Linearity of the continuum and spectral backends at the 40m radiotelescope

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1.0	02-06-2014	P. de Vicente	First draft

Contents

1 Introduction

We have measured the linearity of the spectral and continuum backends in the 40m radiotelescope to determine the optimum input power range from the IFs of all receivers. The IF distribution and the measurements done to determine the best operating IF power are described.

2 IF signal distribution

All receivers in the 40m radiotelescope produce IF signals in the 500 to 1000 MHz bandwidth since this band matches the input IF range of the VLBI backends (one DBBC and one VLBA5 at the time of this report). The 45 GHz IF, which is currently also used for the 22 GHz receiver, and the 87 GHz dual polarization IRAM HEMT receivers, also deliver 2 GHz wide base band signals.

The signal from the receivers cabin is transported using 8 (Andrew FSJ4) cables which connect 2 patch panels with 8 connectors each. Fig. 1 shows a picture of both of them. The upper panel is in the receiver cabin and the lower one in the backends room. Connectors 1 and 2 are used for the signals from receivers at 5 GHz, 8 GHz, 22 GHz, 45 GHz and 87 GHz (IRAM HEMT). Since all of them share the same connection a selection of the required receiver is done in a switch matrix prior to the patch panel in the receiver cabin. The switch matrix composed of 2 outputs and 8 inputs allows to select 2 inputs (LCP and RCP). The patching is summarized in Table 2.

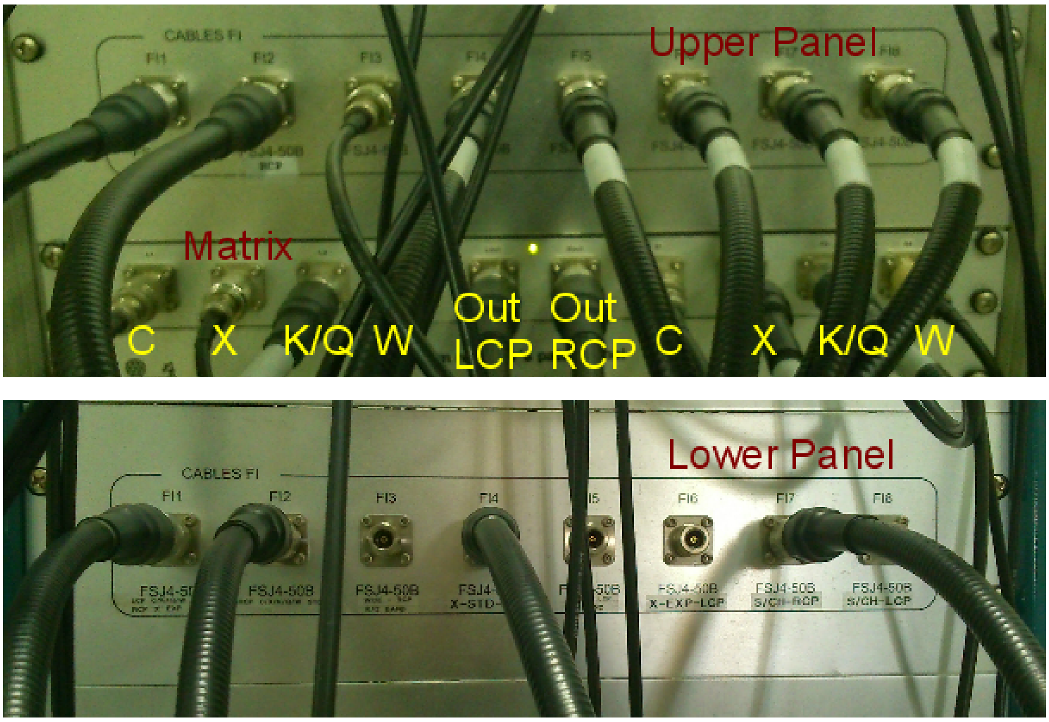

Figure 1: *From top to bottom: upper patch panel, switch matrix and lower patch panel.*

Connector	Signal
Port 1 RCP	5 GHz RCP
Port 2 RCP	8 GHz RCP
Port 3 RCP	22/45/87 HEMT GHZ LCP
Port 4 RCP	87 GHz RCP
Port 1 LCP	5 GHz LCP
Port 2 LCP	8 GHz EXP RCP
Port 3 LCP	22/45/87 HEMT GHZ LCP
Port 4 LCP	87 GHz - No signal

Table 1: *Connections in the switch matrix at the receiver cabin. Only one pair of outputs (RCP and LCP) can be selected at a time.*

Connectors 3 to 8 from the patch panel at the receiver cabin are used for geodetic observations and for wide band observations and do not require any repatching. The distribution is summarized in table 2.

