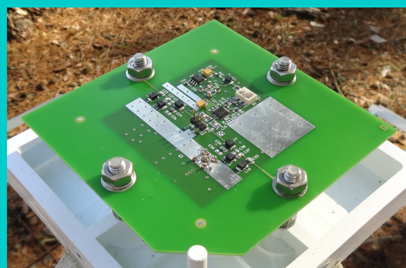
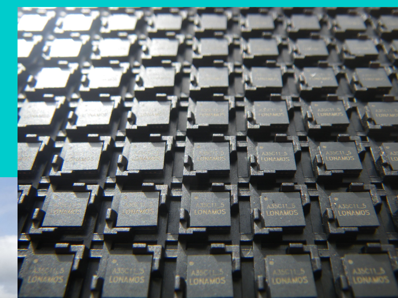
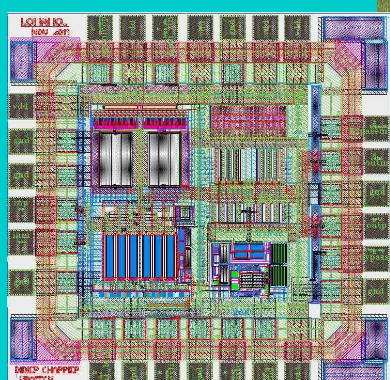
“ New developments around the butterfly antenna”

ARENA 2014
June 9-12
Annapolis, USA







Didier Charrier

Subatech

Nantes, France

New developments around the butterfly antenna

- **Butterfly Antenna presented 4 years ago**
  - ARENA 2010, Nantes
  - Proceeding: 'Antenna development for astroparticle and radioastronomy experiments', D. Charrier, Nucl. Instr. and Meth. A (2010), doi:10.1016/j.nima.2010.10.141
- **Since that time ...**
  - Antenna radiating elements are electrically the same (bow tie type antenna)
  - development of more accurate models
  - development of a new LNA (LONAMOS) to improve the Butterfly characteristics
  - ...

Butterfly historic

- **<u>October 2008</u>: birth of the Butterfly antenna, original version** (6)
  - Single polarisation
  - Antenna radiator made of electric wire and plastic tube frame
  - Use the 'CODALAMP' LNA designed in 2004 at Subatech
  - two antennas were installed in the CODALEMA acquisition
- **<u>2009</u>: first upgrade of the Butterfly**
  - dual polarization antenna
  - Antenna radiator element made of rigid aluminium rod
  - ---> equip CODALEMA extension
- **<u>November 2011</u>: birth of the 'LONAMOS' LNA** (3)
  - Analog CMOS ASIC designed at Subatech
  - better characteristics than CODALAMP LNA
  - Production of ~800 circuits
- **<u>2011-2012</u>: second upgrade of the Butterfly** (2)
  - Design of a mechanic upgrade(wind stabilization) by RWTH Aachen University, III. Physikalisches Institut A, Aachen
  - ---> equip AERA II and III
- **<u>2013</u> : third upgrade of the Butterfly**
  - CODALAMP is replaced by LONAMOS
  - The LNA of the 60 antenna of CODALEMA are substituted

Butterfly, original version

Butterfly, upgrade 1

Butterfly, upgrade 2

The Butterfly is an active antenna

	Antenna radiating element	LNA	Target
Bandwith	X	X	↗
ΔGroup delay	X	X	↘
Sensitivity	X	X	↗
Linearity		X	↗
Isotropy	X		↗

==> the LNA is <u>as important as</u> the Antenna radiating element for the overall active antenna characteristics

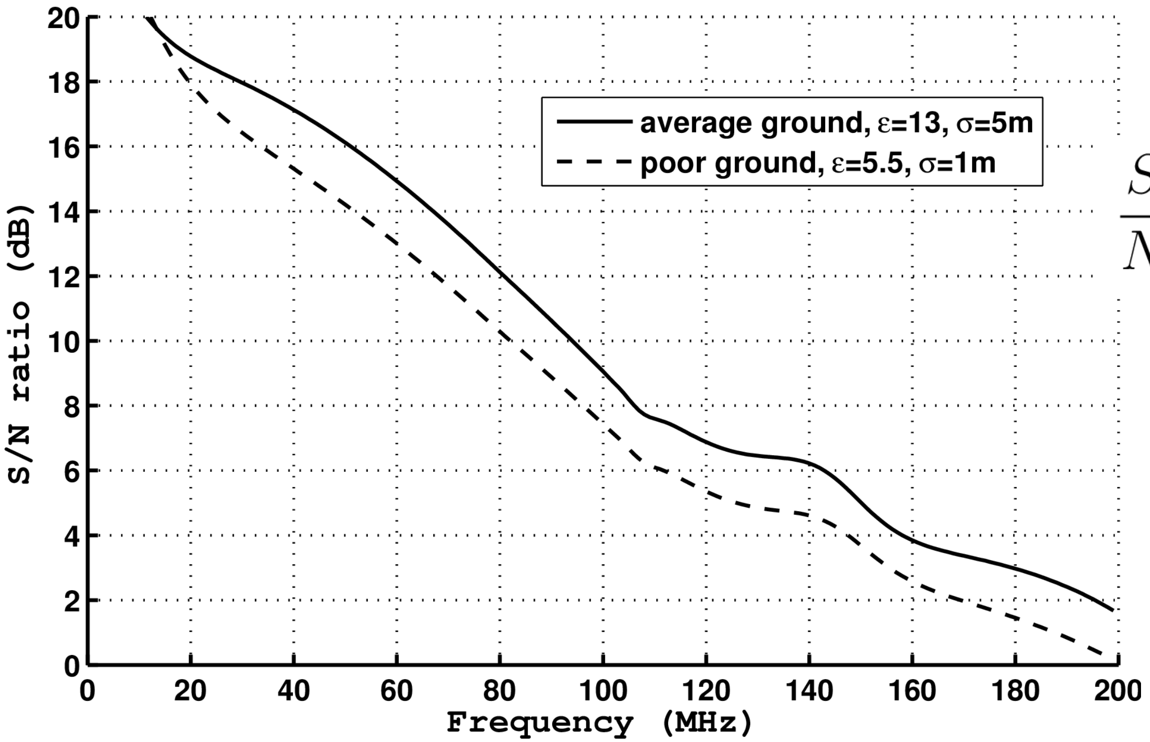
The Butterfly radiating element

- **The butterfly radiating element is a bow-tie dipole**
  - Trade off between a low Q factor - low group delay variation and mechanical complexity
- **The half perimeter length is ~1.6 m**
  - resonance frequency around 45MHz to maximize S/N in [20-80]MHz
- **The height is ~1.5m**
  - Trade off between low frequency antenna efficiency and high frequency isotropy

Sensitivity: signal to noise ratio

- **Noise sources**
  - LNA noise
  - Antenna losses
  - Galactic noise temperature
- **Signal**
  - Ultra high energy cosmic ray (UHECR)
- **For the Butterfly antenna we chose to be galactic noise dominated in [20-80]MHz even if it is not critical for UHECR radio detection**
  - the galactic noise can be used at least as a test source to check the antenna
  - galactic noise may be used to calibrate the antenna
- **We will consider the galactic noise as a signal to qualify the Butterfly sensitivity**

