# Radiofrequency communication on a budget: a software approach

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All references available at http://jmfriedt.free.fr

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# Basics of radiofrequency (RF)

The wavelength of an electromagnetic wave is $\lambda = c/f$ or $m = 300/MHz \Rightarrow$ at VHF (30-300 MHz) and UHF (300-3000 MHz), typical wavelengths range from 10 m to 10 cm

- mutiplexing the use of the electromagnetic spectrum
- small dimension antennas replacement of wires
- sensors: frequency is the physical quantity measured with the best accuracy

BUT

strong dependence of the RF characteristics of components ($C = \varepsilon_r \varepsilon_0 \frac{S}{d}$ and $Y = jC\omega$) $\Rightarrow$ the impedance of the circuit substrate is not negligible, components are not ideal ...

# Outline

- Simplify as much as possible the hardware,
- software based signal processing: flexibilty, reliability, multi-purpose hardware
- trend towards replacing all analog communication protocols with digital (television, radio broadcast)
- widely available chips in consumer electronics can be used for less-trivial purposes.

Two reception case examples: NOAA APT satellite reception (VHF, 137.xx MHz), and ACARS plane communication protocol (VHF, 131.725 MHz, AM)

Emission is more challenging: characterization tool & two-chip FM emitter

# Software tools

Software approach requires some development tools – exclusively Free OpenSource Software (FOSS):

- GNU/Octave (replacement for Matlab, general purpose signal processing and plotting) [1],
- New Electromagnetic Code (nec2, antenna radiation pattern [2])
- `ngspice` [3] or `qucs` [4] (replacement for Agilent ADS)
- `gnuradio` [5] and associated graphical user interface `gnuradio-companion` [6]

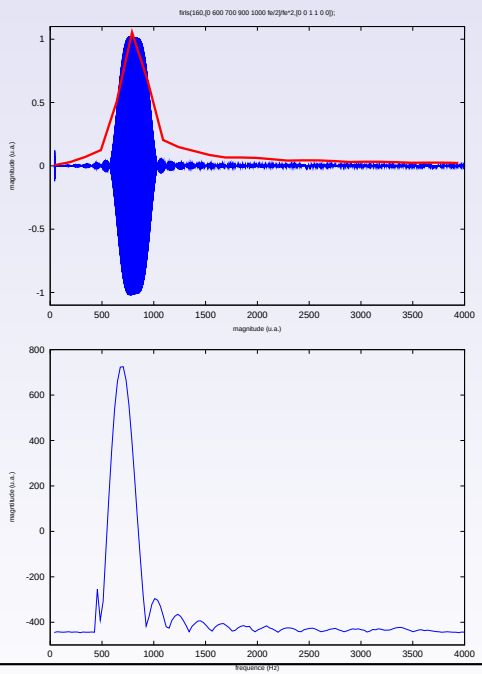
[1] `www.gnu.org/software/octave`
[2] `www.nec2.org`
[3] `ngspice.sourceforge.net`
[4] `qucs.sourceforge.net`
[5] `gnuradio.org`
[6] `www.joshknows.com/grc`

# GNU/Octave

Design of a Finite Impulse Response (FIR) filter using GNU/Octave [7] (mostly Matlab compatible)
Find $b_n$ so that the future ($y$) being a linear combination (convolution) of the past ($x$) matches some known transfer function:

$$y_n = \sum_{k=0..m} b_k x_{n-k}$$

The *sampling rate* $f_e$ is normalized and knowing its value is fundamental in designing the filter




```
fe=16000;
ffin=4000;
fdeb=40;

b=firls(160,[0 600 700 900 1000 fe/2]/fe*2,[0 0 1 1 0 0]);
x=chirp([0:1/fe:5],fdeb,5,ffin);
f=linspace(fdeb,ffin,length(x));
plot(f,filter(b,1,x));

freq=[fdeb:150:ffin];
k=1;
for f=freq
  x=sin(2*pi*f*[0:1/fe:1]); y=filter(b,1,x); sortie(k)=max(y);
  k=k+1;
end
hold on;plot(freq,sortie,'r')
xlabel('frequence (Hz)') ylabel('magnitude (u.a.)')
```