Connector	Signal
Connector 1	From switch matrix
Connector 2	From switch matrix
Connector 3	IF45 wide band RCP
Connector 4	8 GHz LCP
Connector 5	IF45 wide band LCP
Connector 6	8 GHz EXP. LCP
Connector 7	2 GHz RCP
Connector 8	2 GHz LCP

Table 2: *Connections in the patch panels at the receiver and backends rooms.*

Currently the signals in the patch panel from outputs 1, 2, 6 and 7 are divided using 4 splitters, with a pass band between 500 and 1000 MHz, to send them to the VLBA5 terminal and the DBBC. Both backends have 500 MHz input filters and provide a copy of the input signals with 3 dB less intensity which can be sent to another equipment. This setup will become obsolete as soon as the DBBC is validated and can fully replace the VLBA5. The goal of the VLBA5 and DBBC in the distribution of signals from the receivers is twofold: first use their power detectors and second use their capability to switch their inputs to a loaded input with no signal to determine the offset of the backend (a third one or the VLBI backend itself). Both VLBI backends use continuum detectors to determine the power of the signal and generate a continuum analog signal whose amplitude is proportional to the detected power in the IF. These analog signals are fed into the Pocket Backend detector which produces digital readouts with 16 bit resolution (see de Vicente 2013). The VLBA5 continuum detectors are linear and feed PBE 1 to 4 inputs, whereas the DBBC ones are logarithmic and feed PBE 5 and 6 inputs.

Currently the IF copy delivered by the DBBC is sent to a Fast Fourier Spectrometer with

8 channels. The IF signals have to be converted from the 500-1000 MHz band to a base band one (0-500 MHz) prior to getting into the FFTs boards. This downconversion is done by the preprocessor unit which generates two signals per polarization, one for the 100 MHz board and a second one for the 500 MHz board. The preprocesor can also get a copy of each input signal. We plan to connect these copies to two inputs of the Iram Detector (hereafter IDET) also for continuum detection.

Fig. 2 shows a general sketch of the distribution of the signal through the different backends. Every step divides by 2 the signal decreasing its level by 3 dB.

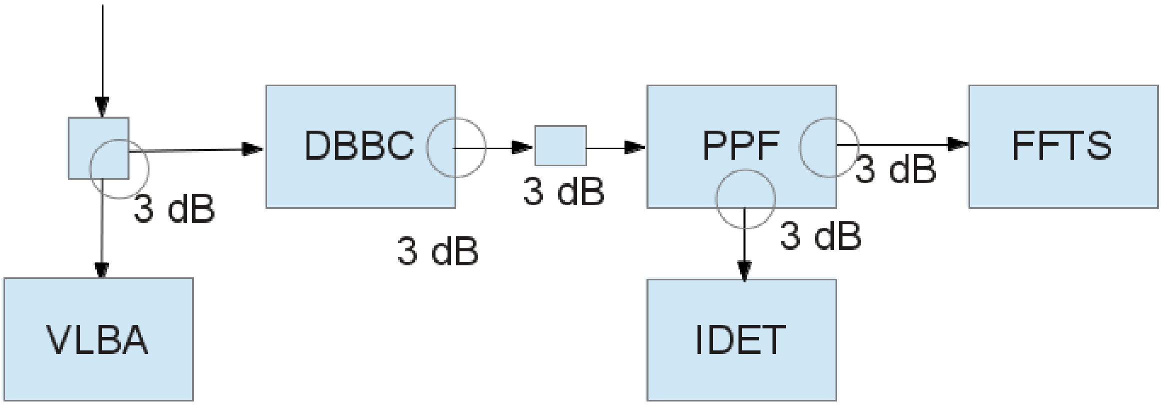

Figure 2: *Distribution of the IF along the different backends. PPF stands for Preprocessor for the FFTS. The signal that comes into every device is splitted and a copy is extracted. Every copy has 3 dB less than the original signal.*

Fig. 3 shows the detailed cabling from the receivers to the backends including patch panels and the switch matrix in the receiver cabin.

3 DBBC continuum detectors and linearity

Since several years ago and up to 2014 the VLBA5 power detectors have been used for continuum observations. The linearity range provided by these continuum detectors is too small, between 1 and 5 volts, and the values of the attenuators at the IFs were adjusted to operate always in that range. Recently we discovered that in some ocassions the detectors were not working in the linear regime, and this caused weird effects in the determination of the gain for both polarizations at X band and 22 GHz. This lack of linearity was specially present in observations at 3 mm, where the usage of a hot load and cold load requires a larger dynamic range than in the centimeter range where the emission from the atmosphere is small and the noise diode power is only a small fraction of the power from the sky. In order to overcome this problem we decided to use the DBBC logarithmic power detectors connected to the PBE and the Iram Dectector (hereafter IDET) since both have a larger dynamic range.