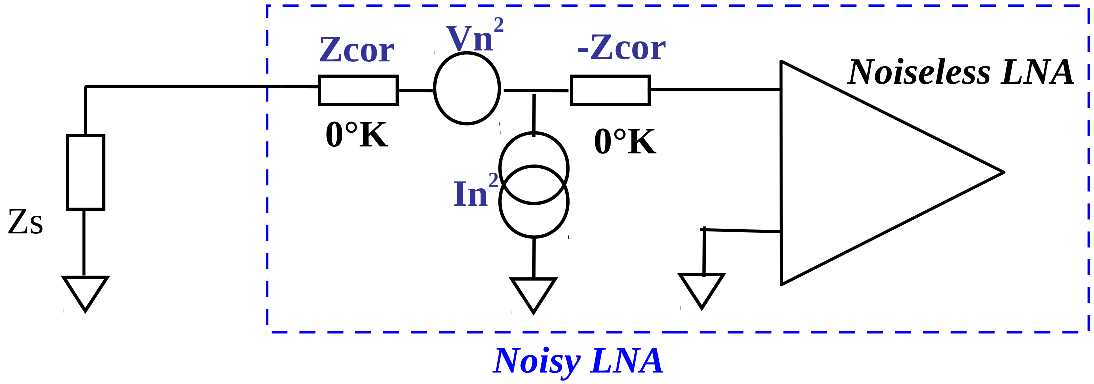
Intrinsic signal to Noise ratio of the Butterfly antenna



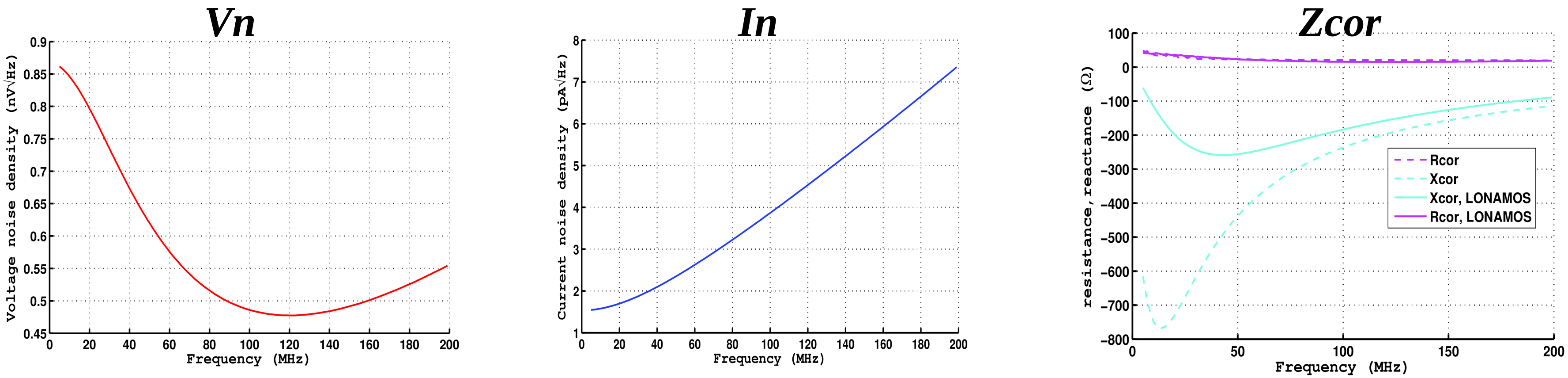
$$\frac{S_{ant}}{N_{ant}} = \frac{T_{gal} R_{rad}}{T_a R_{loss}}, \text{ with } T_a = 290K$$

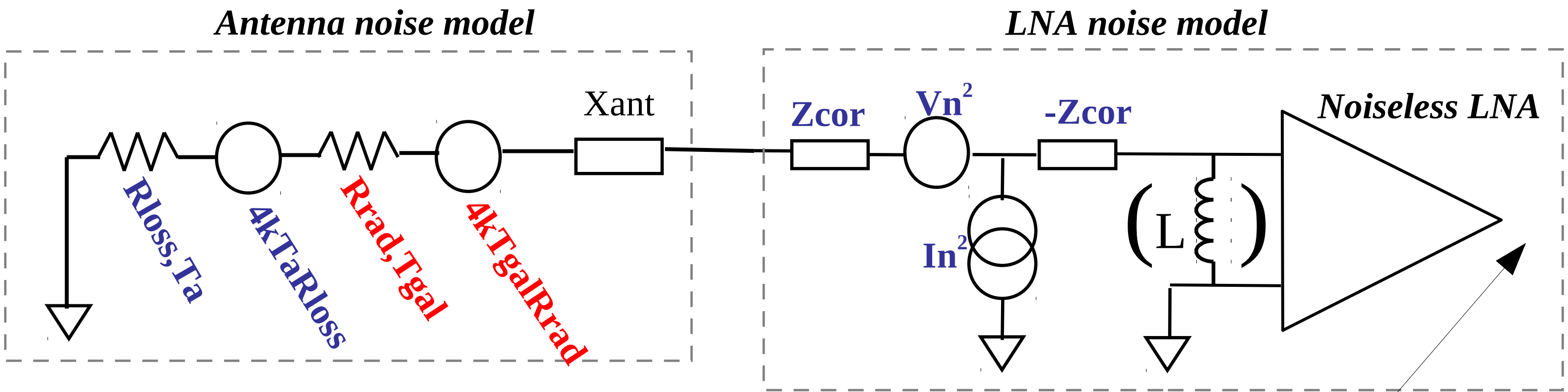
- **The Antenna radiator element as an intrinsic signal to noise ratio**
- **It limits the overall S/N (seen from the LNA output)**
- **It depends on the antenna geometry, the antenna heigh and the ground electric parameters ε and σ**
- **Antenna S/N is decreasing with frequency due to Tgal decrease and is lower than 10dB above ~100MHz ('average' ground)**

Rothe & Dahlke noise model of the LNA



- **4 parameters are required to fully model the noise of a 2-port network**
  - Vn and In are uncorrelated noise sources
  - The correlation is model by Zcor=Rcor + jXcor at 0°K
  - the correlation impedance as no effect on the signal: Zcor+(-Zcor)=0 !
- **Parameters were extracted from simulation on the LONAMOS LNA and cross checked with measurements using reference source impedances: error < 3%**





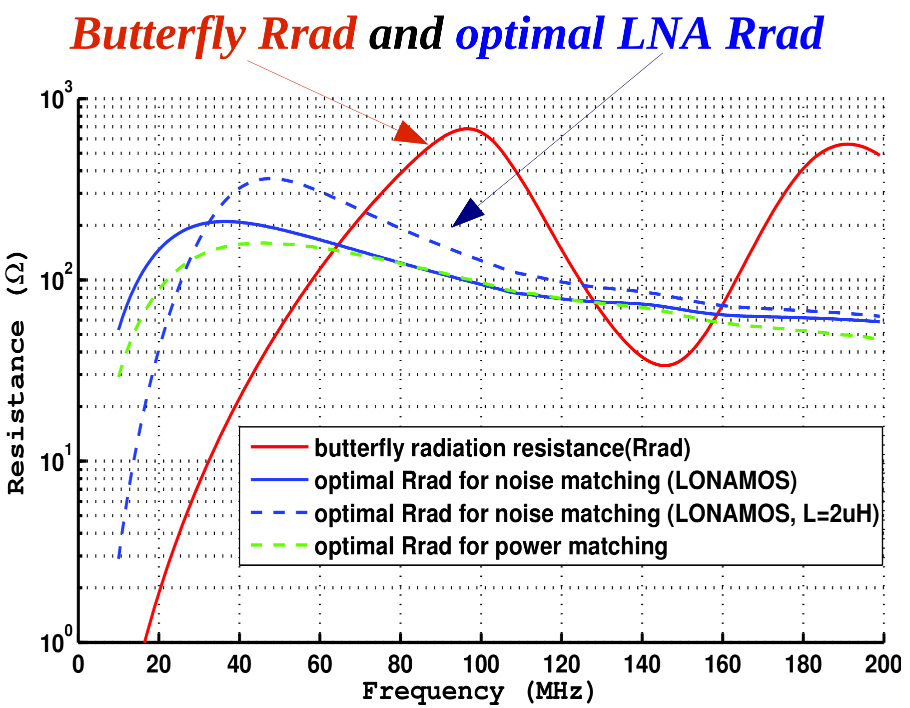
$$\frac{S_{out}}{N_{out}} = \frac{\frac{T_{gal}}{T_a} R_{rad}}{\left(\frac{1-\eta}{\eta}\right) R_{rad} + r_n + g_n \left[\left(\frac{R_{rad}}{\eta} + R_{cor} \right)^2 + \left(X_{ant} + X_{cor} \right)^2 \right]}$$