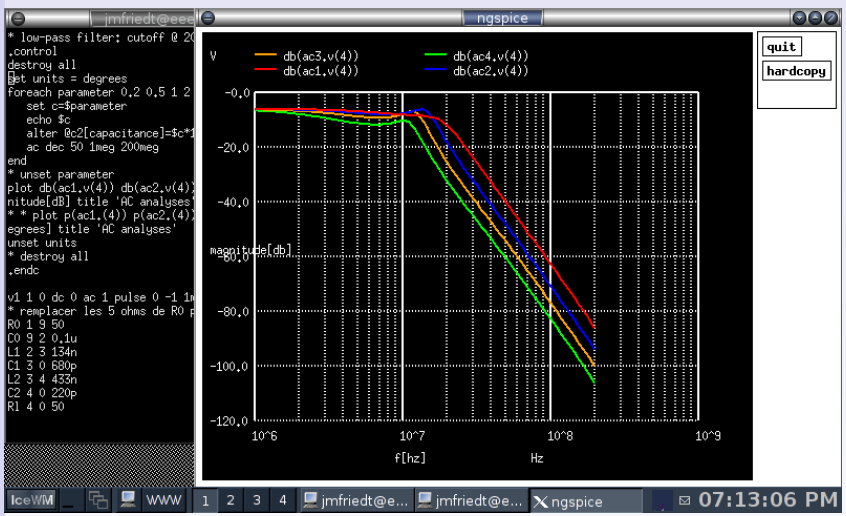
Top: modelling, blue by filtering a chirp, red by sampling discrete frequencies.

Bottom: experimental measurement of a FIR bandpass filter tuned for [700:900] Hz.

[7] J.-M Friedt, *Affichage et traitement de données au moyen de logiciels libres*, GNU/Linux Magazine France, 111 (Dec. 2008), `jmfriedt.free.fr/lm_octave.pdf`

# SPICE simulator

- SPICE (Simulation Program with Integrated Circuit Emphasis) is not dedicated to RF but a general purpose simulator also suitable to mechanical and thermal simulations [8],
- graphical user interface available (`sourceforge.net/projects/gspiceui`) but using the raw text-mode configuration file allows for scripting (parameter loop).




Butterworth low pass filter simulation: transfer function as a function of parameter value

[8] J.-M Friedt, *Introduction à SPICE3 : simulation de circuits électroniques, et au-delà*, OpenSilicum 1 (Janvier-Mars 2011), `jmfriedt.free.fr/lm_spice.pdf`

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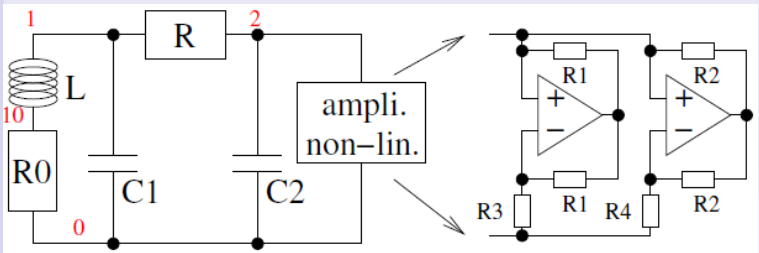
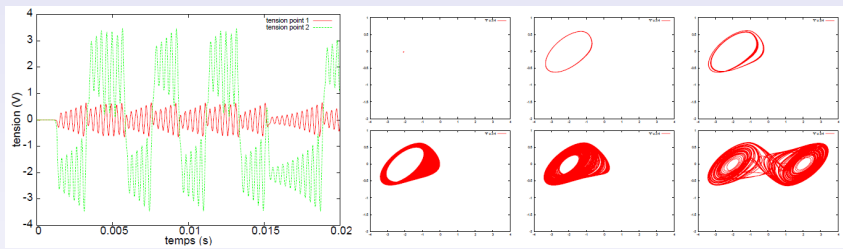