The DBBC has 4 independent IF modules that allow to work with 4 IFs (for example 2 frequencies and 2 polarizations) simmultaneously. Each module has 4 SMA inputs which provide flexibility to use different setups avoiding to move cables from one connector to another. Each

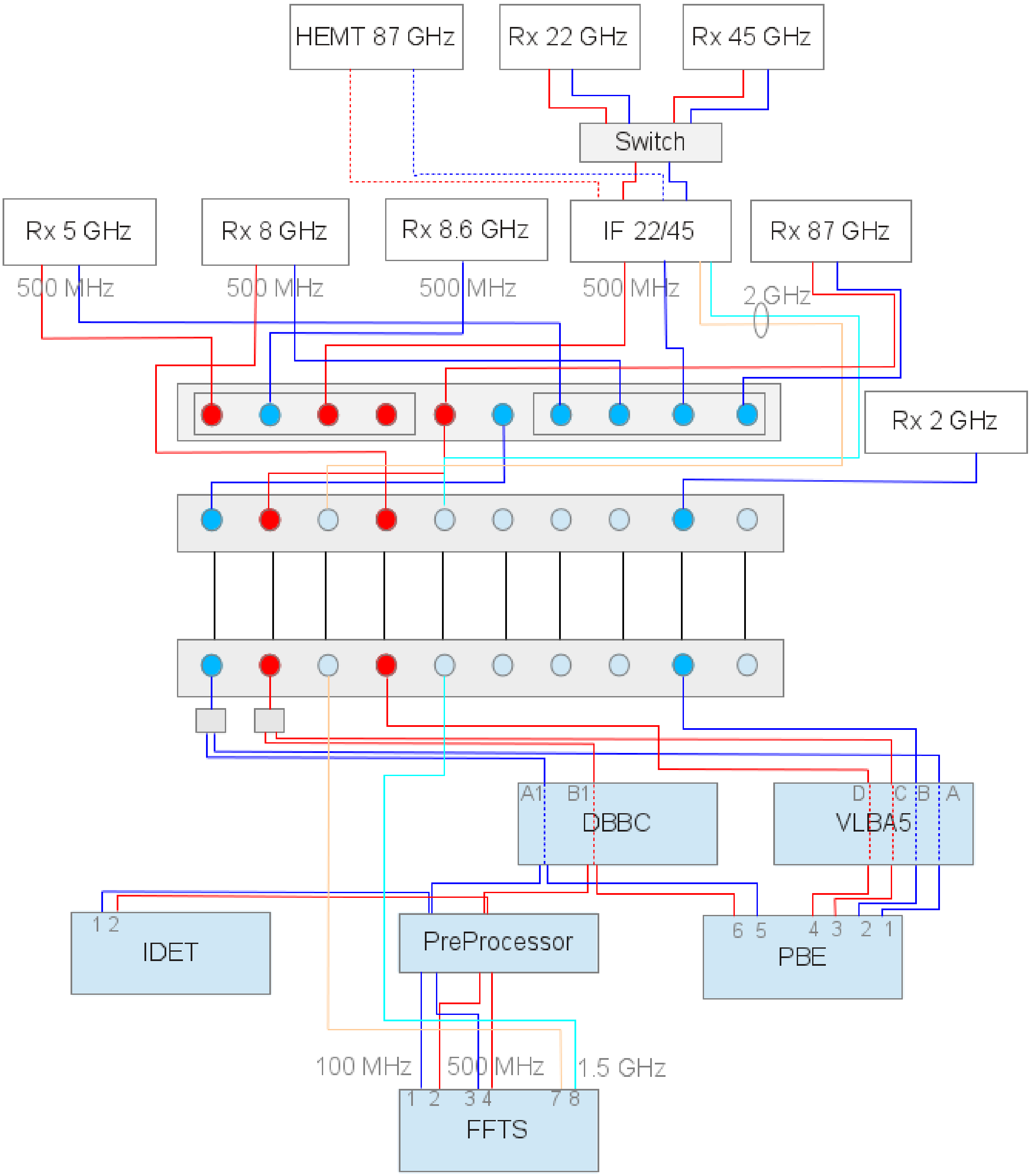

Figure 3: *Intermediate Frequency (IF) distribution at the 40 m radiotelescope*

module only processes the signal from one connector at a time. Input connectors are selected using an internal switch and software commands. Two SMA connectors labeled “RF Mon” and “RF Out” are available in each IF module. “RF Out” is a copy of the input signal with a power 3 dB lower. Besides, and as described in report IT-CDT 2014-12, there is an output BNC connector with an analog signal whose amplitude is proportional to the log of the power detected along the band. Signals from modules A and B are fed into the Pockect Backend (regularly inputs 5 and 6) which acts as an A/D converter and data server (see report IT-OAN 2011-1).

We have measured the signal from the 4 outputs of the IF by injecting it to the Pocket Backend used in single dish observations. As with report IT-CDT 2013-3 we prepared a setup in which we inject noise into the IFs and attenuate it in steps of 1 dB to verify the behaviour of the detected signal. The IFs were set to manual gain and an attenuation of 25, 31, 24 and 28 for IFs A, B, C, and D respectively. Figs. 4 shows the result. The voltage of the detected signal varies from 1.68 (40 dB attenuation) to 2.18 volts (0 dB attenuation). The detected power as read from a socket connection is in arbitrary units.

