EVLA Memo #185
Bandwidth- and Frequency-Dependent Effects in the T304 Total Power Detector

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1 Introduction

The EVLA Intermediate Frequency (IF) system employs a system of power detectors and remotely-programmable attenuators to normalize power levels within the converter modules and at the input to the digitizers. The T304 Baseband Converter has two such detector/attenuator circuits – one just before the 1st LO mixer stage, at 8-12GHz, and one at each output of the module. Each circuit is controlled by an Automatic Level-Setting (ALC) loop in the MIB. A command from the executor initiates the ALC loop:

1. The Executor commands the desired total power target
2. The MIB finds the difference between the present power and the target
3. The MIB commands the attenuator to change by this amount
4. The MIB steps the attenuator in 1dB steps until the power is within +/-1dB of the target

The attenuator and power level before the mixer are set and stabilized first, in order to set the proper dynamic range headroom and noise floor for frequency conversion, then the attenuator and power level at the converter output are set, in order to set optimal levels for the digitizers. Each attenuator can be set in 1dB steps over a range of 0 to 31dB.

Error enters into this process through numerous sources. The detectors that are used to measure the power at the 8-12GHz stage are operating slightly above their design frequency limits, and as a result show significant frequency dependence in their response. There is some gain variation between the input of the T304 and the detector and mixer. There is variation in the output power levels of the receivers themselves, and variation in IF path gain between the receivers and the T304s. The power targets are a function of both bandwidth and frequency. This memo seeks to examine and characterize these sources of error.

2 Gain Variation from the Receiver Output through the IF Path

Direct measurements of receiver output levels and IF path signal levels are impractical, and a complete suite of measurements would be prohibitively time-consuming. However, the same metric that was used in the lab tests, namely the T304 gain, can be used to measure power variation in the antenna, although this method cannot be used to localize the gain variation – all sources of variation appear in the final measurement. However, the laboratory data constrain the amount of variation in the T304 itself; the remainder is due to (a) differing receiver output levels, (b) differing gain through the IF signal paths, or (more likely) both.

All eight receiver bands were included in this study. Given the bandwidth and frequency-dependence effects discussed here, and the possibility of transient RFI, it is not safe to draw conclusions from the gain variation method at the lower-frequency, narrowband receivers. Among the five high-frequency (X, Ku, K, Ka, and Q) receivers, there are three possible paths from receiver to downconverter, and each of these can introduce gain variation:

a. Directly from receiver to downconverter, X-band
b. Through the UX converter “direct path”, regions of K, Ka, and Q band
c. Through the UX converter “converted path”, Ku, and regions of K, Ka, and Q bands

The distributions of corrected total power results from an hour (or more) long observation at each of the eight receiver bands are shown in Appendix A. The statistics of the distributions of attenuator setting, total power, and gain are summarized in Table 1. The T304 values are measured with an X-band (8 – 12GHz) white noise source at -39dBm.

Table 1: T304 "corrected total power" measure by receiver band, and of the T304 with wideband noise input

	Attenuator dB		**Total power dBm**		**Corrected Power dB**	
	Mean	stdev	Mean	stdev	Mean	stdev
L	6	5	-21	2	-15	6
S	4	4	-22	2	-18	4
C	0	1	-24	3	-24	3
X	3	2	-21	2	-18	3
U	12	5	-19	2	-7	6
K	9	4	-21	1	-12	4
A	5	3	-21	1	-16	3
Q	5	5	-20	2	-15	5
T304	3.5	0.5	-20	0.5	-16.5	0.5

Ideally the LSC and UX converters would have unity conversion gain, adjusted for the ratio between the input and output bandwidth. In practice, however, the conversion gain varies among receiver bands, and by frequency within a receiver’s output. Power detectors in the LSC and UX converters can track this variation; the detectors are loosely calibrated and as such do not provide reliable measures of absolute power, but these tend to be offset errors and not scale errors. Relative power measurements are reliable to around 0.5dB. The RF attenuator in the T304 must correct for this variation to ensure linearity between its input and the digitizers.

3 Variation of Corrected Total Power in the T304

In the laboratory, each T304 module can be characterized with respect to its corrected total power – the response of the attenuator and power detector to a wideband noise input of a known power level. This quantity, the sum of the attenuator value and the detected power, is a useful indicator of gain variation. However, there are bandwidth- and frequency-dependent effects that occur between the power detector and the mixer, and these effects require examination. But first it is informative to see the response of the fleet of T304 modules to a full-bandwidth noise signal. However, the phrase “corrected total power” is somewhat cumbersome, so the phrase “T304 gain” will be used in its place, where convenient. These two phrases refer to the same quantity.

3.1 Laboratory-measured gain

Each module is presented with a wideband, 8-12GHz noise signal at its input, at a known power level, in this case -39dBm. The module is commanded to perform the ALC routine, and the resulting attenuator setting and detected power level are recorded. The ALC routine in the MIB terminates when the detected power is within +/- 1dB of the commanded target. Of the 94 modules included in this sample, the power is within this target window in all cases. Figure XX shows the distribution of total power measurements.

Each module is expected to show some gain variation, based largely on manufacturing tolerances within the active components in the module. As a result, we expect to see some spread in the attenuator values that result in the measured power. Figure 1 shows the distribution of corrected total power for all T304 modules, from laboratory measurements. The values below -18dB are due to modules that are scheduled for retrofit; these modules still have old RF circuit boards that do not meet gain specification. Of the remaining modules, all show remarkably consistent and repeatable gain. Therefore the variation in IF path gain seen in the array, across receiver bands, must be due to variation in (a) receiver output levels and (b) intermediate conversion gain in the LSC and UX converter modules.

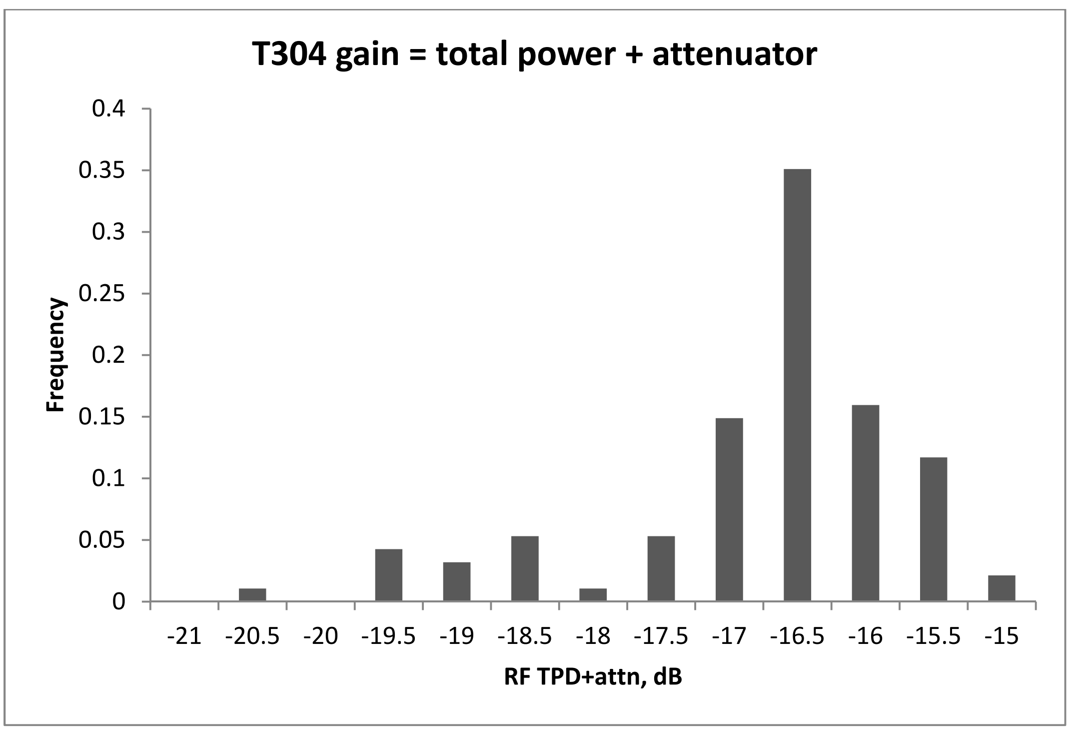


Figure 1: Distribution of T304 gain from laboratory tests.

Excluding the known low-gain modules, we find a mean gain of -16.6dB with a standard deviation of 0.54dB. The remaining modules will be retrofitted within the next few months. For a constant-power, full-bandwidth signal, we can place limits on the variation that we would expect to see when these modules are installed in the antennas.