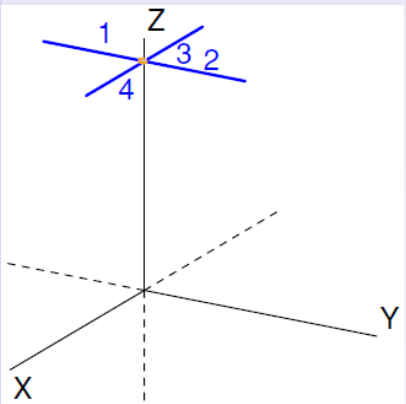



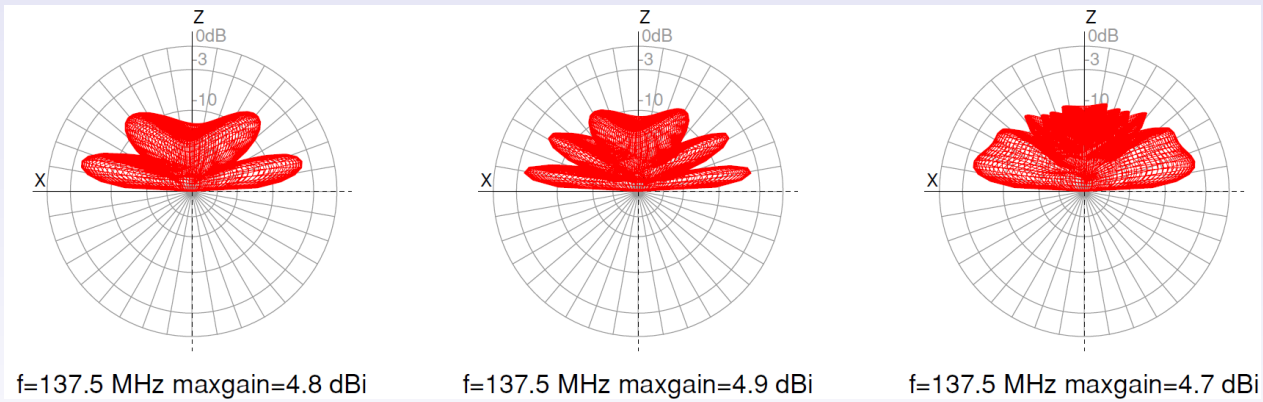

Time-domain evolution of the voltage of Chua's chaotic circuit, and phase-space strange attractor (requires an accurate model of op-amp).

[8] J.-M Friedt, *Introduction à SPICE3 : simulation de circuits électroniques, et au-delà*, OpenSilicum 1 (Janvier-Mars 2011), `jmfriedt.free.fr/lm_spice.pdf`

# NEC antenna radiation pattern simulation

- Radiofrequency $\Rightarrow$ requires a radiating element (antenna) to grab or generate signal
- Two fundamental parameters: impedance at operating frequency, and directivity (radiation pattern)
- Time consuming to tune experimentally