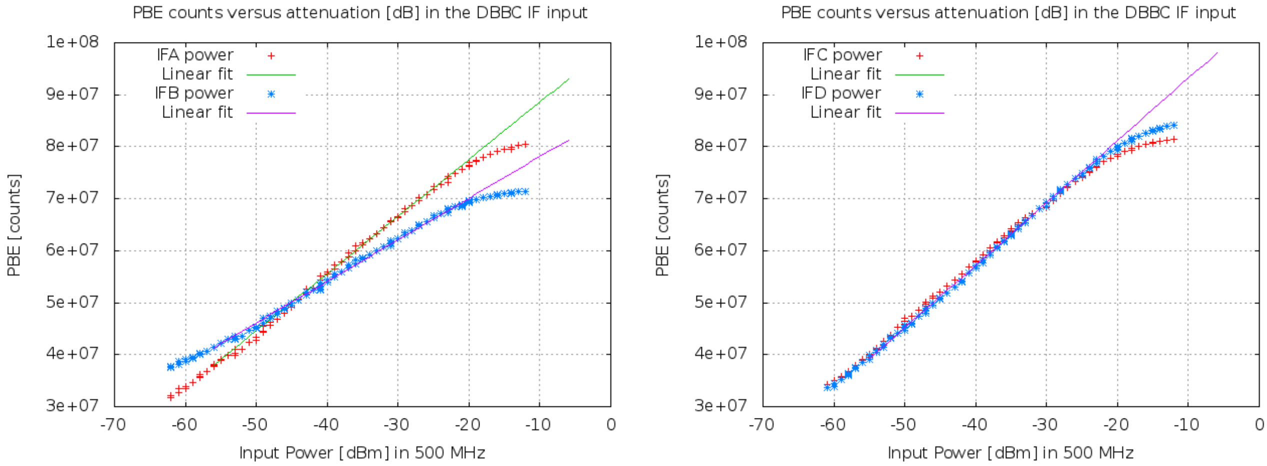

Figure 4: *Results from measuring the analog output signal from the DBBC power detector into the PBE. A white noise signal with different attenuations was injected into the IF modules. The PBE detected power is in arbitrary units.*

As expected, the detection is logarithmic, and the linearity ranges between -53 dBm/MHz and -83 dBm/MHz. In a 500 MHz bandwidth this corresponds to -26 dBm and -56 dBm respectively. The slope is similar for IFs B, C and D and slightly lower for IF A. This difference probably arises from the behaviour of the individual detectors.

In order to produce a linear value that allows to properly calculate the system temperature and the antenna temperature a conversion from a logarithmic unit should be used. As with the Field System this conversion requires a calibration factor related to the slope of the logarithmic detector. The curves in Fig. 5 are used to calibrate and provide a linear value for the detected power.

The relationship is given by the following equation:

$$P = A\,10^{(counts-B)/C} \tag{1}$$

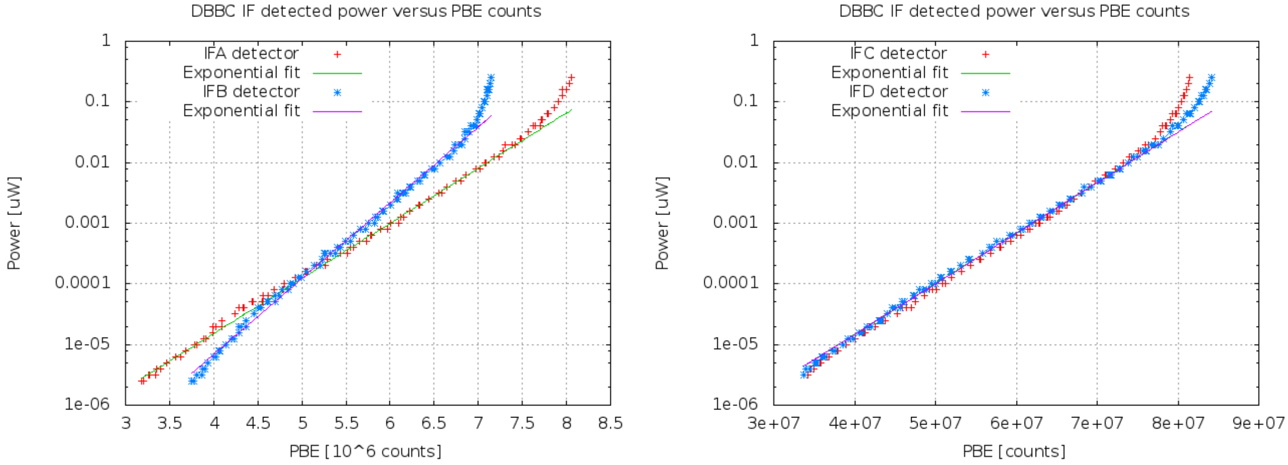

Figure 5: *Power in watts versus PBE in arbirtray units. These curves have been used to calibrate the detected power in a PBE.*

where P is the power in arbitrary units and $counts$ is the power returned by the PBE through a socket connection and after integrating for 1 second. A, B and C are parameters obtained after fitting the curves displayed in Fig. 5. Table 3 contains the calibration factors for the four IF modules. Factor A can be selected arbitrarily to provide a high number and reduce numeric noise or to match the power in μW. At a first stage we selected A to be 1.

