Saturation by the Pizza Slice Method
Experimental Investigation

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Abstract

As a follow up of the analysis submitted by one of us of the ALMA Band3 team's own measurements, we have conducted an investigation of the "pizza slice" method used by Band 3 to characterize the linearity of frontend B3 cartridges. We find, as expected, a spurious excess of non-linearity, strongest when the measurements are performed at a place where the beam is narrowest.

Experimental setup

The measurements were carried out with the 3mm-band HEMT receiver being prepared for IRAM's 30-m telescope. The center RF frequency was 91 GHz and the IF bandwidth 8GHz. The frontend part of the receiver (two mm-wave HEMT amplifiers) was operated cold (4K).

The receiver uses, coincidentally and conveniently, a horn with a phase correcting lens that is identical to the ALMA Band 3 design. The horn aperture is ~29mm (w0=9.3mm). Confocal distance z0=82mm. Far-field angular *radius* at 1/e *amplitude*: 6,5°.

Although a receiver of such technology is believed *a priori* to be free from saturation, we verified its saturation properties using the method in use for the B7 cartridge (partially coupled auxiliary chopper), which has been previously documented, e.g. in the ALMA B7 Test Procedures. We find a total power gain compression (@300K) of 1±0.5%. Part or all of this might be attributable to the 8472B Agilent crystal detector (including option -002 for improved quadratic response), operated at -20dBm. That detector (required for its fast response at the frequency of the auxiliary chopper) was *not* part of the main setup for the "pizza slice" method. In the latter case the IF power was measured with an Agilent E4412A CW power sensor and an E4419B base.

General principle of measurements

Measure output power in four situations:

- Staring at cold load
- Insert absorber with straight edge, covering *approximately* half of the beam;
- Insert similar absorber, *exactly* complementary to the first above;
- Both absorbers, i.e. receiver coupled to ambient load.

Detailed derivations will be given below, but it should fall under reason that for a linear receiver, the mean of the intermediate measurements equals the mean of the extremes. Or should it?

In Practice

Two loads are prepared, made of AN-72 (thickness ~6mm) glued to a backing of stiff cardboard. Each one is cut along straight edge. A support frame with a central aperture defines a plane for each of the two setups (below).

- Note down IF power P_{77}staring at cold load;
- Insert and hold firmly the Left absorber in a position where the IF power is approximately half-way between cold and ambient values; note IF power P_L;
- Still holding the Left absorber, insert the Right absorber flush against the Left absorber; hold it firmly note P_{300};
- Remove Left absorber; note P_R;

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Setup "near"

Receiver staring into a deep elliptical mirror that bounces and refocuses the beam down into a load immersed in a dewar of LN2. Loads are inserted in a plane 35mm from the dewar window.

Setup "far"

Receiver stares into same LN2 dewar, only now through a planar mirror. Cold load coupling is only marginally worse than in "near" setup. Loads are inserted in a plane (between the folding mirror and the LN2 load) 340mm from the dewar window.

From measurements to saturation value

Here we assume that two absorbers that are geometrically complementary have couplings (to the receiver's radiation diagram) that add up to unity. That is a weaker (more generic) assumption than made in the "pizza-slice" method. Under that assumption, we show below that the saturation can be derived from a set of four measurements. Input value: radiometric temperature. Output value: IF power.

Non linear response:

$$P_{out} = P_0 + g \cdot T_{in} \cdot \left(1 - \frac{T_{in}}{T_s}\right)$$

Other parameterizations of saturation are possible; all are equivalent to the first significant order.

The *total power* compression at 300K (we keep the original ALMA spec value for consistency with the verification of the compression of the HET receiver mentioned above) is given by: $C = \frac{300K}{T_s}$

Output power staring at cold load (from now on we omit the "K" unit symbol, a blatant violation of dimensional consistency!):

$$P_{77} = P_0 + g\ 77\ \left(1 - \frac{77}{T_s}\right)$$

And a similar equation for the 300K load is obtained.