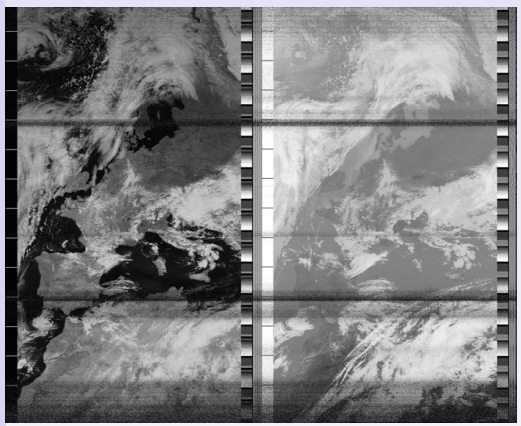


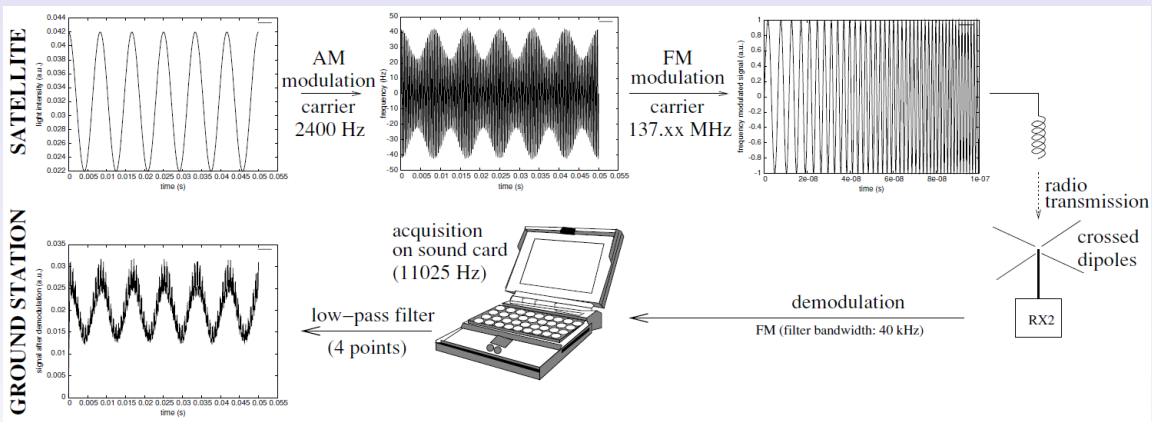




Radiation pattern of a crossed dipole (circular polarization) antenna as a function of height to a conducting ground plane.

# NOAA satellite receiver

- Analog front end, digital DDS defines the mixer frequency (RX2 at `www.rig.org.uk/shop.htm`, 100 euros)
- *Software* decoding using sound card
- Satelllites rotating around the Earth at 800 km altitude (90 minute period), continuously transmitting the received light intensity (scanning probe microscopy approach !)



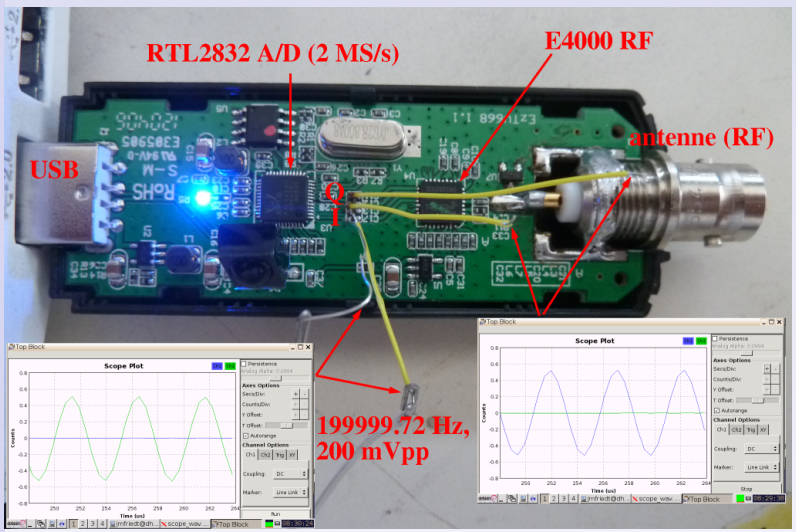


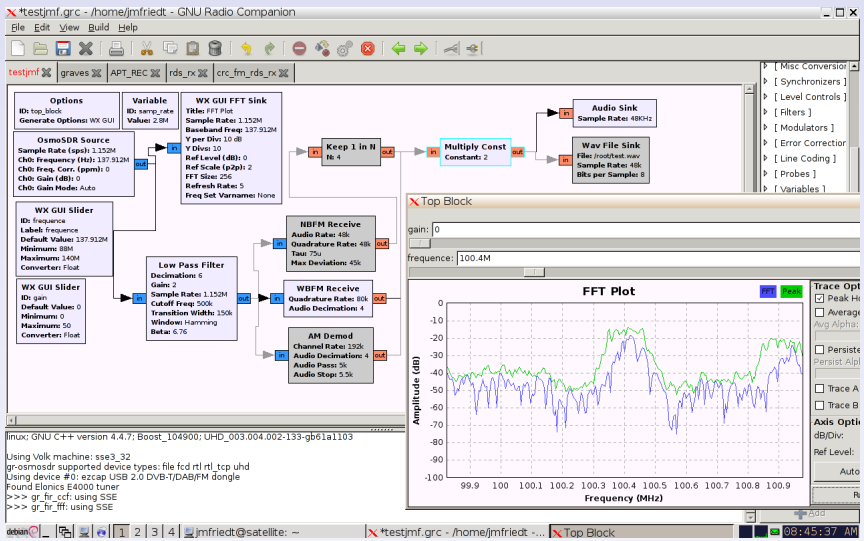

Received image ranges from Scandinavia to Mauritania [9](pixel 4×4 km$^2$)