DBBC IF	A	B	C
IFA	1	$3.3\,10^7$	$8.0\,10^6$
IFB	1	$2.7\,10^7$	$1.1\,10^7$
IFC	1	$2.6\,10^7$	$1.2\,10^7$
IFD	1	$2.6\,10^7$	$1.2\,10^7$

Table 3: *Calibration factors used to get a linear value proportional to the input power when using the PBE together with the DBBC logarithmic power detectors.*

The signal at the power detectors in the DBBC IFs depends on the attenuation commanded from the Field System to the DBBC server, usually running in DDC mode. A fast way of checking if we are in the linear regime is to observe the counts in the FS and verify they are within the linearity range. It is also a good idea to check the PBE voltage display. Table 3 summarizes the equivalence between the input power, counts as measured by the FS, voltage measured by the PBE display and counts using equation 1 for $A = 1$. We have used a fixed attenuation of 15 at the DBBC (attenuation steps in the DBBC are equivalent to 0.5 dB). The numbers for IFA are slightly different since the slope of that power detector is different from the others (B, C and D).

As we know from VLBI observations, the optimum power count in 1 second integration time is between 38000 and 42000 counts, although this number may be increased up to 50000, where the linearity starts to fail. In single dish observations the automatic gain control is disabled and the count number varies, depending on wether we are observing the sky or a hot or cold

Noise source att. (dB)	Input Power (dBm/MHz)	Input Power (dBm in 500 MHz)	FS counts	PBE Volts	PBE counts
10	-43	-16	55374	2.48	63864
20	-53	-26	47006	2.28	16702
25	-58	-31	39917	2.08	5513
30	-63	-36	33750	1.88	1801
40	-73	-46	18509	1.58	154
50	-83	-56	4882	1.28	16

Table 4: *Equivalence between different ways of measuring the power in the DBBC power detectors. Counts and voltage depend on the attenuation selected in each IF module. Values here were obtained for an attenuation of 15 on IF B. Counts from the PBE are computed from equation 1 using factors in Table 3.*

load. However in all these cases the number of counts should be within the linear interval (-53 dBm/MHz to -83 dBm/MHz). In summary to easily check if the DBBC power detectors plus the PBE are working in an optimum regime we should check that the voltage is close 2.02 ± 0.08 or the FS counts between 35000 and 43000.

After examination of Table 3 we have decided to set $A = 10^3$ to increase the counts number (last column in that table) and reduce the numeric noise.

4 FFTS detection and linearity

The linearity of the FFTS has been measured with the same procedure described in previous section for the DBBC power detectors: a wide band noise source injects noise into the FFTS and the power is detected after changing the attenuation in steps of 1 dB. The detected power is obtained using the socket connection. An integration time of 5 seconds was used. We have obtained averages in 5 intervals of the spectra, 0-100 MHz, 100-200 MHz, 200-300 MHz, 300-400 MHz and 400-500 MHz respectively, in both polarizations and represented its intensity as a function of the input power. Results are in Fig. 6. According to that figure the range in which linearity is guaranteed lays between -53 dBm/MHz and -83 dBm/MHz. This interval matches exactly the one for the DBBC power detectors.

Linearity is not the only condition to be met. It is also very convenient to have a correct representation of the data taking into account that the FFTS uses 8 bits for sampling the signal. The FFTS provides two tools to measure the quality of the sampling. There is a graphical monitor application that shows the distribution of bits for a given signal and a color code in the front LED for each module.

When a white noise signal is correctly sampled one gets a gaussian, where the X is the bit number and the Y is the number of times that bit has been obtained. In Fig. 7 we show three examples, with low intensity, correct intensity and high intensity. In the first case only bits close to zero do have an important weight, since the signal is very close to zero. If the signal is too strong the bits at both ends will have much more weight. Together with the bit representation the spectrum of the signal is displayed in an arbitrary scale (dB). This graph is very helpful as a

