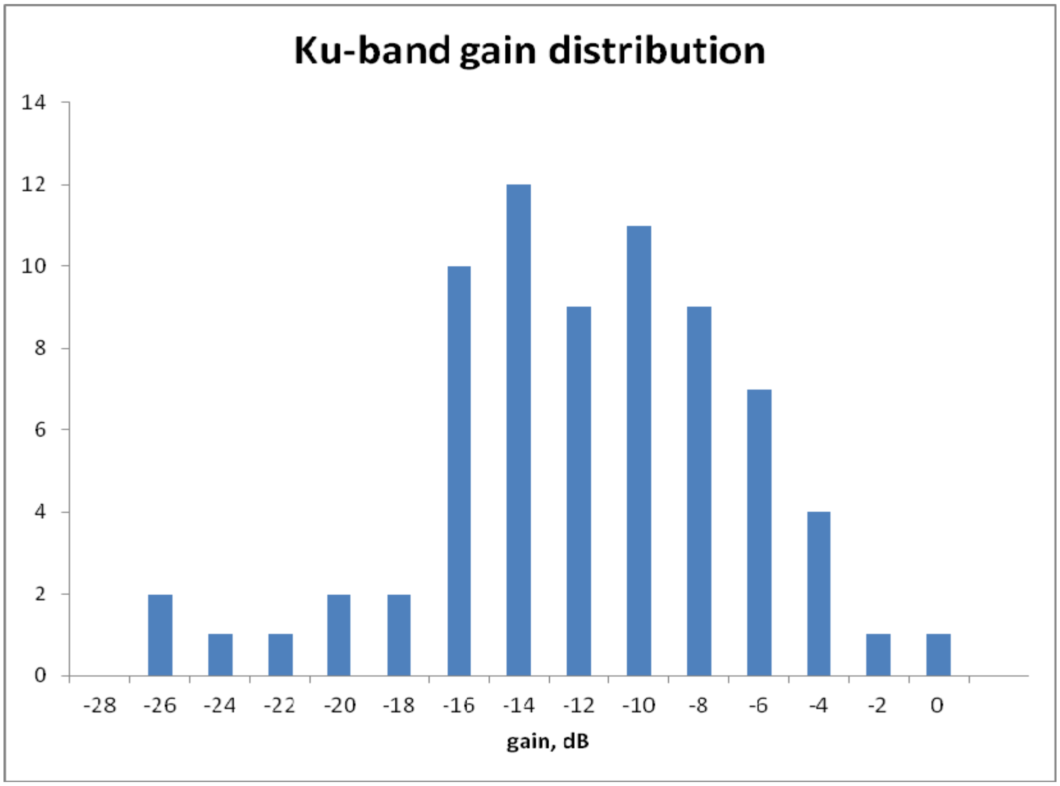
Ku-band gain distribution
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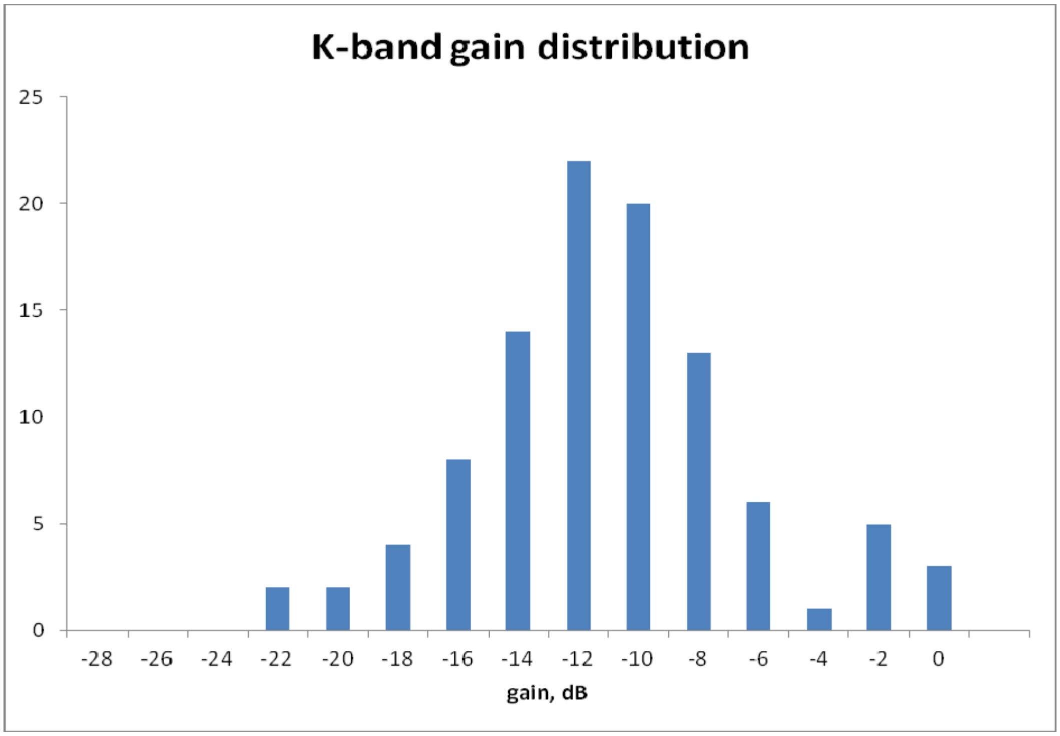
K-band gain distribution
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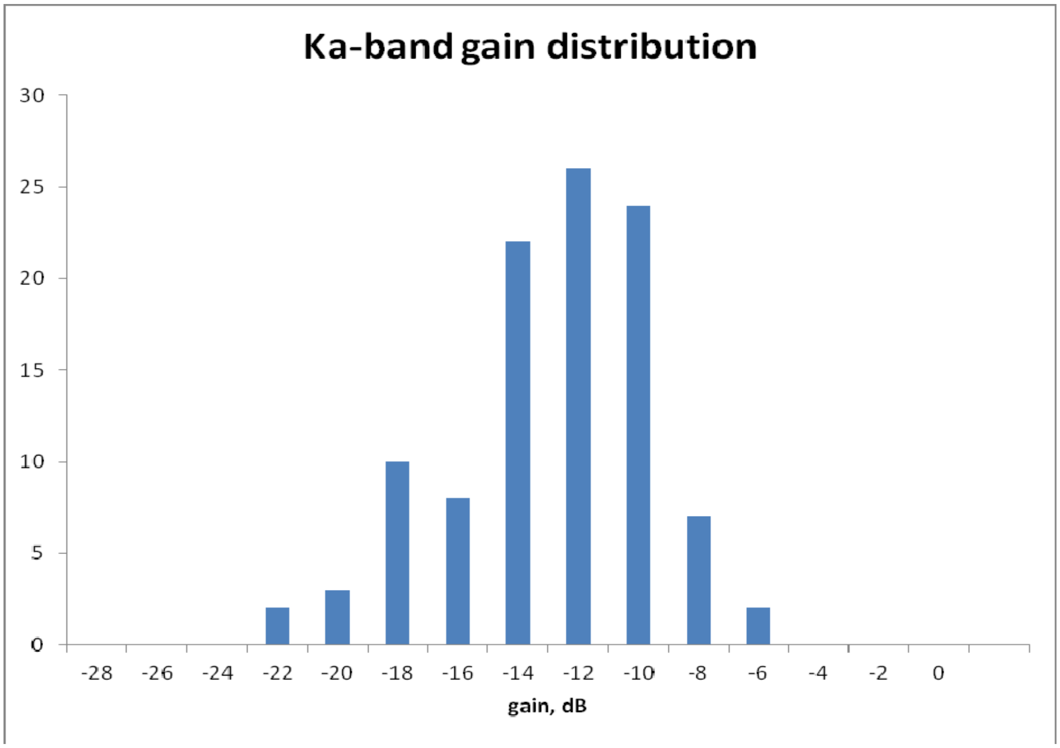