[9] J.-M Friedt, *Satellite image eavesdropping: a multidisciplinary science education project*, European Journal of Physics **26** (Aug. 2005) pp.969-984 `jmfriedt.free.fr/ejp196357p16.pdf`, or J.-M Friedt, S. Guinot, *La réception d'images météorologiques issues de satellites : principes de base*, GNU/Linux Magazine France, Hors Série 24 (Février 2006), `jmfriedt.free.fr/LM_sat1.pdf`

# Digital protocol decoding: gnuradio

EZCAP based on the Elonics E4000 chip ($\leq$20 $ DVB tuner USB dongle) is a general purpose 2.5 MS/s dual channel ADC with a zero-IF RF front end

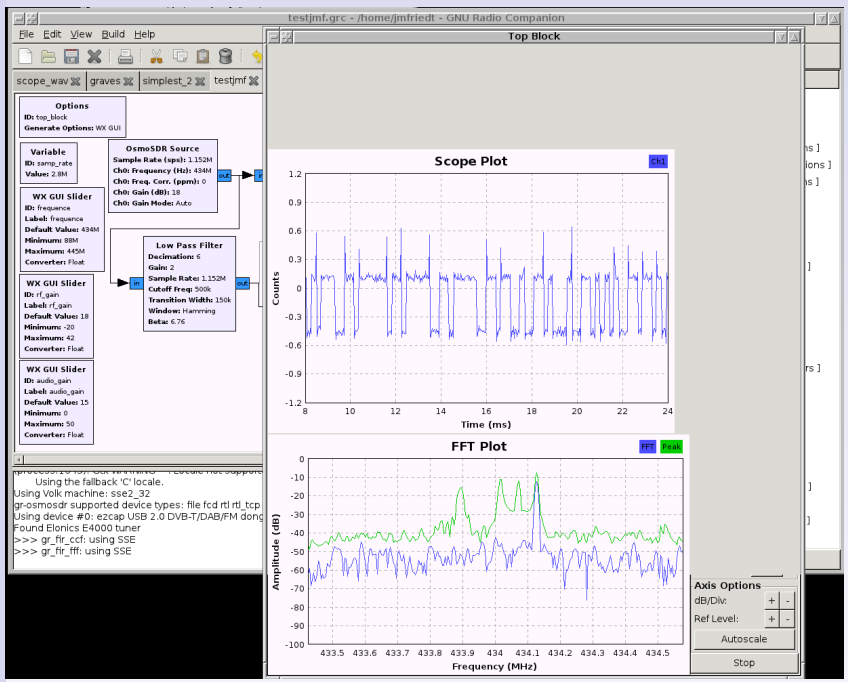



$\Rightarrow$ if the RF front end is not used, convenient fast acquisition card (faster sampling rate than sound card, but lower resolution)[10]

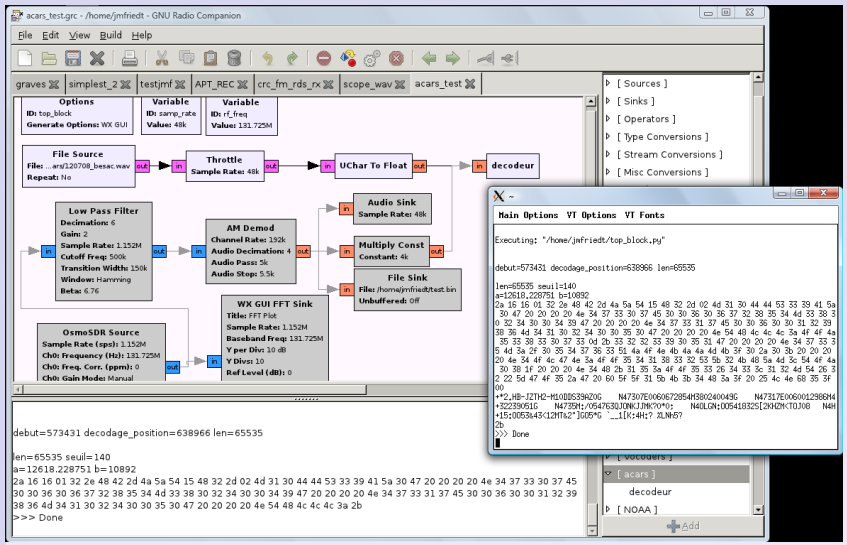
[10] J.-M Friedt, G. Goavec-Mérou, *La réception radiofréquence définie par logiciel (Software Defined Radio – SDR)* GNU/Linux Magazine France 153 (Octobre 2012), pp.4-33, `jmfriedt.free.fr/lm_sdr.pdf`