3.2 Bandwidth- and frequency-dependent gain variation

For those receivers whose total bandwidth is significantly less than the bandwidth of the power detector (specifically P, L, and S), we expect to see a difference in response that depends upon bandwidth, $10\log_{10}(BW_{rcvr}/BW_{detector},)$ and a frequency-dependent response that must be measured in the lab. In addition, the power difference between the signal measured at the detector and the signal incident upon the mixer varies both with bandwidth and frequency.

To test the frequency dependence, we filter a wideband noise source at C-band, 4 – 8GHz, with one of two filters -- 800MHz centered on 4.75GHz, to simulate the L-band noise power density, or 2.3GHz centered on 5500MHz, to simulate the S-band noise power density. This signal is upconverted through the LSC converter and fed to the input of the T304. The center frequency of the upconverted narrowband noise signals can be varied from 8.5 to 11.5GHz, allowing full characterization of the response of both the circuit gain and the detector for signals with bandwidth less than the full input bandwidth of the module or the detector.

The T304 1dB gain compression point has been determined from wideband noise measurements, and from this the 1% compression point can be derived. The total power target is based on this value, the 1% compression point, and an assumption about the offset between the detected power and the power at the mixer. The compression point of the T304 is known to vary with the RF attenuator setting. The attenuator allows for linear operation in the stages following it in the signal path, but some compression occurs in the amplifier stage immediately preceding the variable attenuator.

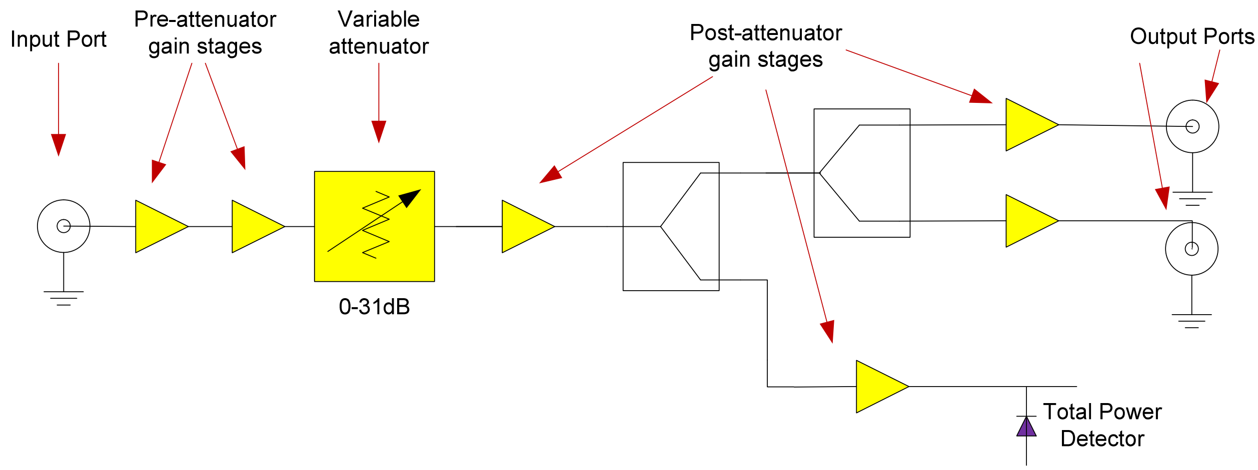


Figure 2: Simplified schematic diagram of the T304 input section.

The RF attenuator in the T304 is set so that the total power detector reads -20dBm for all bands except P, L, and S (these have bandwidth-correction factors which will be treated separately). This target assumes full occupancy of the input bandwidth of the T304. To the extent that the noise signal from the receiver is narrower than the input bandpass filter of the T304, or that the receiver signal is not centered on the T304 input passband, some additional correction to the power target may be required.

Figure 2 shows a simplified schematic diagram of the input section of the T304. There are two gain stages in the signal path before the adjustable attenuator, and two more gain stages afterwards. Laboratory results show that the compression point varies with the setting of the adjustable attenuator, indicating that some compression takes place in the amplifiers before the attenuator, and some in the amplifiers that come after. The gain is arranged such that the power at the Total Power Detector (TPD) is a copy of the power at the output connectors leading to the 1^{st} conversion mixer.

4 Frequency Response of the Total Power Detector

The total power detector has a unique frequency response that is not reflected in the output ports. A power meter placed at the output port will not necessarily read the same value as the TPD for a given input signal. In general, this arises from the fact that the particular detector chip is being used beyond its rated frequency range. Much of this effect is accounted for in the device characterization and calibration that accompanies each T304 module, and the results tend to be quite accurate – within 0.5dB of the true value -- but only over a limited range of power (nominal power target +/- 10dB) and only for wideband noise. For the narrowband signals, L and S, the results are quite different.

Figure 3 shows the TPD error, or the difference between the total power detector and a power meter placed at the output port, versus the total power reading for a narrow-band signal measured at the T304 TPD for five values of LO tunings. The red box indicates the portion of bandwidth that is used at the standard L301 frequency of 12672MHz. For the full-bandwidth signal, the error is low, around 0.5dB. This error increases with frequency, particularly in the vicinity of the L-band total power target. Results are shown for one particular T302/T304 combination.

The difference between the full-bandwidth measurement and the narrowband measurements includes both the bandwidth-occupation factor and the frequency-dependent factor. For S-band, the L301 tuning of 12928MHz places the receiver output squarely in the center of the T304 input band, where the detector measurement is the most "accurate" (compared to a power meter).

Figure 4 shows a different view of the data from Figure 3, namely the TPD measurement referenced to the input power (rather than the output power). This is the relation that will inform level-setting at the input the module, which could be different for each receiver band. Additionally, the gain compression data can be referenced to the TPD, which can be referenced to the input level. This gives us an informed basis for choosing at input power level, based on the bandwidth of the signal and its location within the 8-12GHz input passband. For the X-band case, the error near the total power target is less than 1dB. This error increases significantly for narrow-band signals as the L301 frequency is increased. For the default L-band L301 tuning of 12672MHz, the target is achieved when the power in the converted L-band signal at the input to the T304 is -33dBm.