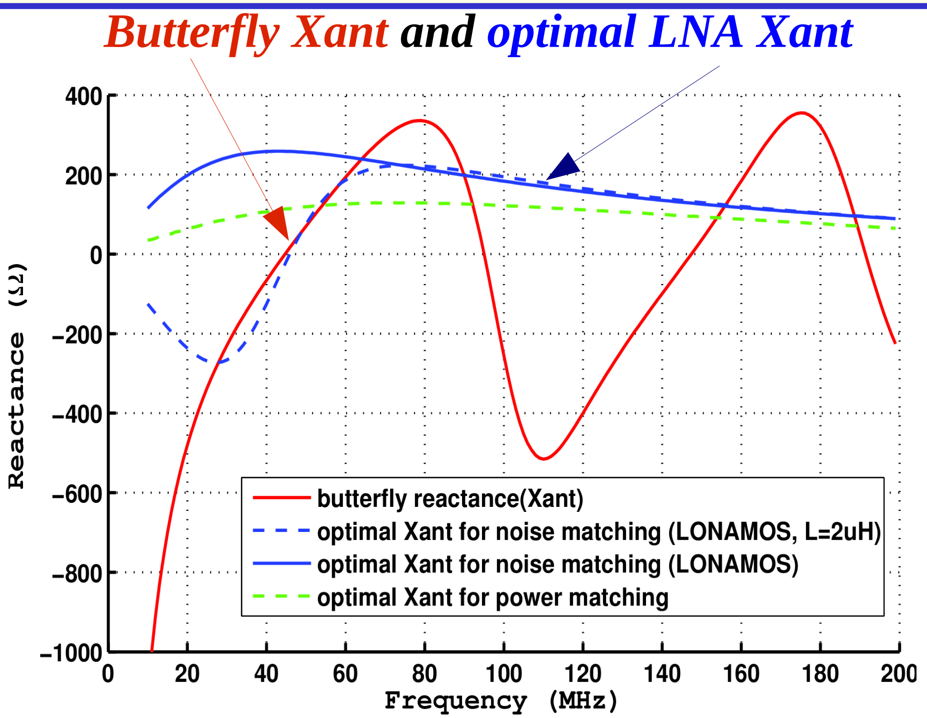
$$r_n = \frac{v_n^2}{4kT_a}$$

$$g_n = \frac{i_n^2}{4kT_a}$$

- **From the full noise model, we calculate the total S/N at the LNA output**
- **The Butterfly antenna is active: LNA placed at the antenna feedpoint**
  - ==> power matching is not required
  - ==> noise matching becomes possible
- **1st solution: adjusting the LNA parameters (rn, gn and Zcor)**
  - minimizing gn ...
  - cancelling Xant by Xcor

Towards noise matching



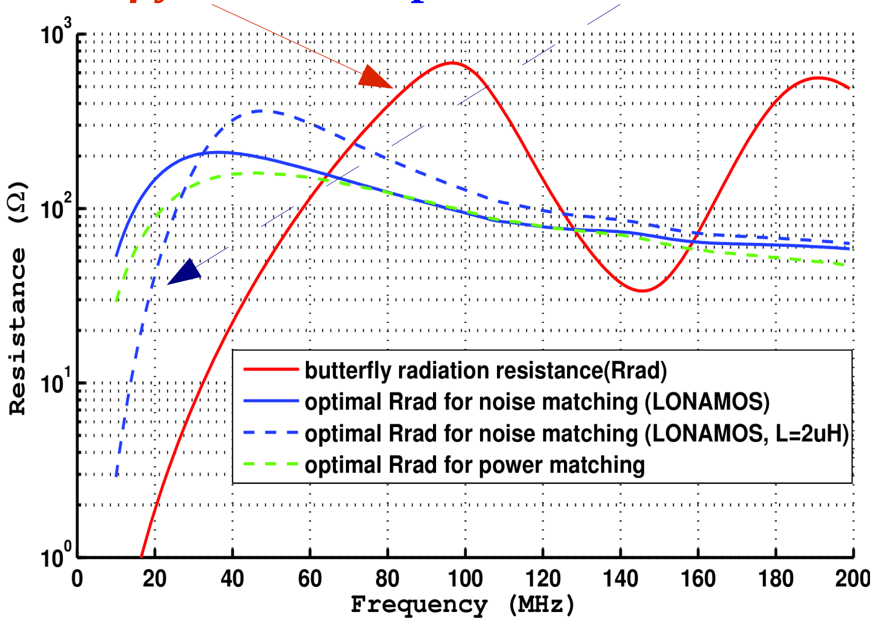


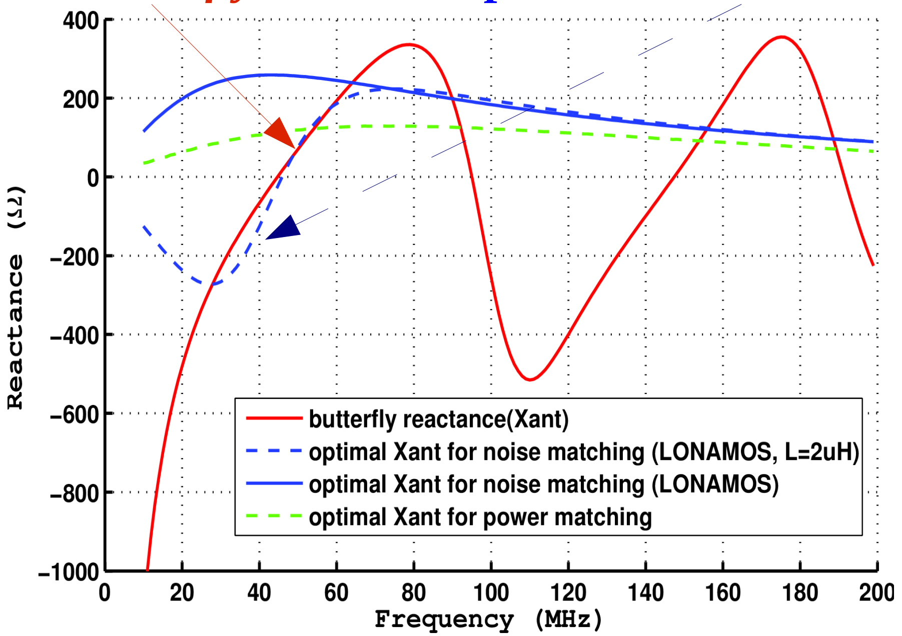
$$R_{rad}^{opt} = \eta\sqrt{R_{cor}^2 + \frac{r_n}{g_n}}$$

$$X_{ant}^{opt} = -X_{cor}$$

- **2nd solution: adjusting the antenna parameters (Rrad, Xant and η)**
  - we calculate the optimum Rrad and Xant that maximize the S/N for a given LNA configuration and a given antenna efficiency
  - We need to decrease the Antenna reactance and radiation resistance variation
  - **==> FAT dipole**