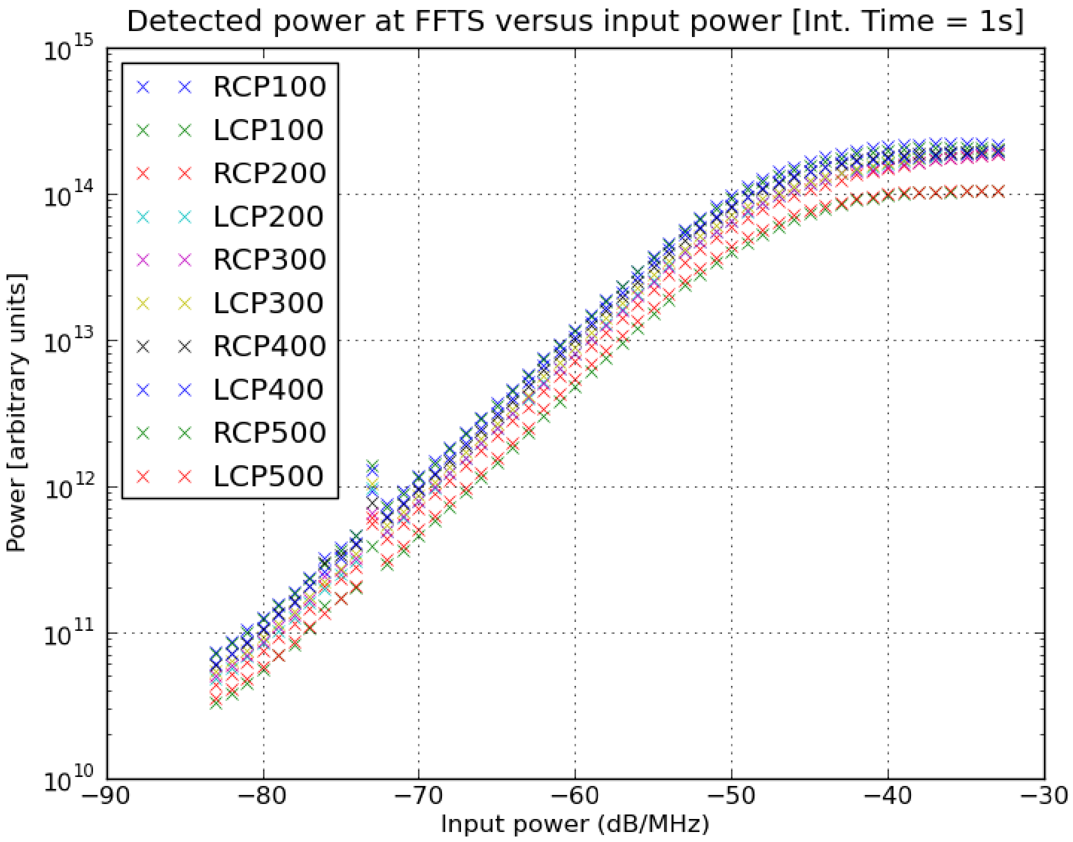

Figure 6: *Linearity study for the FFTS. Measured power is in arbirtrary units and was obtained averaging the signal in 100 MHz intervals from 0 to 500 MHz and using an integration time of 1 second.*

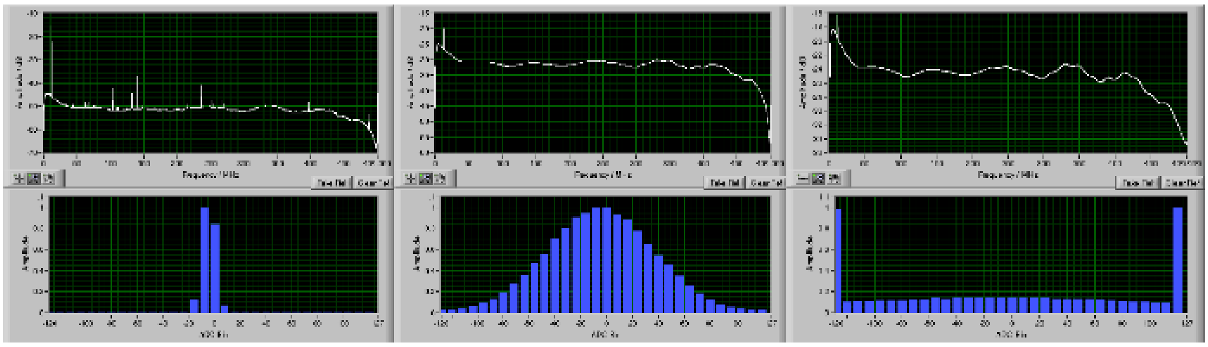

Figure 7: *From left to right, bin sampling with a low level, correct level and high level power input signal at the FFTS channel 3*

reference to associate the intensity of the signal with the optimum working range.

The color code at the front LED of each module also works depending on the intensity of the signal. From high to low amplitude signal the codes are: red, blinking red, green, blinking green, orange and blinking orange.

Taking into account these two tools we injected a signal from the noise source generator modifying its intensity in steps of 1 dB from 0 to 50 dB. We consider that the optimum working interval is the one in which the color code is green or blinking green. The bit representation displays a gaussian easily recognizable. Results are summarized in Table 4. The optimum working interval is between -57 dBm/MHz and -47 dBm/MHz for a 100 MHz bandwidth and -63 dBm/MHz and -53 dBm/MHz for a 500 MHz interval when using an integration of 1 second.