Output power with the L̲eft half-load inserted, covering a fraction "x" of the radiation diagram:

$$P_L = P_0 + g\ [x \cdot 300 + (1-x) \cdot 77] \cdot \left[1 - \frac{x \cdot 300 + (1-x) \cdot 77}{T_s}\right]$$

And a similar equation for the R̲ight half load. Just exchange "x" and "1-x".

After some expansion and simplifications, we obtain:

$$\frac{T_s}{g} \cdot [P_L + P_R - P_{77} - P_{300}] = 2\ x\ (1-x)\ (300-77)^2$$

Neglecting higher-order terms (we need only the leading order term for compression): $g \approx \frac{P_{300} - P_{77}}{300-77}$, and:

$$C = \frac{(P_L + P_R - P_{300} - P_{77})}{2\ x\ (1-x)\ (P_{300} - P_{77})}\ \frac{300}{300-77}$$

In the present investigation and experiments, the values of "x" were close to, but not equal to 1/2; but, in the Results section, we assumed x=1/2. Justifications:

1. $x\ (1-x)$ is maximum and stationary at $x = \frac{1}{2}$
2. Using $x = \frac{1}{2}$ in the equation for C above when the actual value is different *underestimates* the derived value for C. Since we are about to demonstrate that the "pizza slice" method *overestimates* C, we are erring on the safe side in the context of our demonstration.

Results

Setup "near"

Powers in μW at output of receiver IF.

P(77)	P(R)	P(300)	P(L)	C
3.043	5.464	8.135	6.365	0.344
3.045	6.000	8.147	5.878	0.362
3.044	6.612	8.183	5.198	0.305
3.043	6.170	8.159	5.670	0.336
3.042	5.763	8.147	6.080	0.345
3.043	5.350	8.140	6.444	0.323
3.043	5.645	8.140	6.245	0.373
3.041	6.111	8.180	5.731	0.325
3.043	6.340	8.180	5.500	0.323
3.040	5.467	8.140	6.410	0.368

Note that the values in the rightmost column are natural numbers, *not* percentages. As the values for C looked so large that they might raise doubts about the validity of the whole approach, we repeated similar measurements in the "far" configuration (see above for definition).

Setup "far"

P(77)	P(R)	P(300)	P(L)	C
3.206	5.546	8.260	6.040	0.064
3.203	5.617	8.261	5.960	0.060
3.203	5.375	8.220	6.202	0.083
3.203	5.690	8.197	5.850	0.075
3.201	5.988	8.158	5.504	0.072
3.203	5.915	8.133	5.570	0.081
3.201	4.650	8.135	6.824	0.075
3.201	4.454	8.185	7.054	0.066
3.200	5.200	8.177	6.334	0.085

Now the numbers for "C" are almost plausible (if taken in isolation) but clearly incompatible with the separate determination by the auxiliary chopper method *and* the results in the "near" setup. .

Discussion and conclusions

While the method used in the present investigation is not exactly the "pizza slice" method, it rests upon the same fundamental assumption: that the *physical* coupling of an absorber to a beam pattern equals the *geometrical* coupling, i.e. the integral of the power pattern over the area of the absorber. In fact, our derivation of C values rests upon a weaker property (a consequence of the previous): that two complementary plane absorbers have physical coupling values whose sum is unity.

The values derived using the "half-pizza" method are:

- Incompatible with the results of the auxiliary chopper method;
- Variable and inconsistent according to the axial position in the beam.

We will not dwell too much on theoretical explanations, feeling that the experimental results are what really matters. Possible tracks:

- Finite thickness of absorber; interaction of the wave with the absorber edge along its thickness;
- Diffraction. Classical results in optics and QM: a black disk has an absorption cross-section $\sigma_{inel} = \pi a^2$, but *also* an *elastic* (diffraction) cross section σ_{el} of *equal magnitude*. Translate: diffraction at the edge couples the transmitted wave outside the target cold load.

One of us (PS) is of the opinion that the pizza slice method could be useful (because of its simpler setup) after calibrating the systematic error against another proven method. The other author (BL) is of the opinion that the said systematic errors being of poorly known physical origin and clearly variable with the experimental conditions, such a correction would be hazardous.

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