Towards noise matching

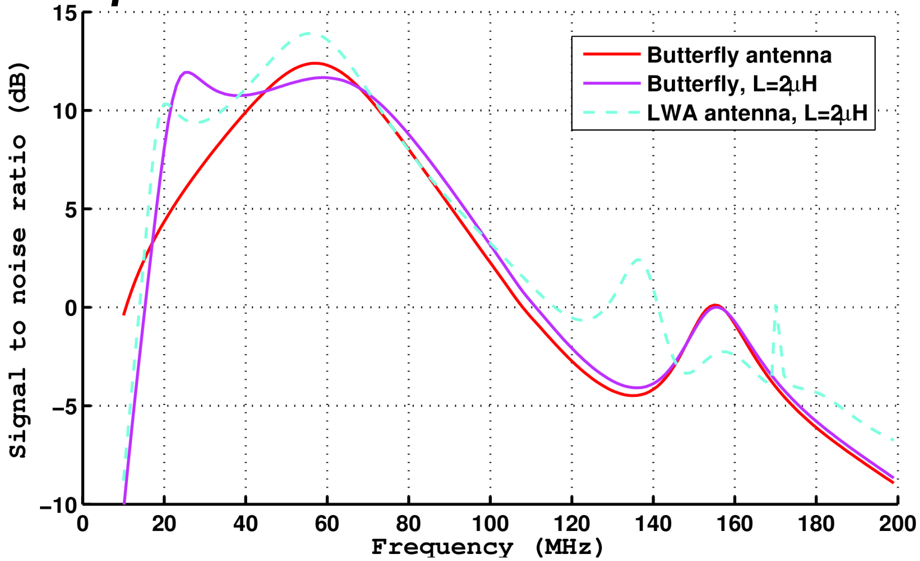




- **3rd solution: adding a noise matching array between the antenna and the LNA**
  - noiseless passive components (transformer, inductance,capacitance)
  - The inductance L connected at the LNA input has 2 purpose
    - filtering low frequencies RFI
    - enhance the low frequencies noise matching
  - ==> noise matching becomes much better in the 15-40MHz band !
  - but, additional matching array may increase the group delay variation

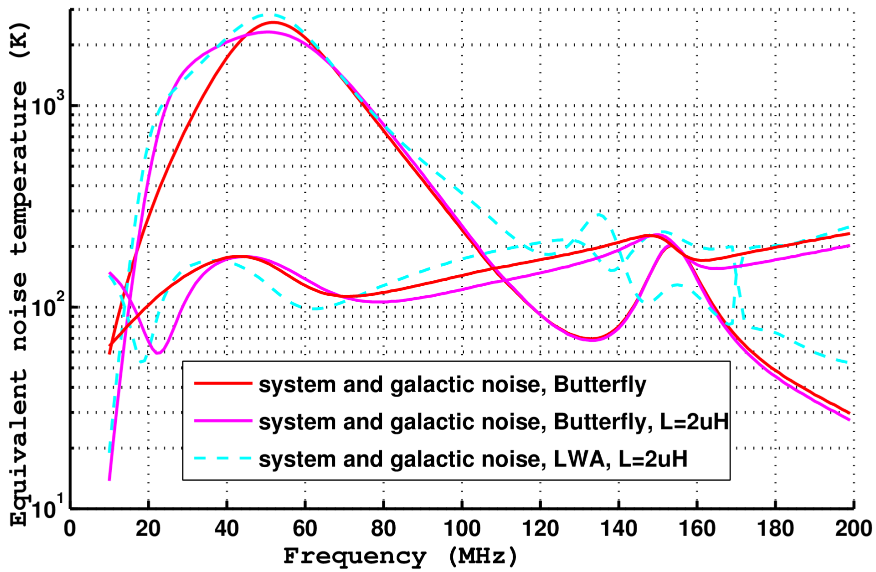
Signal to Noise ratio of the Butterfly antenna

S/N of the BUTTERFLY with LONAMOS LNA



- S/N of the Butterfly-LONAMOS is more than 10dB in ~[40-72]MHz
- The bandwidth is increased to ~[22-75]MH with a noise matching inductance

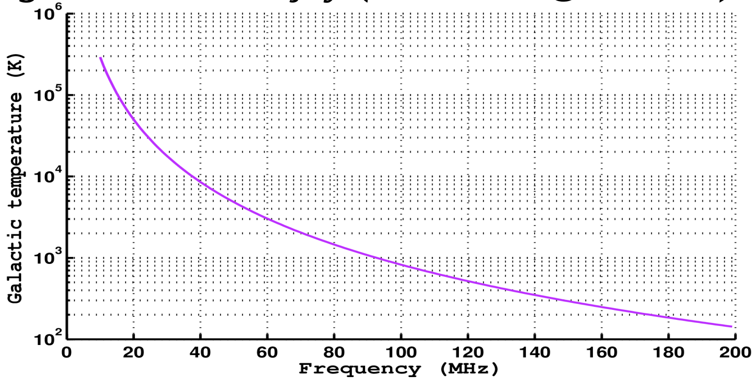
Equivalent noise temperature of the LONAMOS-BUTTERFLY



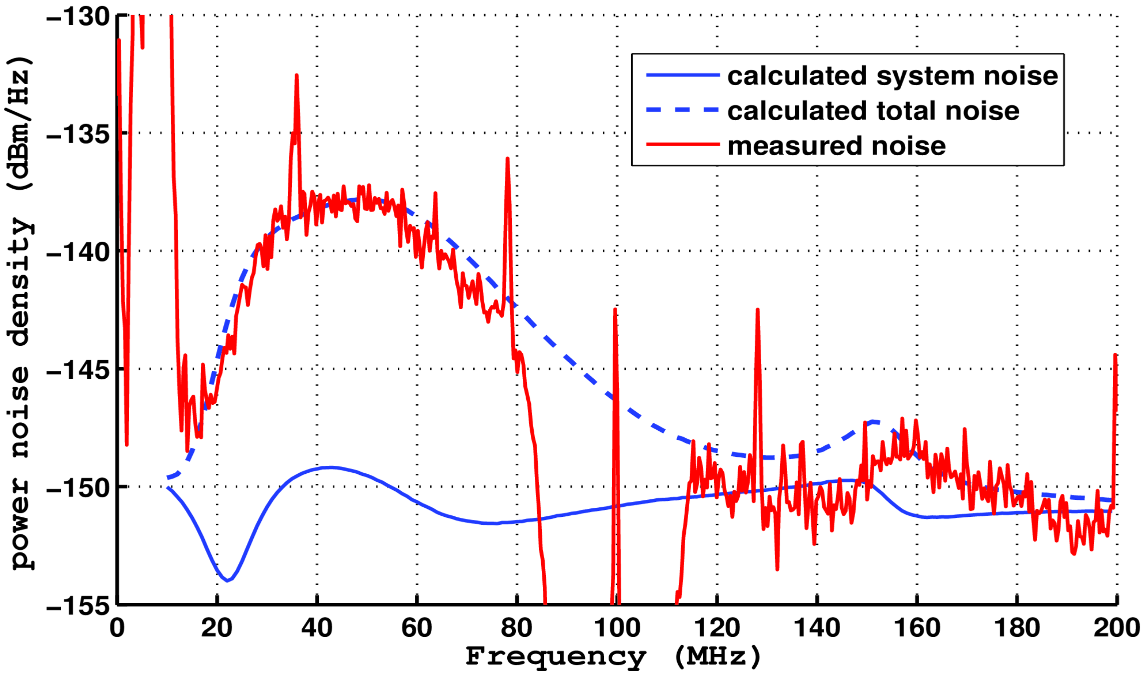
- The equivalent noise temperature of the LNA and the Butterfly losses with the Butterfly impedance as source is less than 200K

Noise measurement versus simulation on the galaxy level

Known galactic temperature data for the minimum galactic at Nançay (T=4830K @ 50MHz)