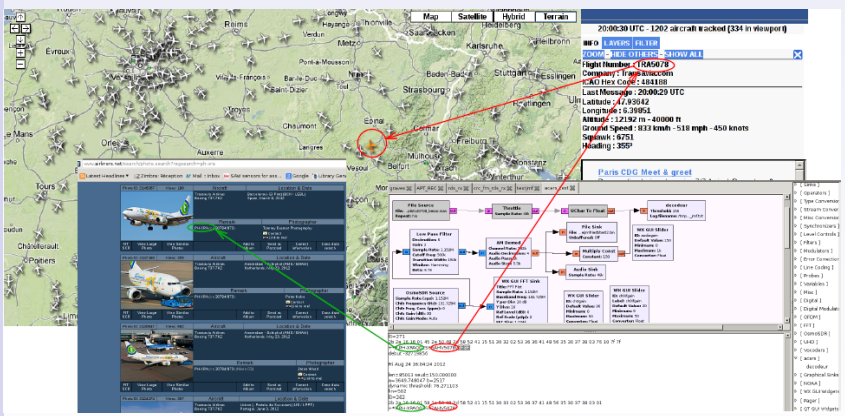
# Digital protocol decoding: `gnuradio`




1. Frequency shift keying: the demodulator output is immediately representative of the bit coding.
2. Decoding the digital information is a matter of threshold, identify message beginning, and checksum verification

# Digital protocol decoding: gnuradio




Beyond the use of the readily available signal processing blocks, use the basic functions of `gnuradio` (demodulation) and add our own processing functonalities:

1. record the demodulated signal as a binary file
2. develop all processing algorithms under a scipting language (GNU/Octave, SciPy)
3. convert these algorithms to C(++)
4. comply with `gnuradio-companion` block architecture

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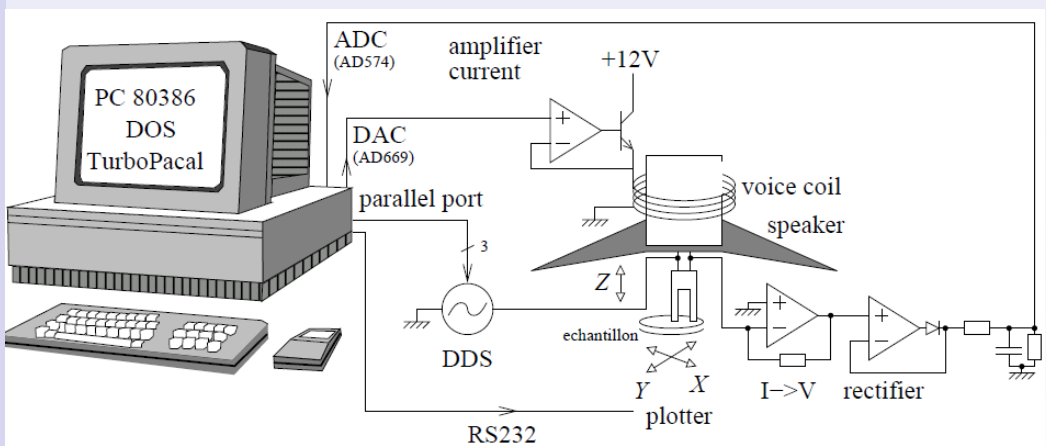
# SDR-based reception of signals from space