Bandwidth (MHz)	Noise source att. (dB)	Input Power (dBm/MHz)	FFTS power (dB)	LED color code
100 MHz	[24, 34]	[-57, -67]	[-46, -56]	orange
	[16, 24]	[-49, -57]	[-38, -46]	green
	[14, 16]	[-47, -49]	[-36, -38]	blinking green
	<14	>-47	>-36	red
500 MHz	[30, 40]	[-63, -73]	[-39, -48]	orange
	[23, 30]	[-56, -63]	[-32, -39]	green
	[20, 23]	[-53, -56]	[-29, -32]	blinking green
	<20	>-53	>-29	red

Table 5: *Detected power at the central channel of the FFTS in an arbitrary scale (but in dB) and color code versus input power and noise source attenuation. Two bandwidths were used: 100 and 500 MHz. Integration time: 1 second*

According to Table 4 the input power signal for 100 MHz should be approximately 13 dB higher than the one for 500 MHz. We have also done some tests to compare the levels when using 1 second and 5 seconds integration time. As before, the former (1 second) requires a signal 7 dB higher than the latter (5 seconds). However in this case, where the integration time changes and hence the level of the detected signal, the sampling behaviour is not modified and no adjustement in the output attenuators is required. Therefore the control system should only adjust the output attenuators from the different IFs in the receiver cabin when the FFTS bandwidth is changed. As in the previous section we can summarize the results by stating that, when using an integration time of 1 second and 500 MHz bandwidth, the signal should be within the -46 to -36 dB in the monitor tool, and between -39 and -29 dB for an integration time of 5 seconds, but the attenuation tuning for the first case is exactly the same as for the second one.

5 IDET Linearity

The IDET, which has 6 individual detectors, has also been measured using the same procedure described in previous sections for the other backends. The result from channels 1 and 2 are shown in Fig. 8. The noise generator produces a signal between 10 MHz and 1 GHz and the results should be scaled to the 500 MHz standard output band from the receivers. In case of wider bandwitdhs the control system should take it into account when setting the attenuation values.

According to Fig. 8 the interval where linearity is guaranteed lays between -45 dBm and -12 dBm, which corresponds to -75 dBm/MHz and -42 dBm/MHz respectively. The right panel shows the same dependency but the power detection is an a different scale and comes from the graphical chart recorder. In both panels only 2 channels have been plotted for comparison. As explained in report IT-CDT-2014/6 the IDET comes with a graphical chart recorder that displays the power as a function of time and assigns an arbitrary number to the detected power. This number ranges from 0 to 200. If the signal goes above 200 the detectors may get damaged.

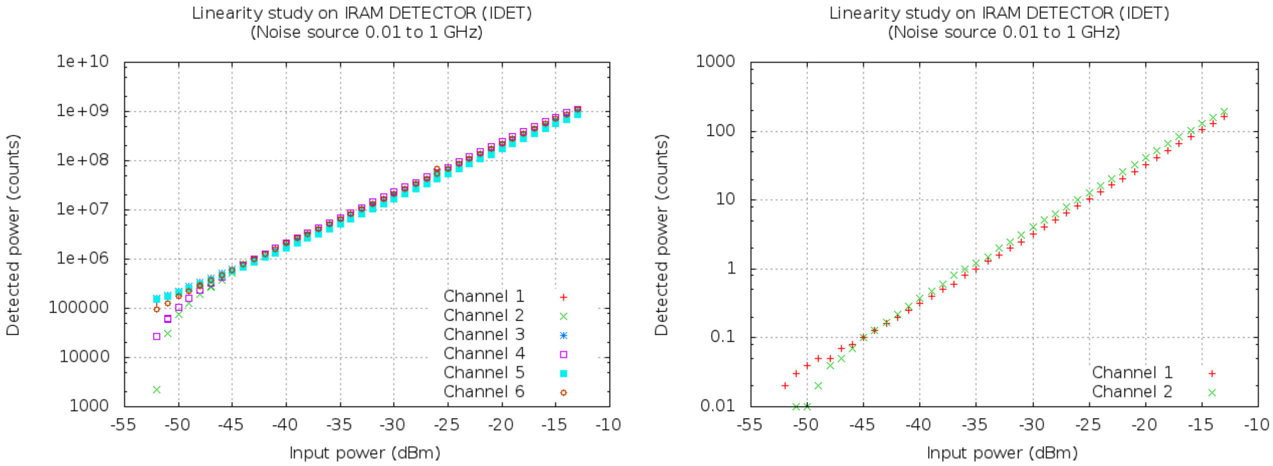

Figure 8: *Results from measuring the signal from a noise detector. The upper panel shows the power as reported by the remote client and the lower by the graphical chart recorder.*

In summary, the signals will be in the linear regime if the power from the chart recorder is in the range between 0.1 and 120.

6 Testing the dynamic range

We have checked that backends provide a sufficient dynamic range for normal operations and work in the linear regime. This can easily be tested by performing two kind of mesurements:

- Receivers in the centimeter range which use noise diode sources for calibration should be tested doing two measurements towards the sky: at the horizon and the zenith. The power added by the noise diode is at most 10% of the power towards the sky but it is less than the difference between the atmospheric emission between the horizon and zenith, even if the atmosphere does not have a big contribution at cm wavelengths.

- Receivers in the millimeter range and/or which use hot and cold loads should be tested mesuring the level signal with hot and cold loads and also performing a sky measurement towards the zenith and the horizon.

Results are shown on Table 6. These results were obtained with an optimum setting in the IF attenuation of every receiver and provide the information we need to check that the behaviour is correct for all subscans. In next section we discuss the optimization of the settings. The integration time was 1 second for all backends. The FFTS used a bandwidth of 500 MHz.