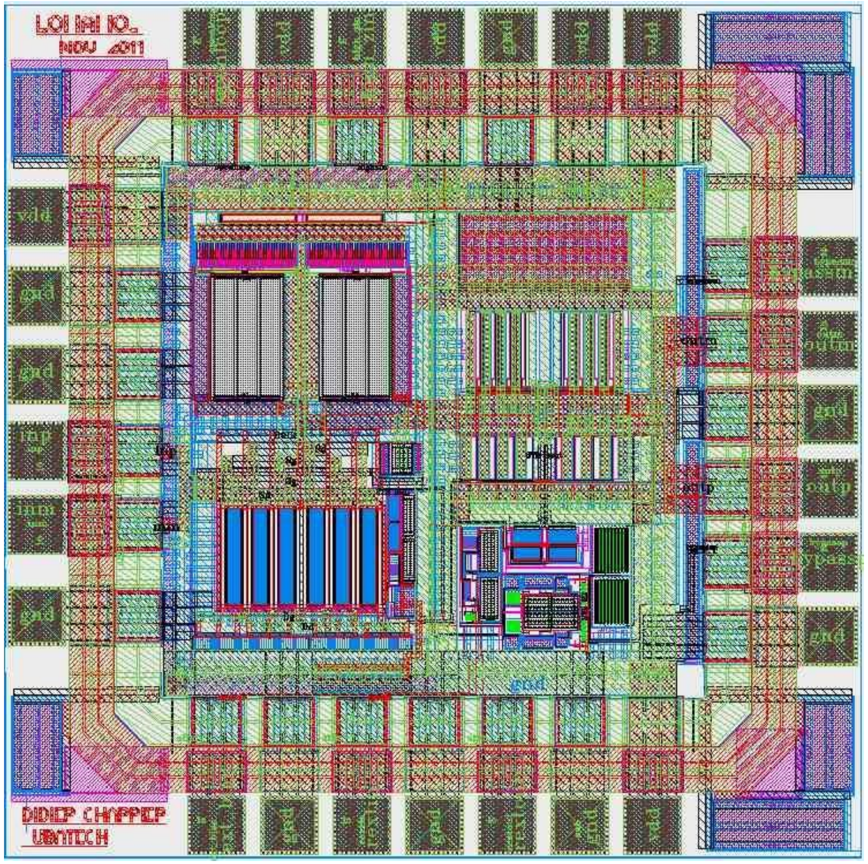
Measurement performed December, 17 2013 at 5H21UTC, minimum galactic



Absolute noise calculation match the measurement.

==> The noise model is fine

the LONAMOS layout

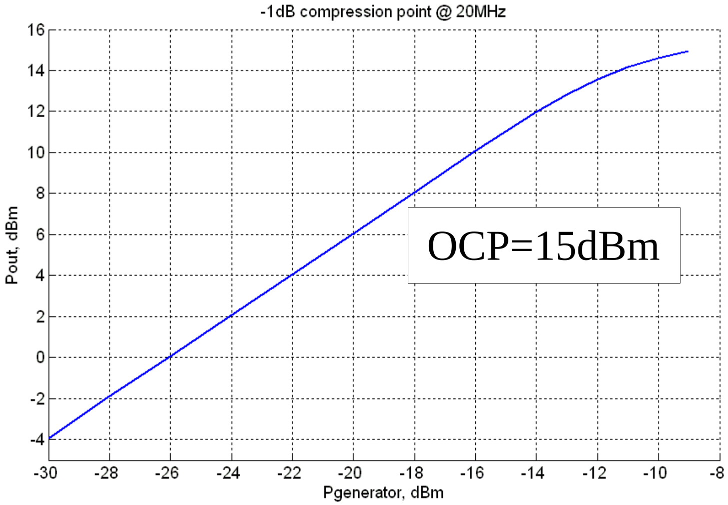


- Fully differential architecture
  - reject even order harmonic products
  - reject common noises
  - no input BALUN required
- Adjustable input impedance

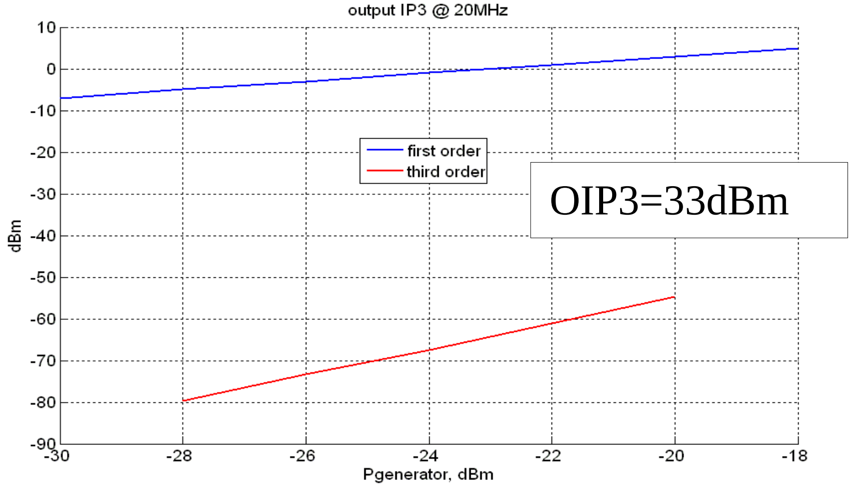
- ASIC (Application Specific Integrated Circuit) designed in 2011 to substitute to the CODALAMP with an up to date technology
- Main goal:
  - Increase the linearity characteristics
  - Decrease the temperature drift and gain uncertainty
- Use the unexpensive AMS CMOS 0.35μ technology
- Area: 1400μ x 1400μ

LONAMOS measurements, OCP, OIP3, NF

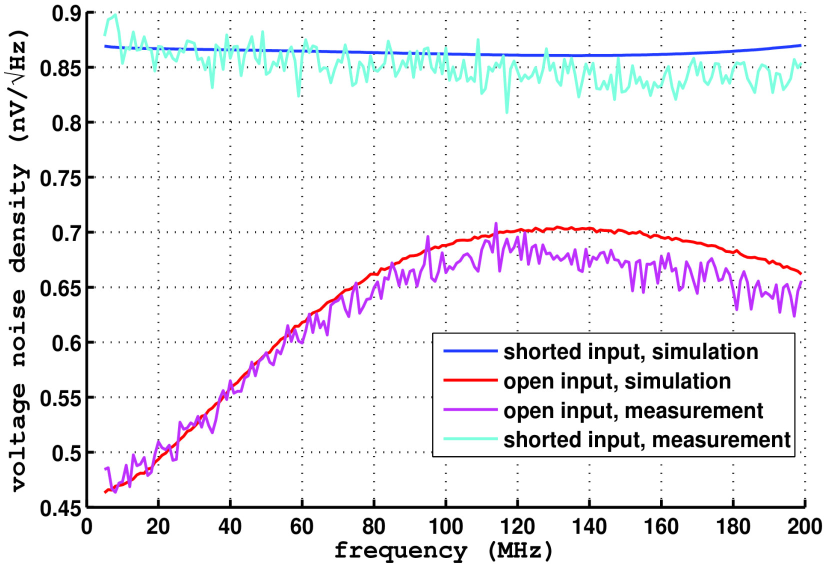
Output compression point measurement



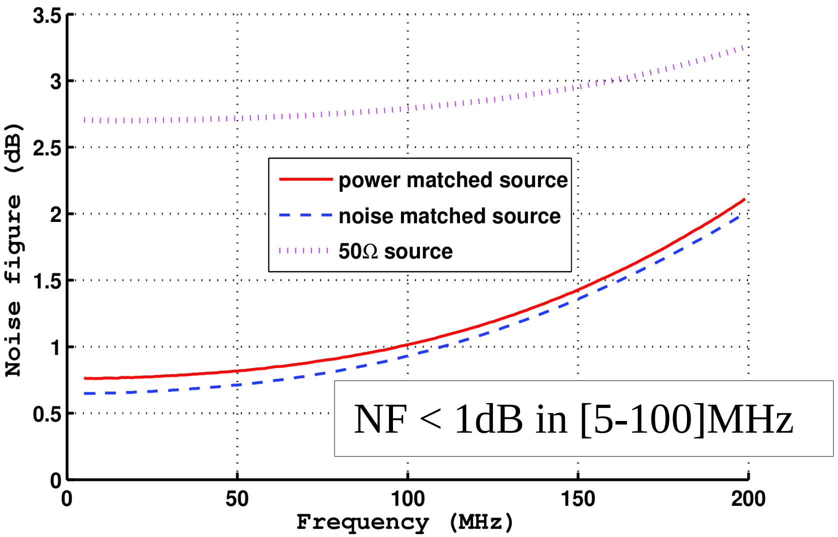
Output 3rd order intercept point measurement