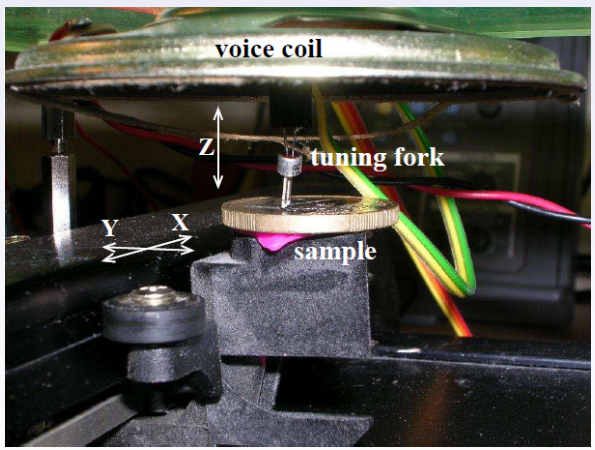
- S. Markgraf has demonstrated reception of NOAA satellite using the EZCAP dongle: `http://rof.li/pic/groundplane/`
- J.A. Lázaro at Barcelona has demonstrated the reception and decoding of GPS signals using this SDR:
  `http://www.gnss-sdr.org/documentation/gnss-sdr-operation-realtek-rtl2832u-usb-dongle-dvb-t-receiver`

Decoding raw GPS information opens the realm of atmospheric research (moisture, ionospheric electron density, secondary reflection of GPS signals)

# Radiofrequency emission

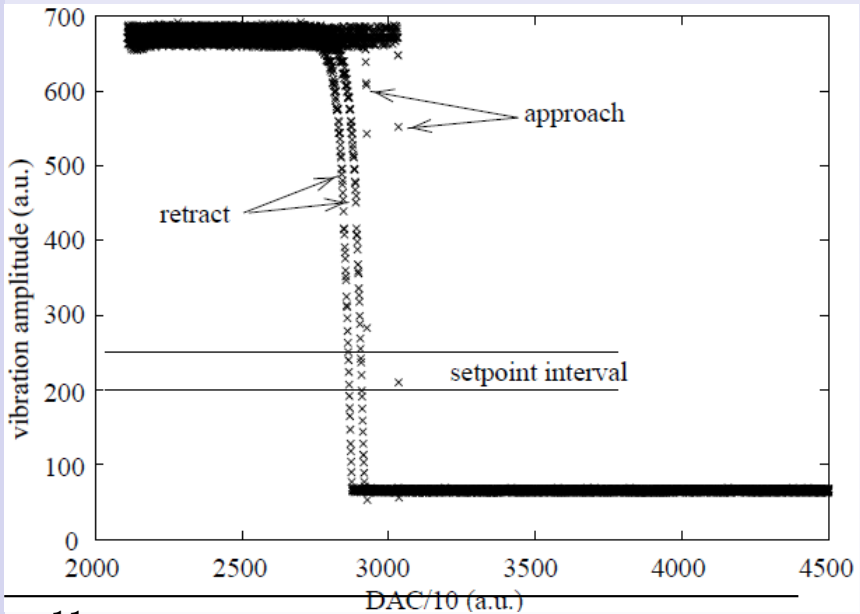
- Challenge of complying with regulations: requires characterization of multiple parameters (emitted power, harmonics, spurious)
- Intrinsic radiofrequency transducer characterization: Quartz Crystal Resonator as gravimetric detector (ten ng/cm$^2$ typical resolution) and quartz tuning fork as scanning probe distance sensor
- Availability of digitally controled radiofrequency sources: Direct Digital synthesizer (DDS) – Analog Devices AD9851 & AD9954S
- Availability of I/Q demodulators, power detectors (AD8302, AD8362) $\Rightarrow$ homemade network analyzer ($S_{21}$)