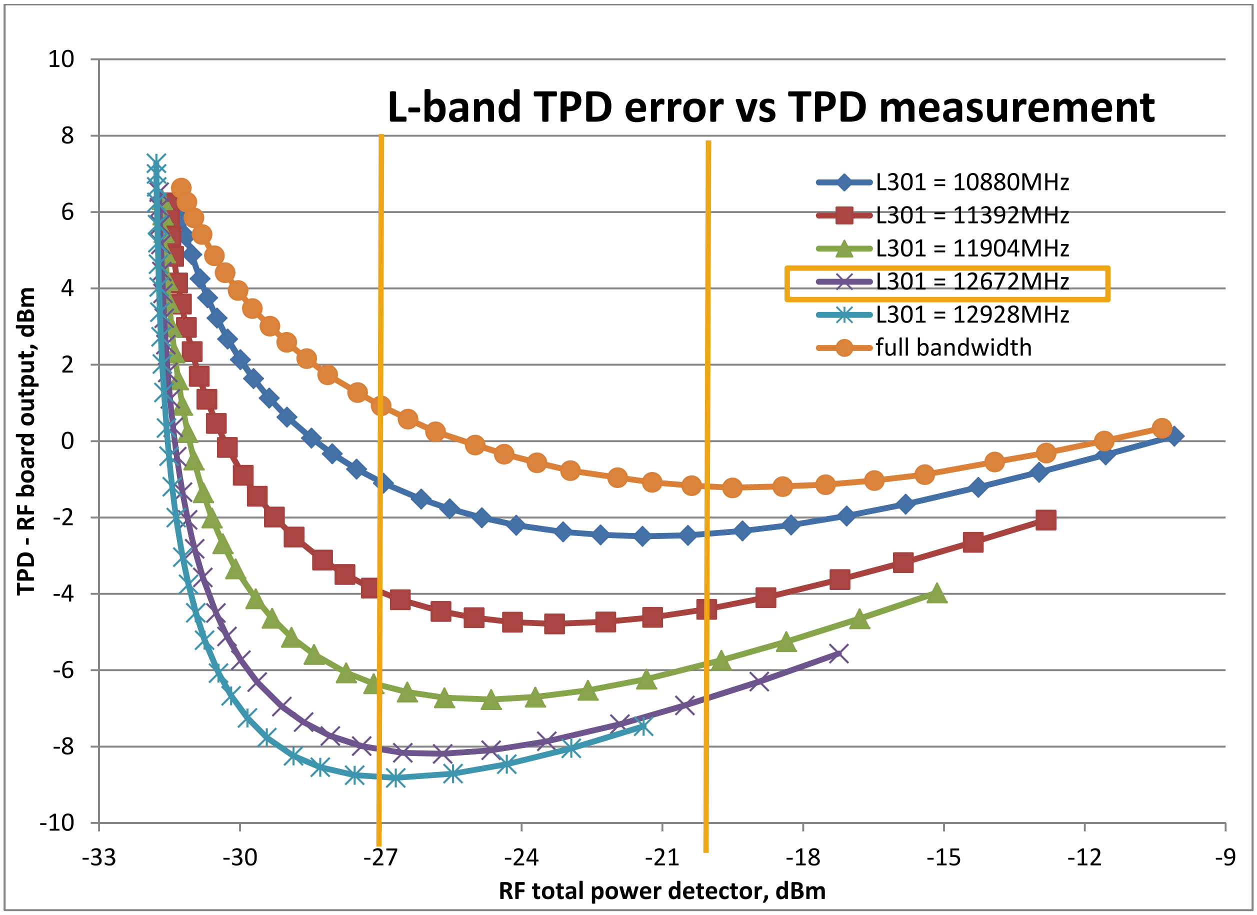


Figure 3: TPD error, defined as the difference between the total power detector measurement and a power meter measurement of the same signal, versus TPD measurement, for each of six input signals. The vertical yellow bars represent the total power targets for L-band (-27dBm) and X-band (-20dBm).

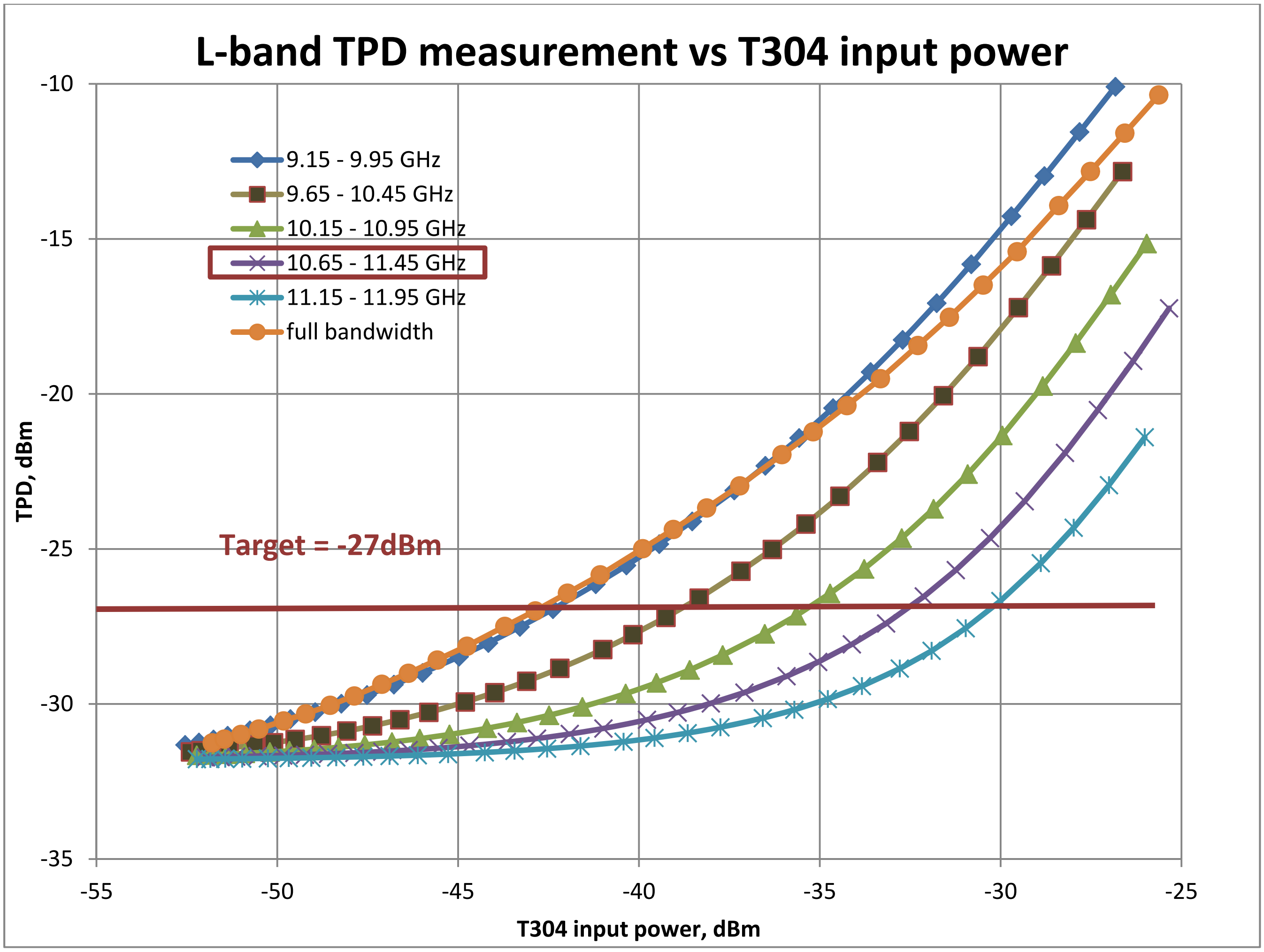


Figure 4: Total power detector measurement versus power meter measurement of the power at the T304 input port. The horizontal red bar indicates the L-band total power target of -27dBm. For reference, the X-band or "full-bandwidth" total power target is -20dBm.

Figure XX shows the total power detector error at three different tunings for a simulated S-band signal, with the full-bandwidth X-band signal shown for reference. Figure XX shows the total power measurement referred to the input power for S- and X-band signals. The intersection of the total power target horizontal red bar with the curve for the standard (13440MHz) S-band tuning gives an optimal input power for S-band of approximately -32dBm.

The recommended input power levels for L- and S-band are taken in the absence of the LO signal. In practice, the output of the LSC converter contains a significant leaked LO signal which contributes to the total power measured at the input of the T304. Appendix B shows the relative fraction of total power expected for L301 tunings in L-, S-, and C-bands as they are measured by a power meter at the T304 input and by the T304 total power detector. This LO leakage is in-band to the T304 input bandpass filter, and therefore is seen by the total power detector. At the standard C-band L301 tuning of 16000MHz, no appreciable LO power is measured at the total power detector.