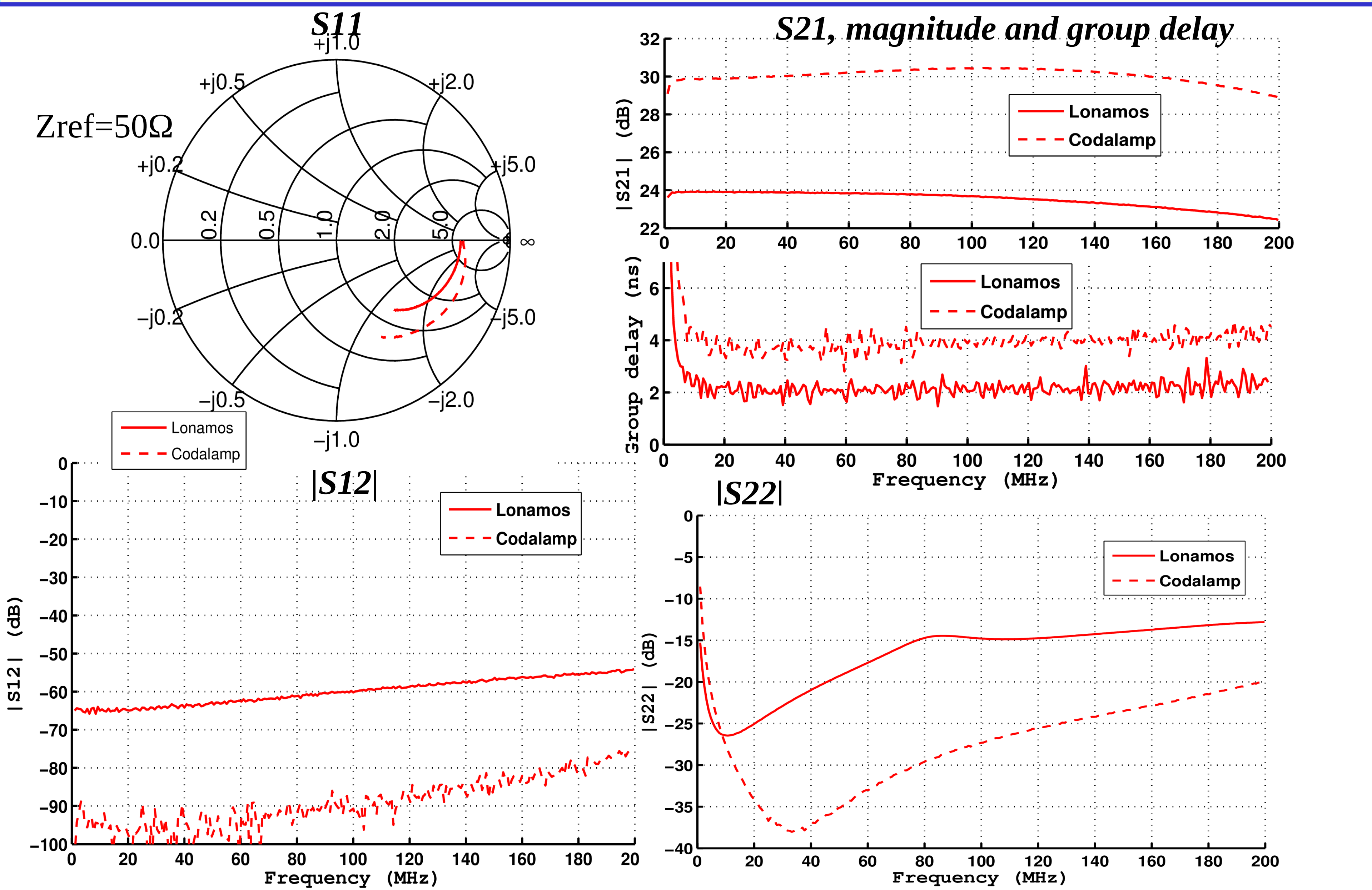
Total output noise measurement/simulation



Noise Figure



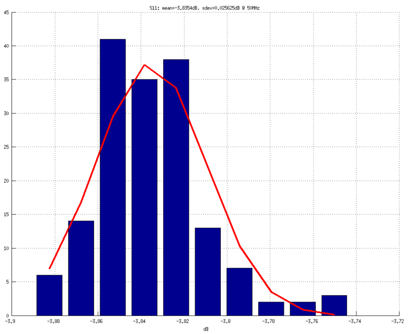
LNA measurements, Scattering parameters



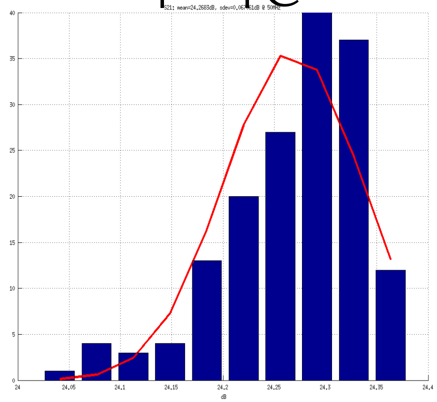
Uncertainty measurements

LONAMOS histogram, N=160

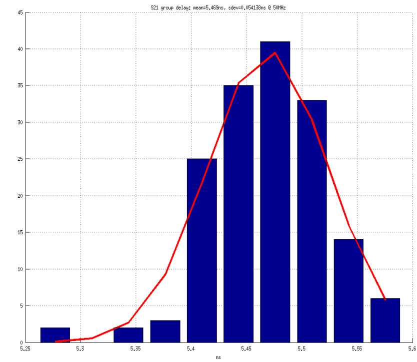
|S11| @ 50MHz



|S21| @ 50MHz



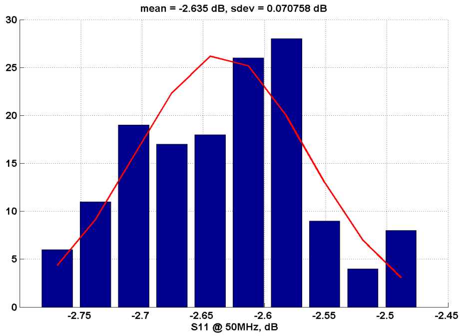
group delay (S21) @ 50MHz



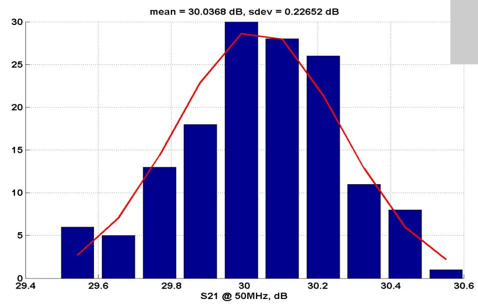
@50MHz	LONAMOS	CODALAMP
|S11|, dB mdB	μ=-3.84 σ=26	μ=-2.6 σ=71
|S21|, dB mdB	μ=24.27 σ=67	μ=30 σ=227
GD(S21), ns ps	μ=5.47 σ=54	μ= σ=

CODALAMP histogram, N=146

|S11| @ 50MHz



|S21| @ 50MHz



LNA characteristics, summary and comparison

	CODALAMP	**LONAMOS**
OIP3, dBm	14	33
OCP(-1dB), dBm	0	15
Gp, dB	33	**27**
IIP3, dBm	-19	6
IIP3, Volt	0.063	**1.1**
NF(matched), dB		**0.8**
NFoptimal, dB		0.7
NF (50Ω), dB	~3.5	2.7
Band, MHz	>200	>200
Sdev(Gain), dB	0.23	**0.07**
Sdev(GD(Gain)),ps		50
T° drift, mdB/°C	-26	**-4**
consumption, mW	310	340