Receiver	Load	PBE (Volts)		PBE (Counts)		FFTS (dB)		IDET	
(GHz)		RCP	LCP	RCP	LCP	RCP	LCP	RCP	LCP
5	15°	1.98	2.08	41012	39296	-38.5	-38.5	22.7	18.8
5	Noise diode	1.98	2.08	41788	40229	-39.5	-39.7	16.5	13.9
5	sky 85°	1.98	2.08	41012	39296	-40.7	-40.5	14.5	12.0
8	sky 5°	1.98	2.08	43114	42939	-39.3	-38.5	17.1	15.7
8	Noise diode	1.98	2.08	41003	41361	-40.8	-40.0	13.0	11.2
8	sky 85°	1.98	2.08	43114	42939	-39.3	-38.5	17.1	15.7
22	hot load	1.99	2.18	42292	42140	-38.0	-39.5	32.4	30.5
22	sky 5°	1.93	2.08	41256	41286	-38.9	-40.3	26.4	24.5
22	sky 85°	1.88	1.98	34888	35383	-43.8	-45.2	7.9	7.6
45	hot load	1.98	2.18	41705	43363	-41.1	-37.8	30.9	23.4
45	sky 5°	1.88	2.08	40135	42040	-42.5	-39.1	22.4	16.5
45	sky 85°	1.80	2.00	35077	36965	-46.5	-42.7	9.4	6.6
87	hot load	1.93	2.10	41248	41658	-40.1	-39.4	23.1	22.7
87	sky 5°	1.98	2.09	40750	41215	-40.4	-39.7	21.1	20.9
87	sky 85°	1.88	2.00	36694	37164	-43.5	-43.0	9.6	9.8
87	cold load	1.86	1.98	34178	34333	-45.5	-45.0	6.0	6.4

Table 6: *Detected power with different loads and different receivers with the PBE, FFTS and IDET. In all cases the scale is arbitrary. The power in the FFTS was determined at 250 MHz (the central channel). Integration time for FFTS was 1 second. The noise diode was switched on at 85 degrees elevation*

According to Table 6 the receiver which shows the largest variation is the 22 GHz receiver, between the hot load and the emission from the sky towards the zenith. The difference ammounts up to 6 dB (a factor 4). The 45 receiver shows a maximum difference of 5 dB and the 87 IRAM HEMT receiver 4 dBs. Differences decrease if the receiver temperature increases. Therefore it may be possible that when the new 45 amplifiers are installed at the telescope the 45 receiver will require a wider working range. In the 3 mm receiver we can see that the sky towards the zenith has a stronger emission than the cold load.

As we will see in next section these measurements allow to set the IF attenuator of each receiver so that the backends always work in the same input power interval.

7 Operation issues and IF attenuation

The IF attenuators for each receiver were adjusted so that the backends work in the optimum input power range, that is, guaranteeing linearity and the best sampling interval for the signal.

Since the optimum range, according to the FFTS, is approximately 10 dB and the maximum input power difference is 6 dB, the setting was quite easy. The procedure was as follows:

- We set the IF attenuation of each receiver when the power was maximum so that the FFTS was in the upper end of the optimum regime described in section 2.
- Then the attenuation was checked to be within the optimum interval for the FFTS and IDET when the power was minimum.
- We set the attenuation in the dBBC to get a detection number (number of counts) close to 42000 or 43000 when the power was maximum.

The attenuation values determined for the IFs are summarized in Table 7. We have also added the manual attenuation value used for the DBBC and the IF attenuation when using the VLBA5 for VLBI.

Receiver	DBBC att.		IF Att.		IF (VLBA) att.	
	RCP	LCP	RCP (dB)	LCP (dB)	RCP (dB)	LCP (dB)
5 GHz	8	10	15	15	15	15
8 GHz	8	10	2	2	2	2
22 GHz	11	11	6	8	11	16
45 GHz	8	10	6	9	10	15
87 GHz	9	9	6	11	10	15

Table 7: *Attenuation values in the DBBC and the IFs for single dish observations with the DBBC and VLBI observations with the VLBA5. VLBI Observations at 45 and 87 GHz with the VLBA5 are not advised due to lack of linearity in the calibration process.*

These settings are valid for the current chain between the IFs and the backends where several splitters divide the signal as depicted in Fig. 2. Currently the input power in the DBBC is 6 dB higher than for the FFTS and the IDET. When the splitter that divides the signal to send to the VLBA5 and to the DBBC is removed, the input signal will be 3 dB larger and the attenuators should be adjusted accordingly.

The control system takes into account these values and sets the correct attenuations for all receivers. It also sets the attenuation for the Field System when using the DBBC+PBE for single dish observations. The control system also manages the different bandwidths of the FFTS to set accordingly the IF attenuators. This means that, unfortunately, it is not possible to do simultaneous observations at 100 and 500 MHz since the optimum working range is not guaranteed.

The VLBA5, still in operation only for VLBI observations, requires a lower signal level and this is also taken into account in the control system. We expect that the VLBA5 will stop operations within two months.

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