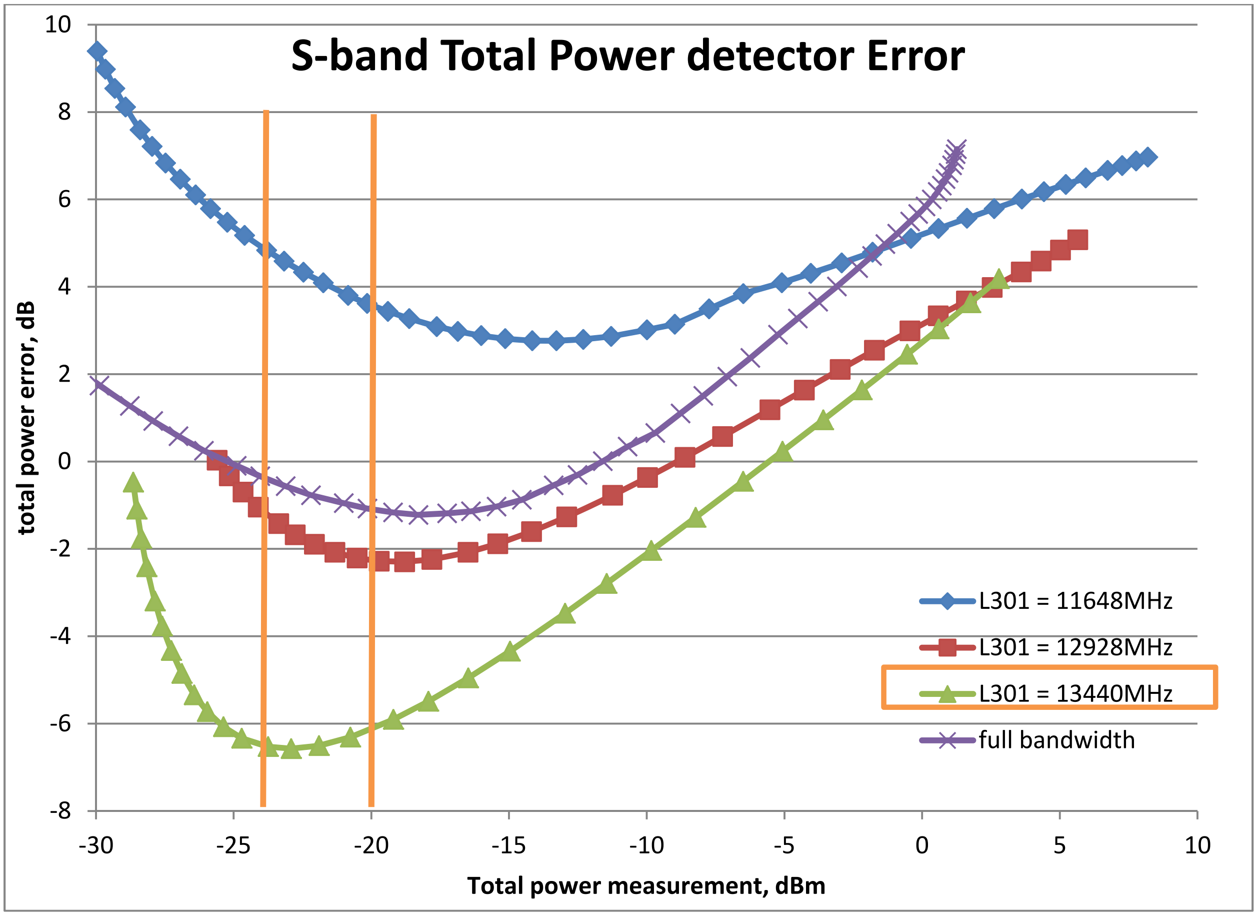


Figure 5: Total power detector error for simulated S-band signals at three L301 tunings, and the full-bandwidth X-band equivalent for comparison. Vertical bars indicate total power targets for S-band (-24dBm) and X-band (-20dBm). The default S-band L301 tuning, green trace, is highlighted.

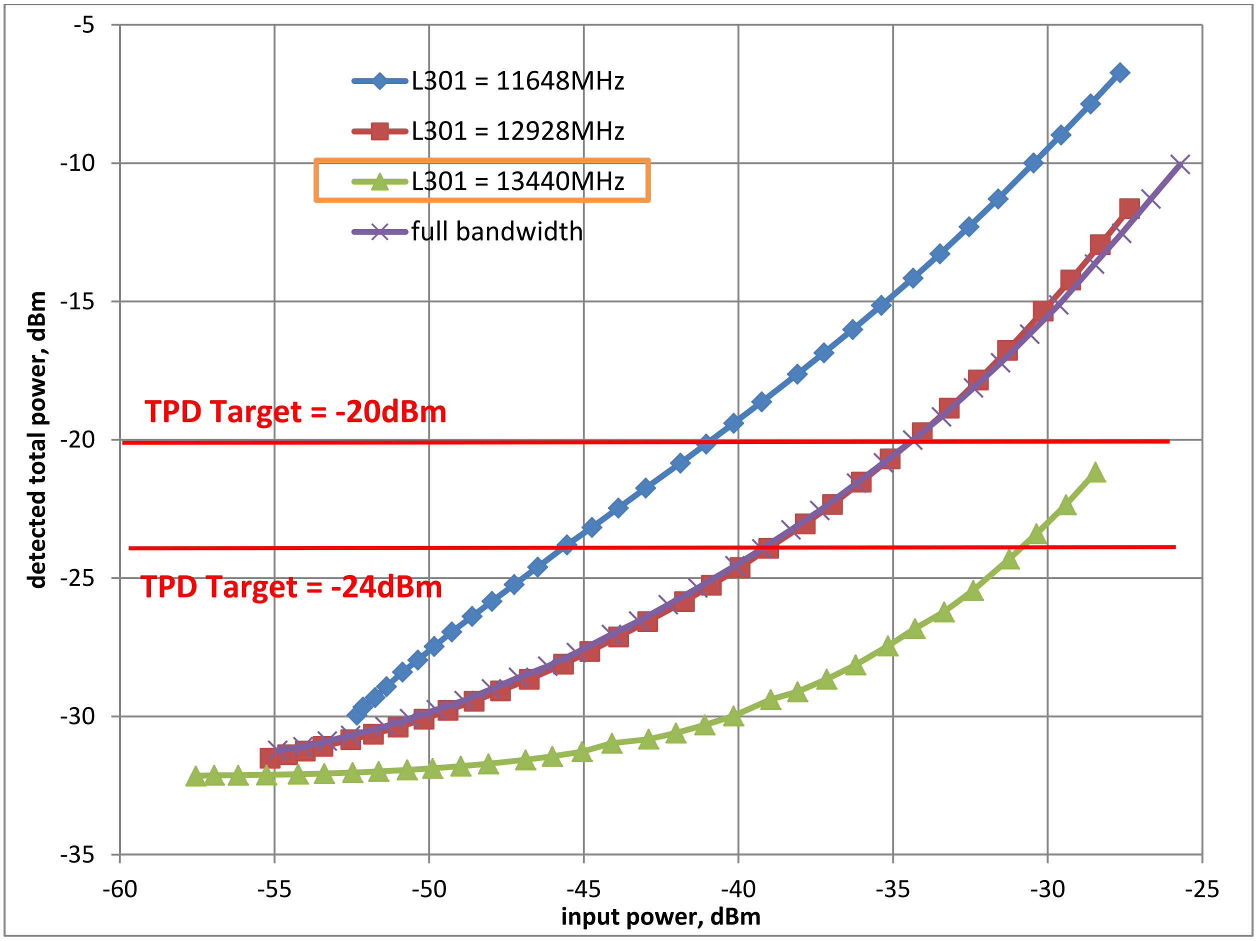


Figure 6: S-band total power measurement vs T304 input power at three L301 tunings. The horizontal red bar indicates the TPD target of -24dBm.

4.1 Bandwidth- and frequency-dependent gain compression

The power target must be chosen such that dynamic headroom is maintained throughout the signal path. Table XX shows measured 1dB gain compression points for two narrowband noise signals at a range of center frequencies, and a full-bandwidth noise signal centered on the T304 input bandwidth. The 1% gain compression point is taken axiomatically to be 12dB below the 1dB compression point. The EVLA Project Book (*Table 6.14.4 Baseband*) states that the astronomical data signal shall be 18dB below the 1% compression point, or 30dB (1 part in 1000) below the 1dB compression point, *with no attenuation applied*.

Table 2 lists the compression points for and L-band signal at each of five L301 tunings, and an X-band signal for comparison. Table 3 lists the compression points for an S-band signal at each of three L301 tunings, with the X-band signal for comparison.

Table 2: 1dB and 1% compression points for simulated L-band signal at five different L301 tunings, with X-band signal shown for comparison.

L301 frequency MHz	RF frequency GHz	P_{1dB} dBm	$P_{1\%}$ dBm	Project Book limit dBm
10880	9.15 -9.95	-1	-13	-31
11392	9.65 - 10.45	-4	-16	-34
11904	10.15 - 10.95	-5	-17	-35
12672	10.65 - 11.45	-8	-20	-38
12928	11.15 - 11.95	-13	-25	-43
N/A	7.5 – 12.5	-3	-15	-33

Table 3: 1dB and 1% compression points for simulated S-band signal at three different L301 tunings, with X-band signal shown for comparison.

L301 frequency MHz	RF frequency GHz	P_{1dB} dBm	$P_{1\%}$ dBm	Project Book limit dBm
11648	7.5 - 9.5	5	-7	-25
12928	9 - 11	2	-10	-28
14464	10.5 - 12.5	0	-12	-30
N/A	7.5 - 12.5			

4.2 Power Targets

As mentioned in Section XX, the T304 RF attenuator is commanded to a value of -20dBm for all receiver bands except P (-30dBm), L (-27dBm), and S (-24dBm), where the standard full-bandwidth power target has been adjusted by the ratio $10*\log_{10}$(Receiver BW/5) for the receivers whose bandwidth is less than 4GHz. This generally results linear gain-structuring within the T304 input stage. However, many antenna/IFs set up with attenuator = 0, implying that the signal feeding the T304 was too low, and achieving the total power target may result in premature compression of the amplifier stage directly before the variable attenuator. In general, the higher the RF attenuator value, the higher the 1dB compression point of the T304.