* ICP is 21dB higher
* gain is 6dB lower
* IIP3 is 25dB higher

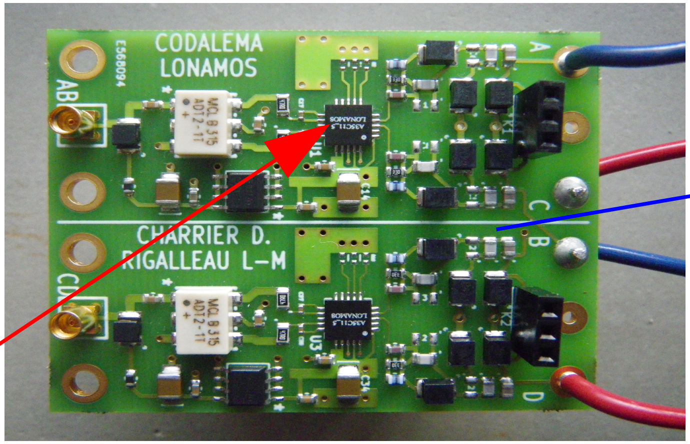
* NF is less than 1dB in [5-100]MHz

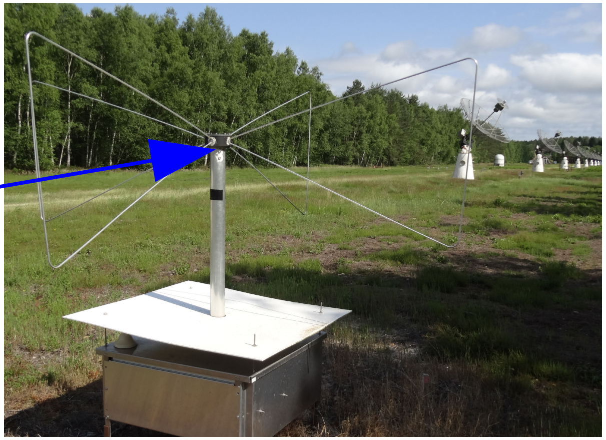
* Gain Dispersion is 3 times lower

* Temperature drift is 6 times lower
* Consumption is similar

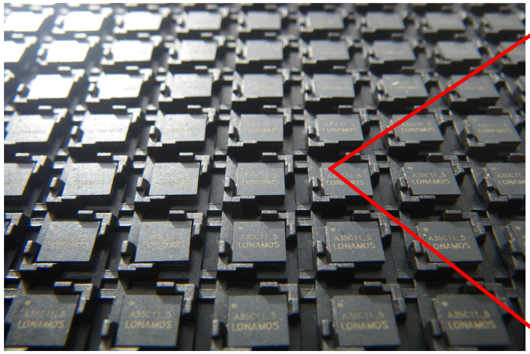
The LONAMOS LNA boards

The CODALEMA-LONAMOS LNA board: equip Butterfly antennas

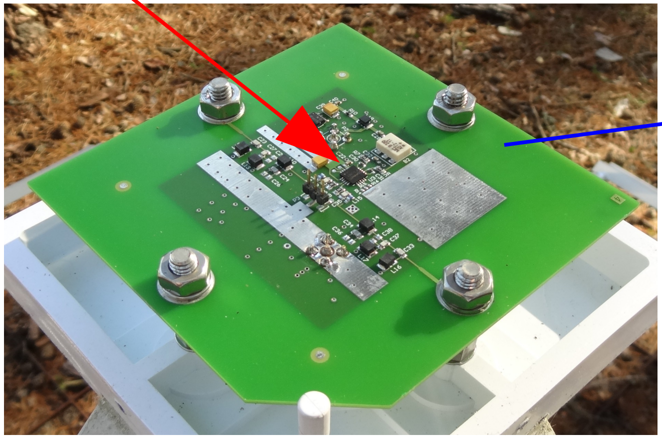


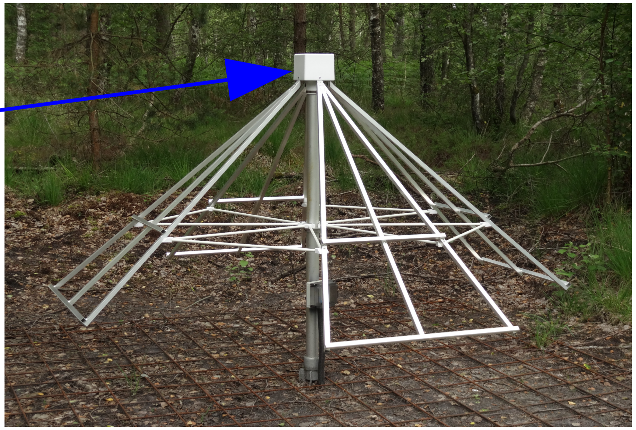


The LONAMOS chip: ~800 circuits were produced



The NenuFAR-LONAMOS LNA board: equip LWA antennas



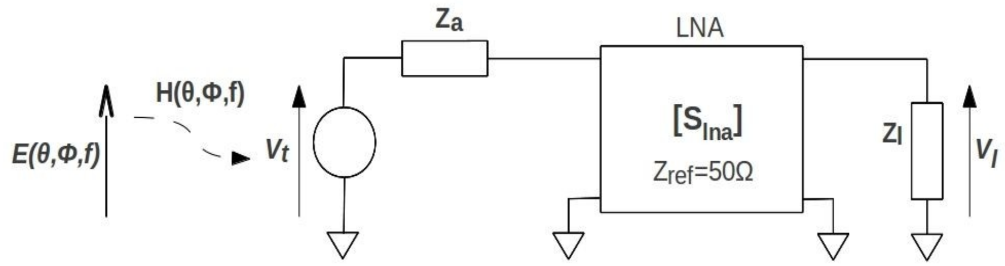


Antenna isotropy in the time domain

- **Antenna are often characterized in the frequency domain by |G|**
  - But We need the phase to work in the time domain !
- **==> we use the vector equivalent length H_{bfy} calculated as the product of**
  - The antenna vector effective height...
  - ...by the transfer function from the antenna terminal point to the LNA output

$$\vec{H}^{bfy}_{(\theta,\phi,f)} = j\frac{2c}{\eta I_t f}\vec{E}_{(\theta,\phi,r,f)} r e^{\frac{j2\pi f r}{c}} \frac{S_{21}}{\frac{Z_{ant}}{Z_{ref}}(1-S_{11})+(1+S_{11})}$$