Ka-band gain distribution
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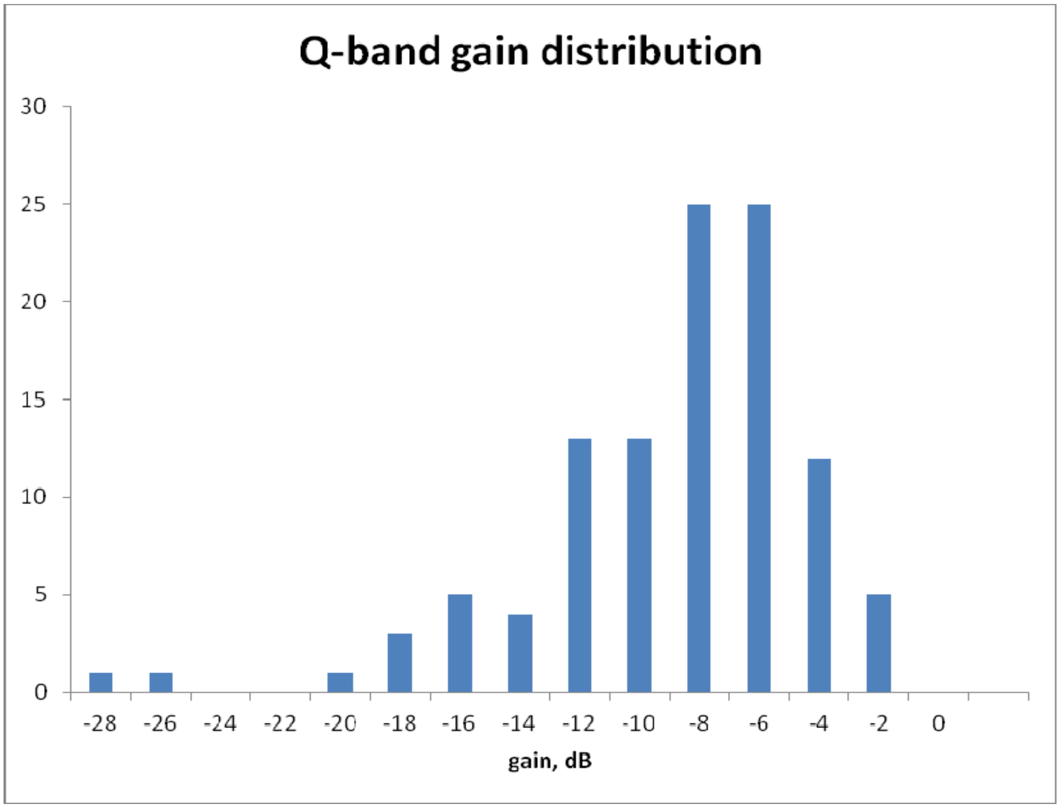
gain, dB


Q-band gain distribution
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-10
-8
-6
-4
-2
0
gain, dB