4.3 Receiver output levels

The input signal level to the T304 is specified in terms of power density, or dBm/GHz. This ensures that the post-conversion, band-limited signal presented to the digitizer has constant power and gain linearity, adjusted by the T304 attenuators, independent of the bandwidth of the receiver. The X-band receiver presents the simplest case, since its output passband sits exactly on the input passband of the T304, with no intervening frequency conversion or band-limiting. Results from X-band can be used as a standard for all receivers, once they are extrapolated and adjusted for bandwidth.

Table 4gives the nominal receiver output power densities, the power levels at the various converters, and the assumed gain or loss between. These values are an excellent starting point for a future endeavor to standardize receiver and up/downconverter power levels.

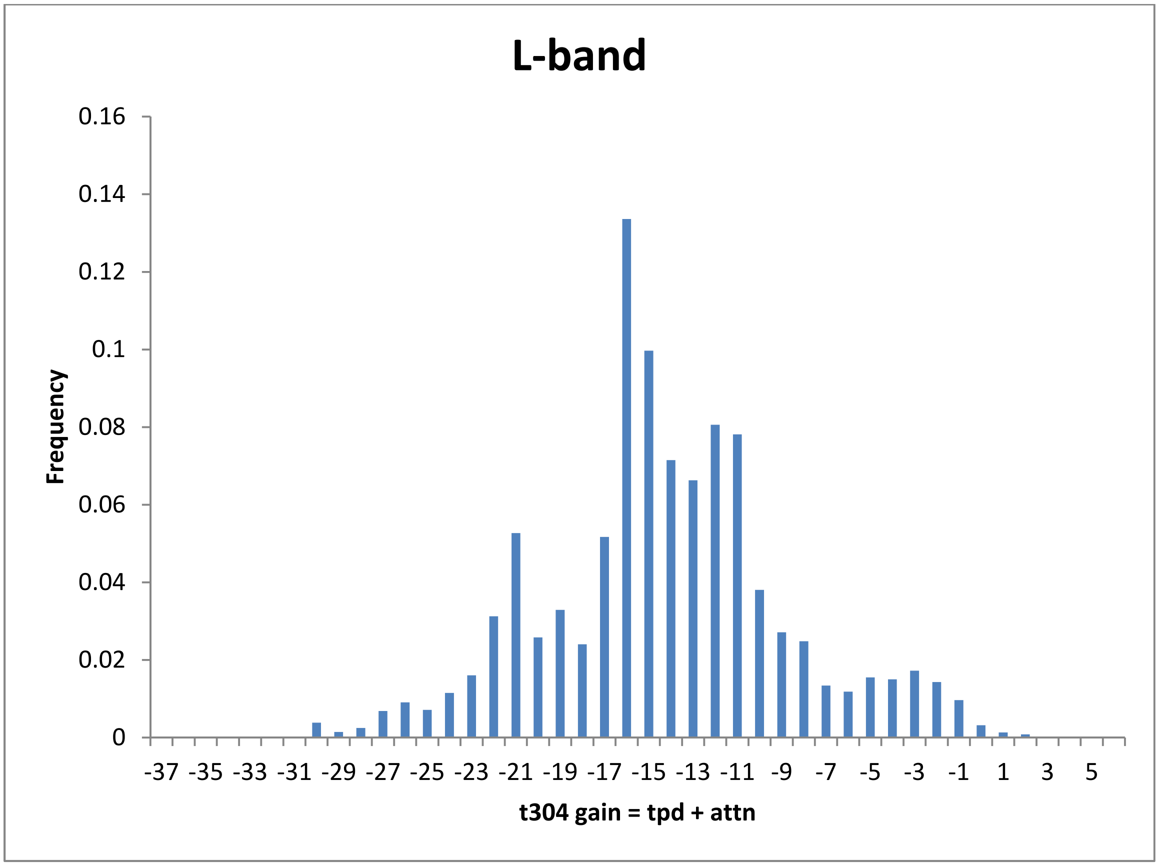
Table 4: Nominal power levels from receiver output through to T304 input.

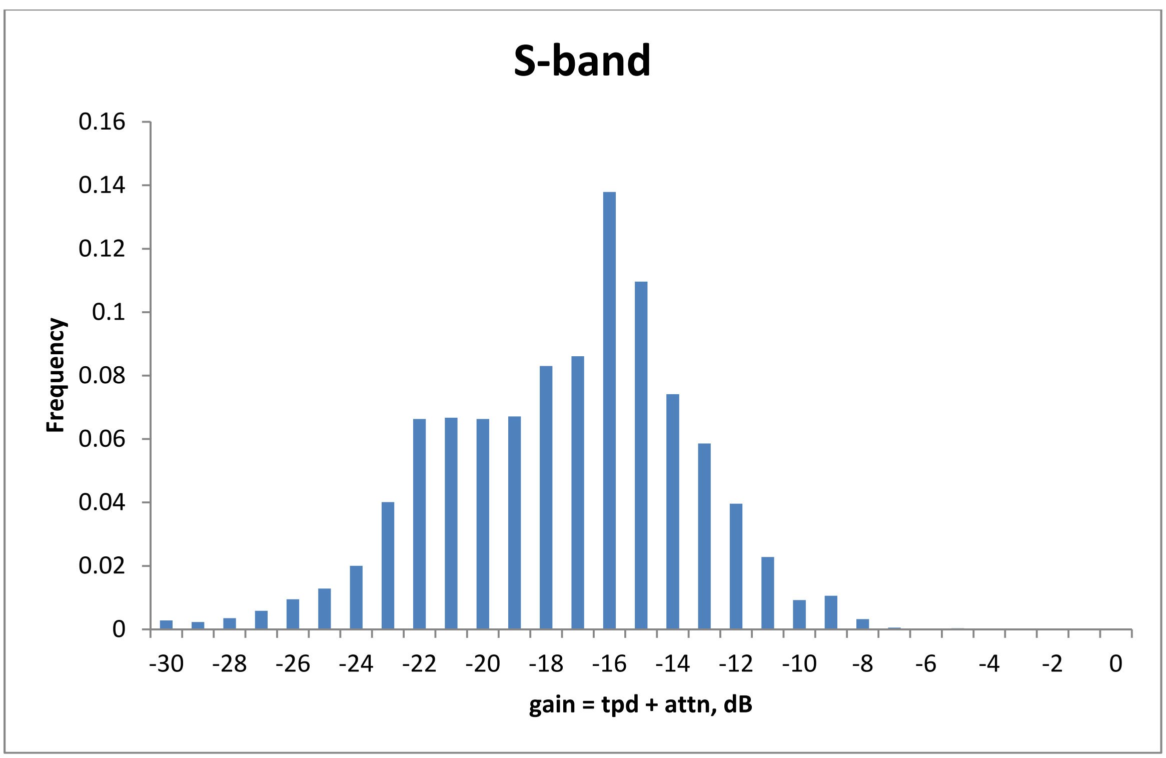
Band	Density @ Rx (dBm/GHz)	BW (GHz)	Power @Rx (dBm)	Conversion Gain (dB)	Cable, Switch, and Splitter Loss (dB)	T304 Input BW (GHz)	Power @ T304 (dBm)
L	-39	1.4	-38	3	-1	1.4	-44
S	-38	2.4	-34	5	-1	2.4	-41
C	-39	4.4	-33	7	-1	4.4	-39
X	-38	4	-33	N/A	-6	4	-39
U	-48	8	-39	10	-2	5	-38
K	-48	10	-38	10	-2	5	-38
A	-47	14	-36	8	-2	5	-38
Q	-47	12	-36	8	-2	5	-38