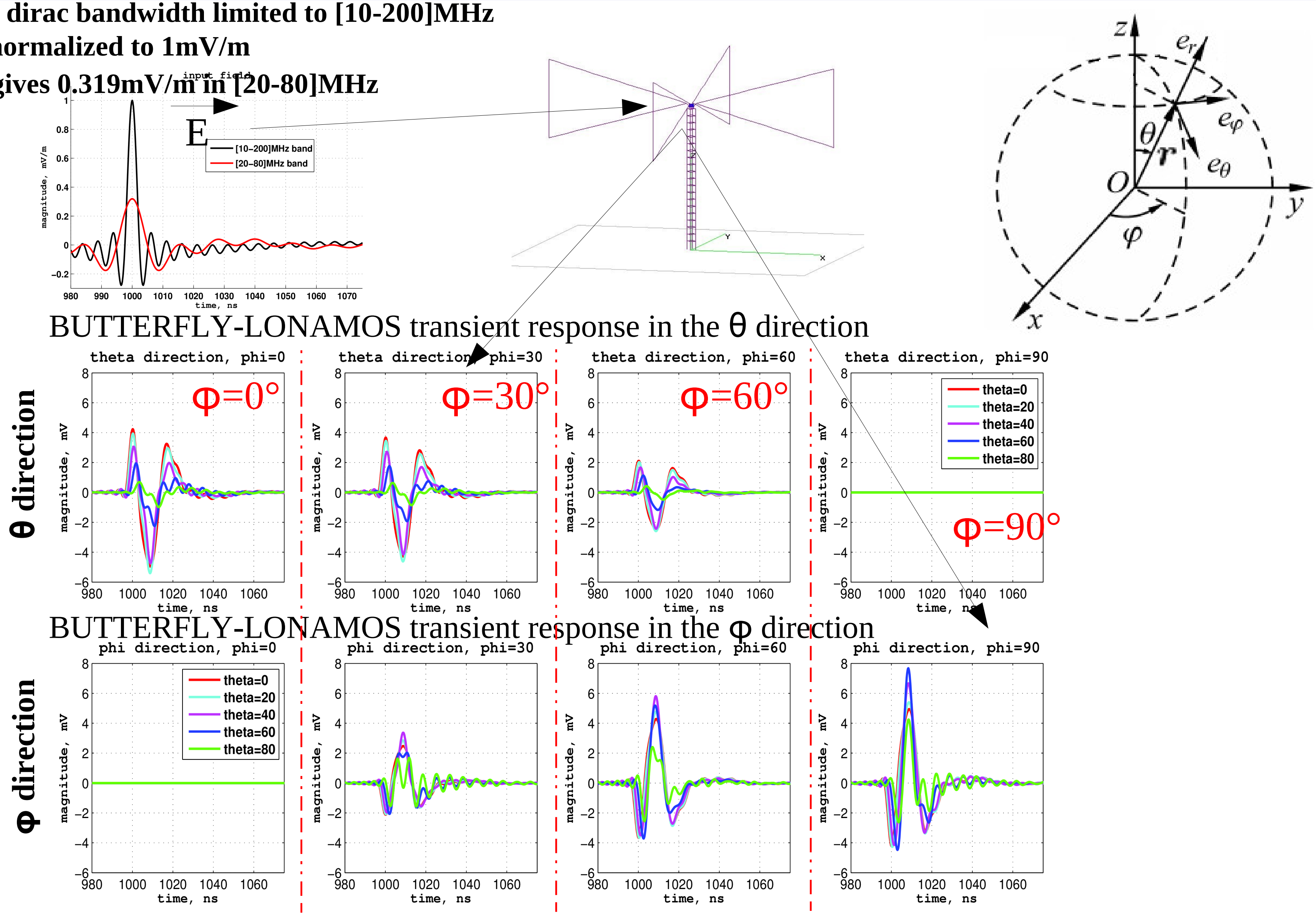
with Zref the reference impedance, η=377Ω, It is the current value used for the transmitting mode simulation, E the vector simulated electric field simulated with NEC



- **The vector equivalent length is calculated along the theta and phi direction of a spherical coordinate system**
- **The vector equivalent length knowledge is necessary to unfold the antenna response and calculate the received electric field in time or frequency domain**

Butterfly response to a Dirac pulse

input dirac bandwidth limited to [10-200]MHz and normalized to 1mV/m
==> gives 0.319mV/m in [20-80]MHz



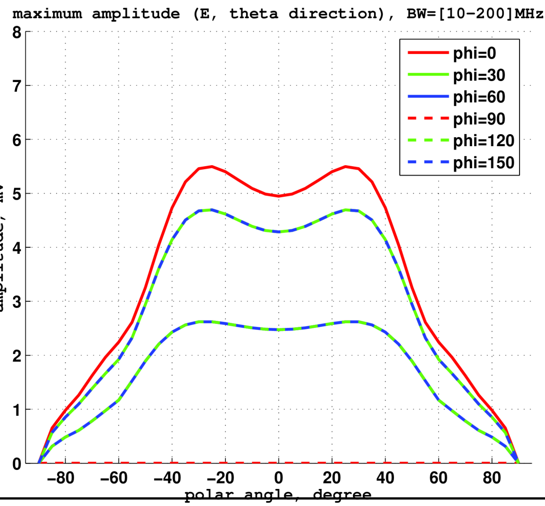
Time domain 'isotropy pattern'

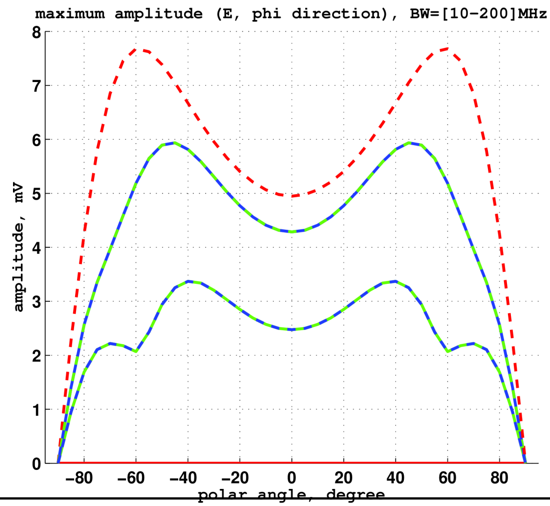
- **We calculate a time domain pattern max(|Vl(t)|) as a fonction of θ, φ and the bandwidth**

theta direction | **phi direction**

[10-200]MHz bandwidth limited

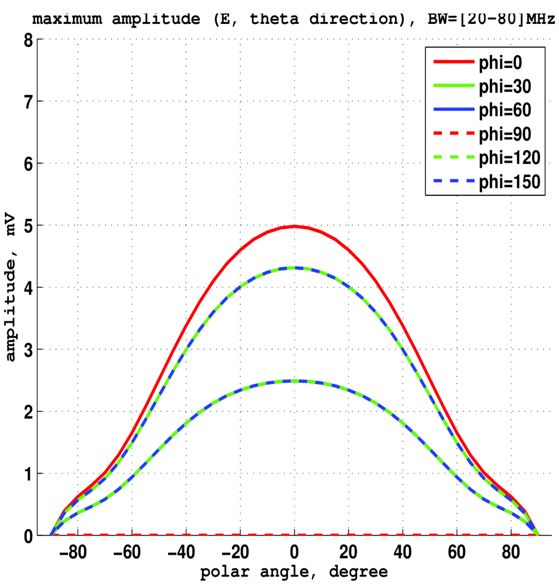
Input impulse amplitude = 1mV/m in [10-200]MHz

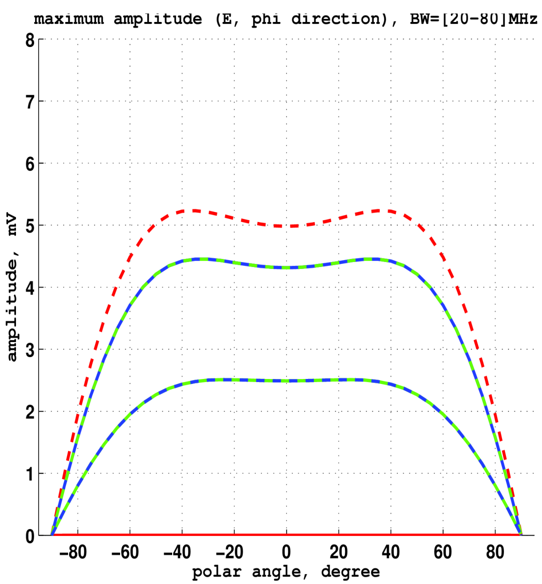




[20-80]MHz bandwidth limited

Input impulse amplitude = 0.319mV/m in [20-80]MHz





Conclusion and outlook

- **The Butterfly antenna is used by many experiments**
  - CODALEMA, Nançay, France: 60 antennas
  - AERA, Malargüe, Argentina: 100 antennas
  - HELYCON, Greece: 6 antennas
  - TREND, Ulastaï, China: 54 antennas
- **The LONAMOS LNA improves characteristics**
  - Linearity
  - Gain uncertainty
  - Temperature drift
  - Sensitivity
- **The LONAMOS gives good results with the LWA antenna on**
  - COMPACT ARRAY, Nançay, France: 10 antennas
  - NenuFAR, Nançay, France: ~57 antennas (~2000 antennas foreseen)
- **A three polarization 'Butterfly like' antenna is under study**

Thank you for your attention