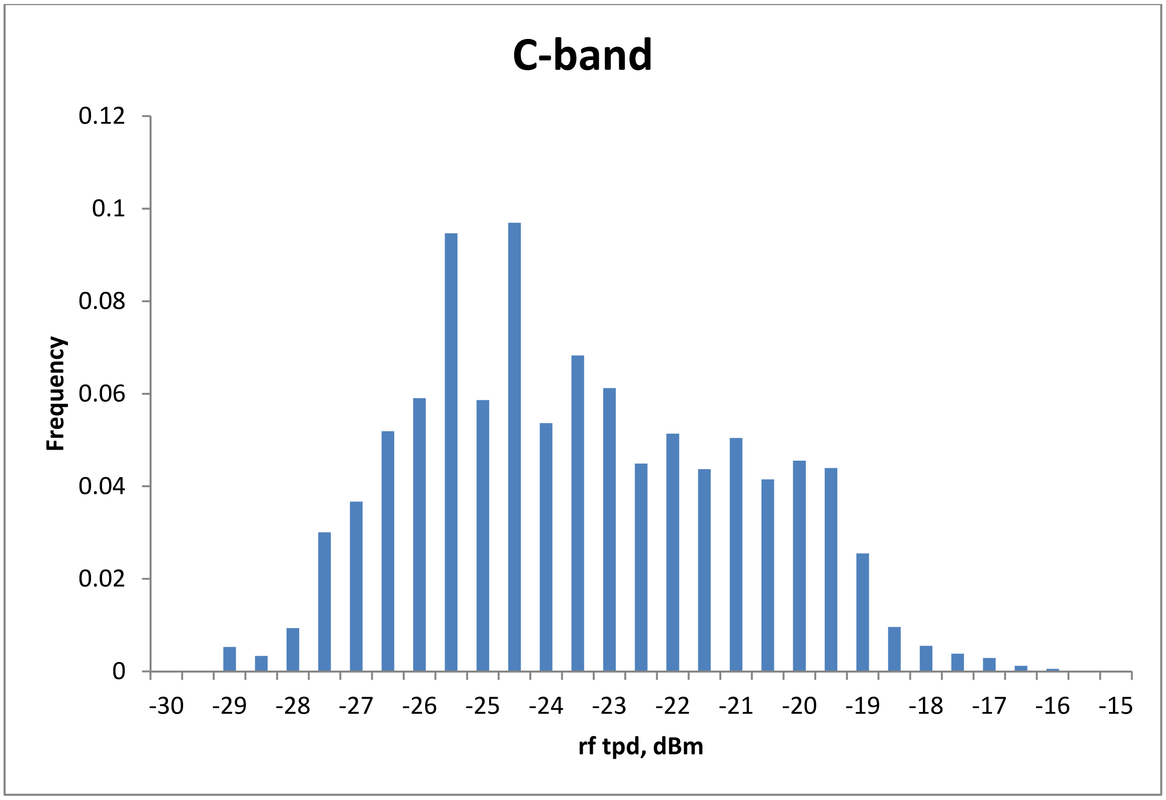
The X-band receiver output level can be inferred from the T304 corrected power, but this inference should not be used as a substitute for power measurements made in the array. Once the relationship between the measured receiver output power and the T304 corrected power monitor point is known, the monitor point can be calibrated against this and used as a basis for determining the remaining receivers' proper output power levels.

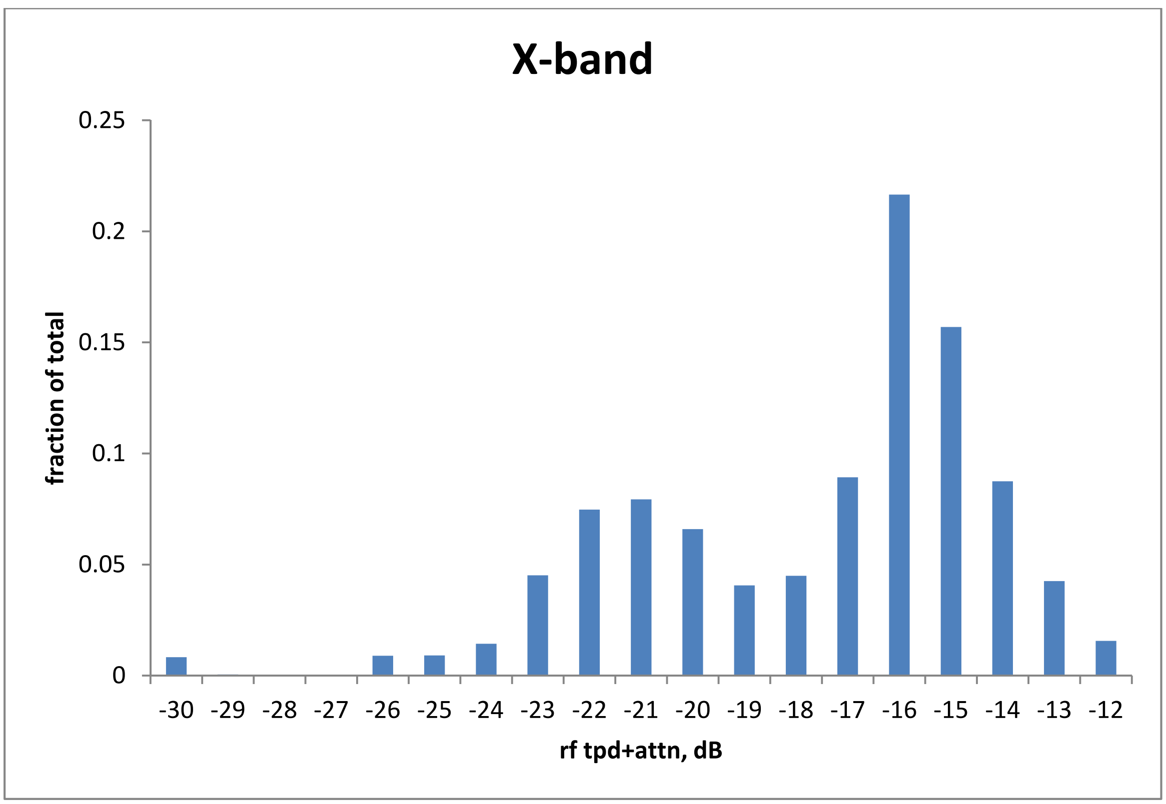
See *EVLA Memo 184: Gain and Pdiff Compression in the EVLA IF Signal Path* for a discussion of test methods for identifying and locating the origins of apparent gain compression within the IF signal path, as well as strategies and recommendations for identifying and setting receiver output levels.

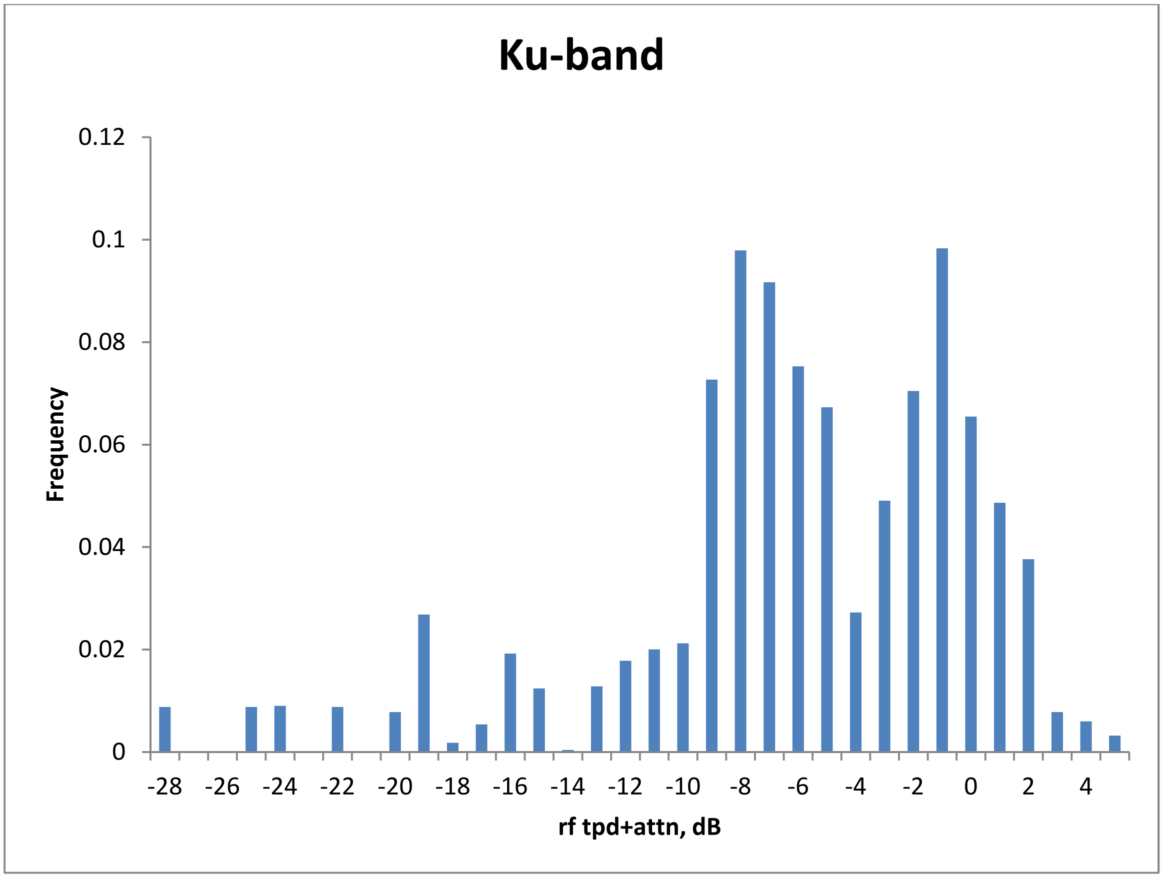
Appendix A: Distributions of IF Path Gain by Receiver Band

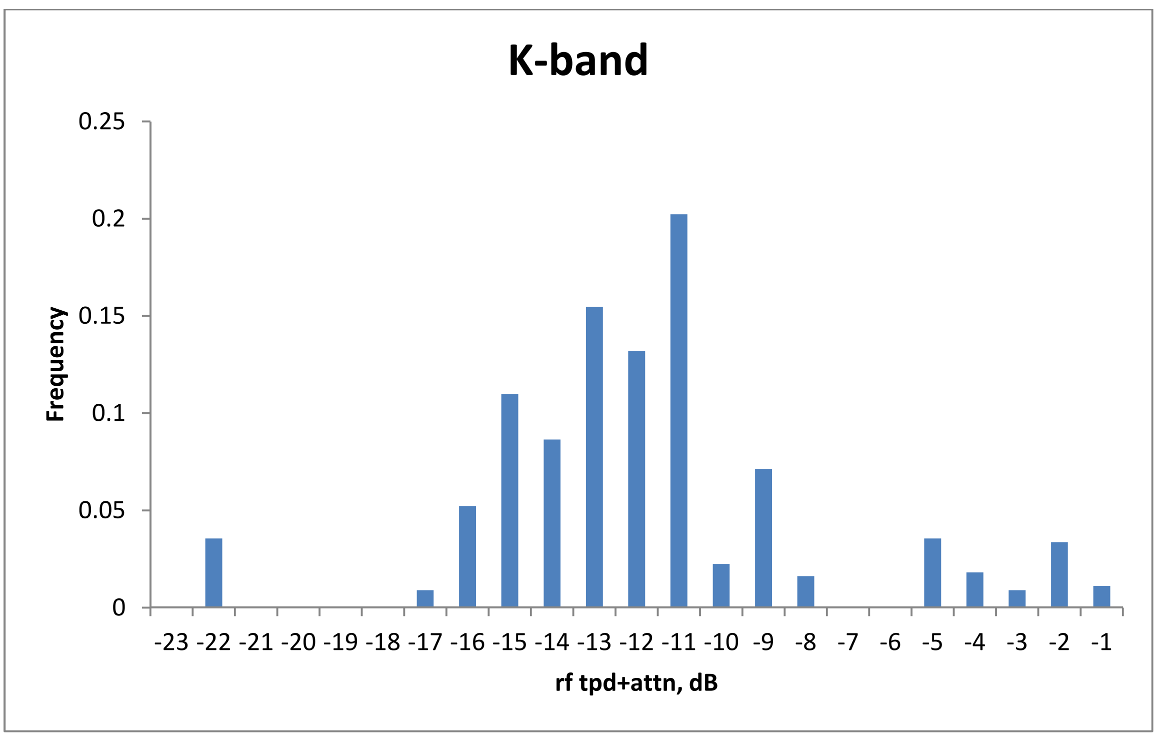


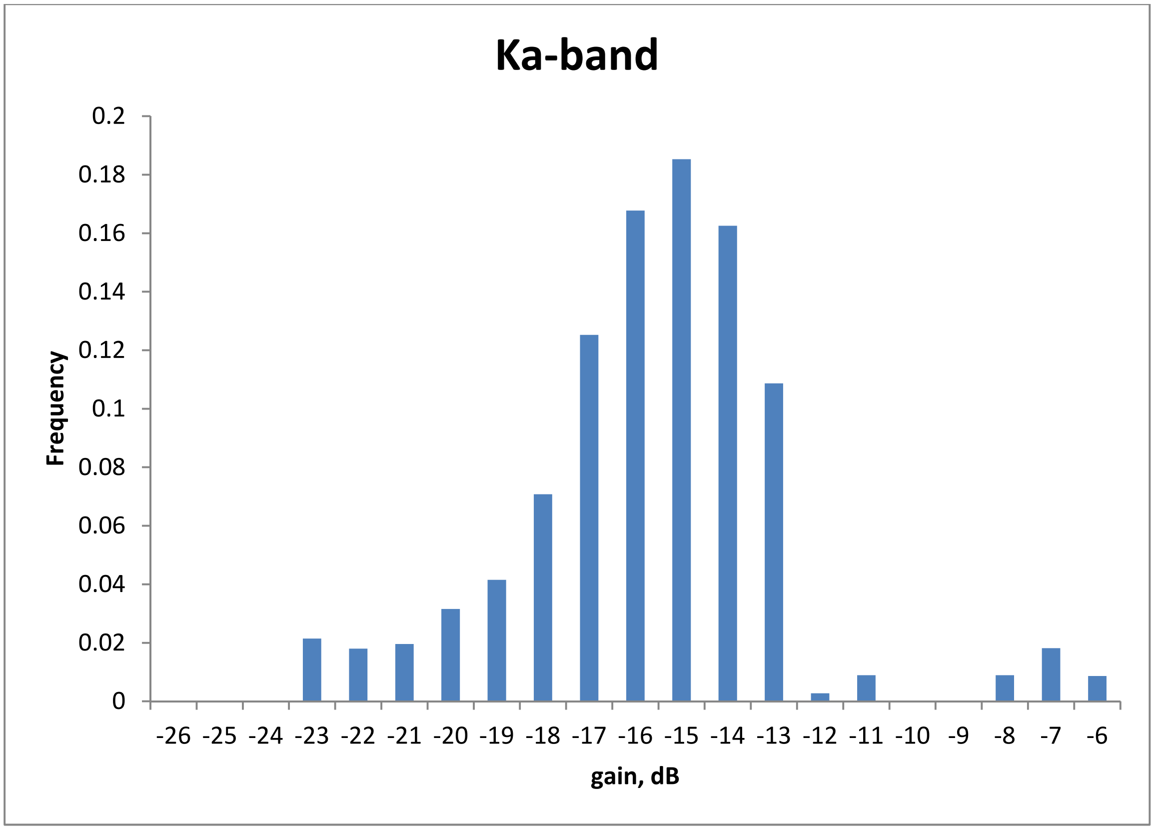


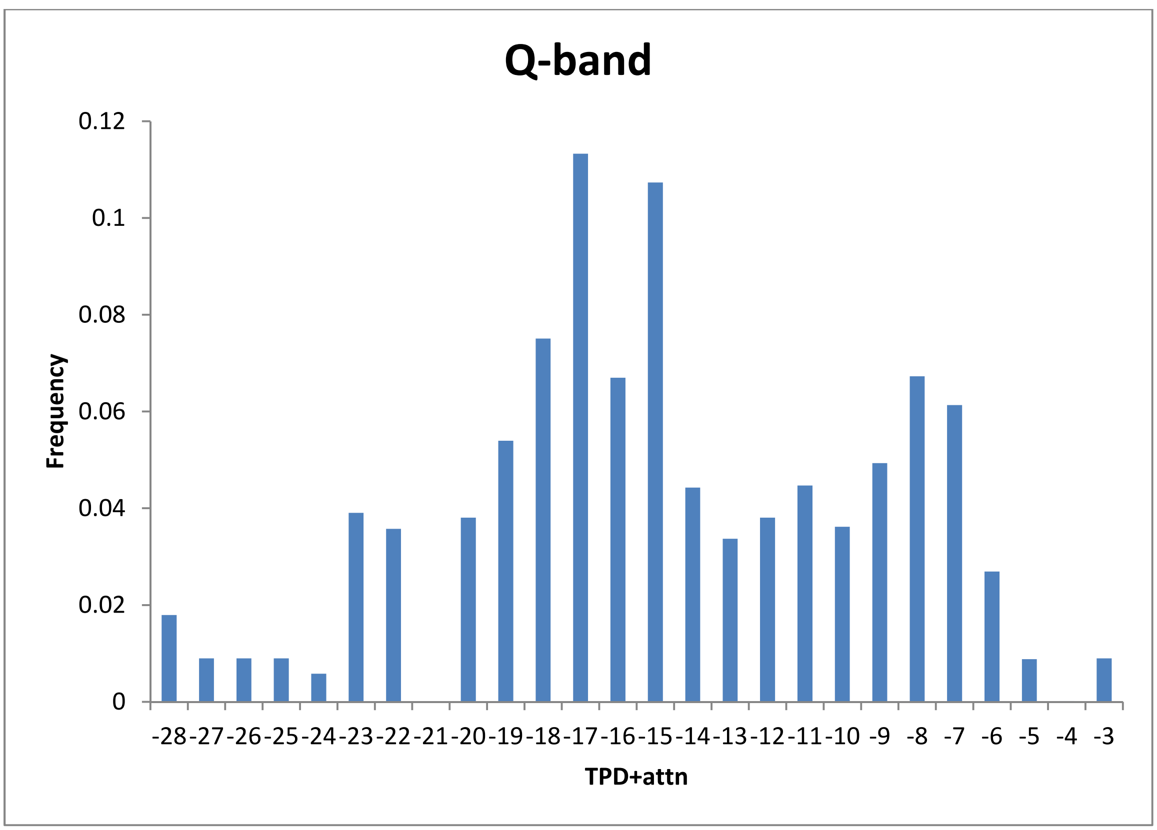

C-band
Frequency
0.12
0.1
0.08
0.06
0.04
0.02
0
-30 -29 -28 -27 -26 -25 -24 -23 -22 -21 -20 -19 -18 -17 -16 -15
rf tpd, dBm


X-band
fraction of total
0.25
0.2
0.15
0.1
0.05
0
-30 -29 -28 -27 -26 -25 -24 -23 -22 -21 -20 -19 -18 -17 -16 -15 -14 -13 -12
rf tpd+attn, dB


Ku-band
Frequency
0.12
0.1
0.08
0.06
0.04
0.02
0
-28 -26 -24 -22 -20 -18 -16 -14 -12 -10 -8 -6 -4 -2 0 2 4
rf tpd+attn, dB


K-band
Frequency
0.25
0.2
0.15
0.1
0.05
0
-23 -22 -21 -20 -19 -18 -17 -16 -15 -14 -13 -12 -11 -10 -9 -8 -7 -6 -5 -4 -3 -2 -1
rf tpd+attn, dB


Ka-band
Frequency
0.2
0.18
0.16
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
-26 -25 -24 -23 -22 -21 -20 -19 -18 -17 -16 -15 -14 -13 -12 -11 -10 -9 -8 -7 -6
gain, dB


Q-band
Frequency
0.12
0.1
0.08
0.06
0.04
0.02
0
-28 -27 -26 -25 -24 -23 -22 -21 -20 -19 -18 -17 -16 -15 -14 -13 -12 -11 -10 -9 -8 -7 -6 -5 -4 -3
TPD+attn

Appendix B: Fraction of LO and RF Power in Total Power Measurement

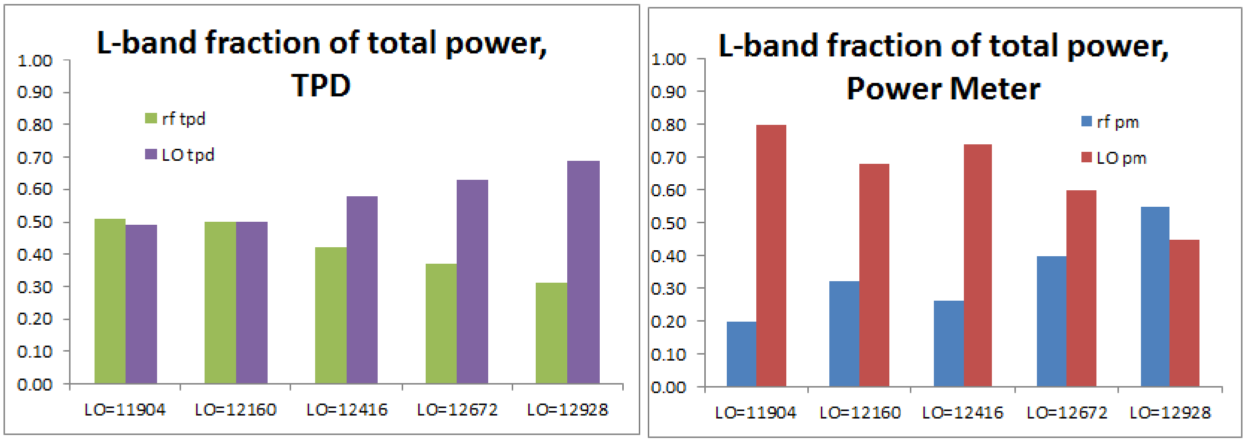


Figure 7: Fraction of L-band LO and RF power appearing at the total power detector (left) and a power meter placed at the T304 input (right).

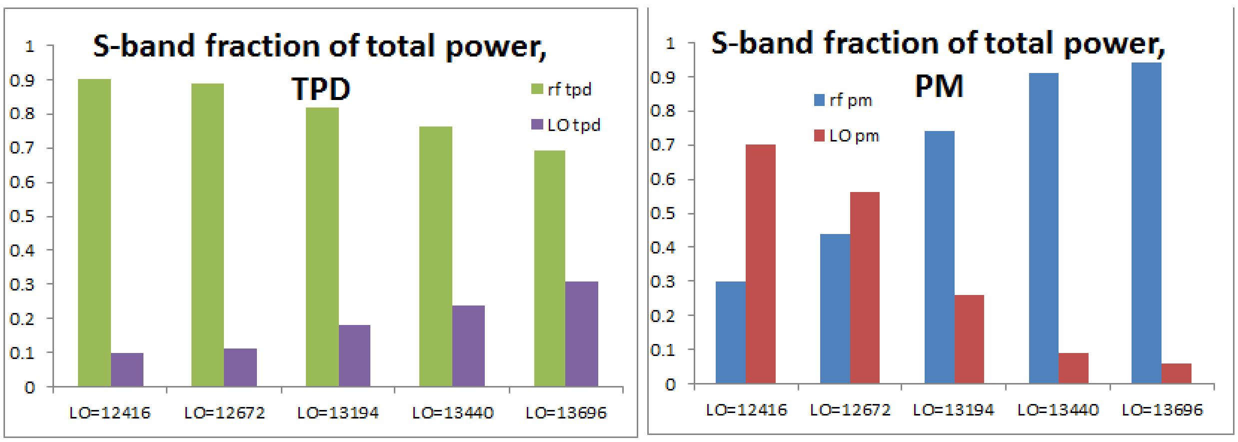


Figure 8: Fraction of SL-band LO and RF power appearing at the total power detector (left) and a power meter placed at the T304 input (right).

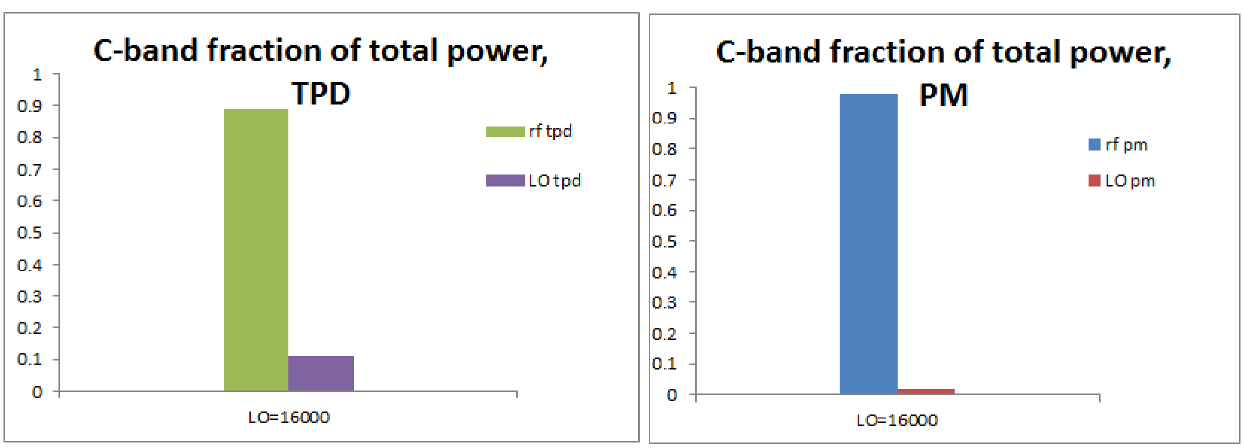


Figure 9: Fraction of C-band LO and RF power appearing at the total power detector (left) and a power meter placed at the T304 input (right), provided for comparison.