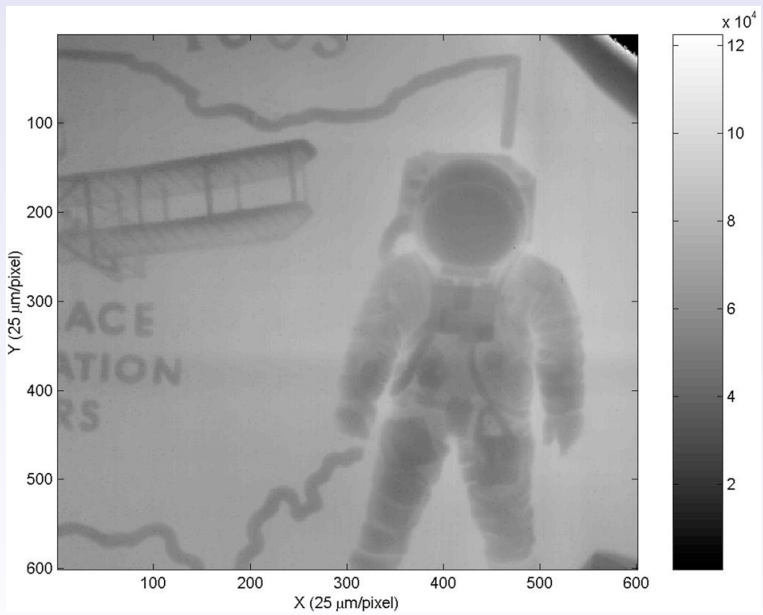


# Scanning probe microscopy application

- Having identified the signal-distance transfer function (bijective), raster scan the probe over the surface of the object to be characterized.
- Either closed loop (keep the operating poing of the sensor: increased range and linearity related to the transducer) or open loop (record signal as a function of position – fast !) [11]

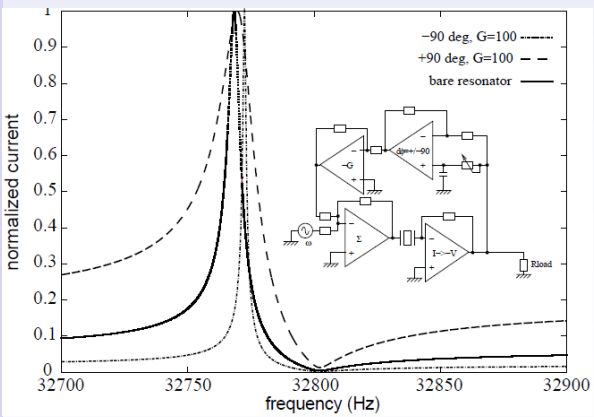


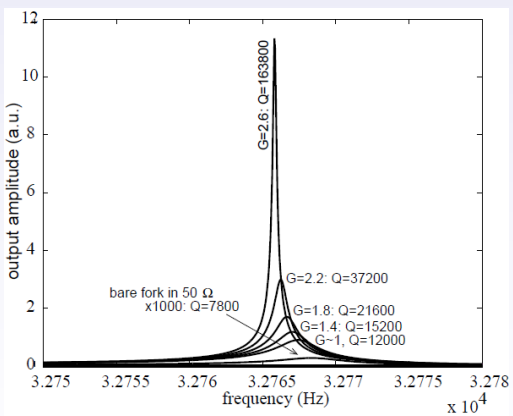



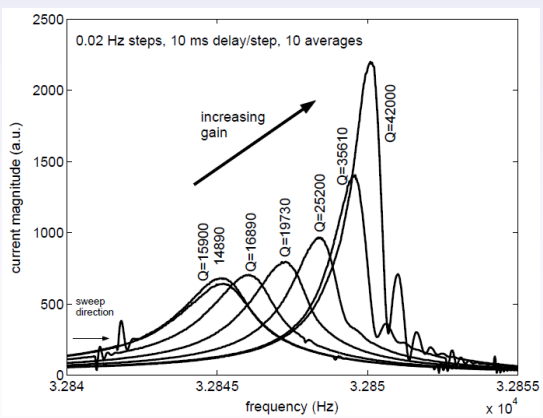

[11] J.-M Friedt, E. Carry, *Introduction to the quartz tuning fork*, American Journal of Physics (May 2007), pp.415-422, `jmfriedt.free.fr/proof_AJP_diap.pdf`

# Quality factor tuning

- Oscillation is only an asymptotic case of injecting more energy in a band pass filter (resonator) than the losses.
- By injecting energy in phase or out of phase with the electromechanical transducer current, quality factor $Q$ (defined as stored energy/energy lost during each period) is increased or decreased.
- Application to scanning probe microscopy: the higher the $Q$, the more accurate the resonance definition, but the longer the settling time ($Q/\pi$ periods) $\Rightarrow$ use in liquid (increase) or air (lower) $Q$ tuning

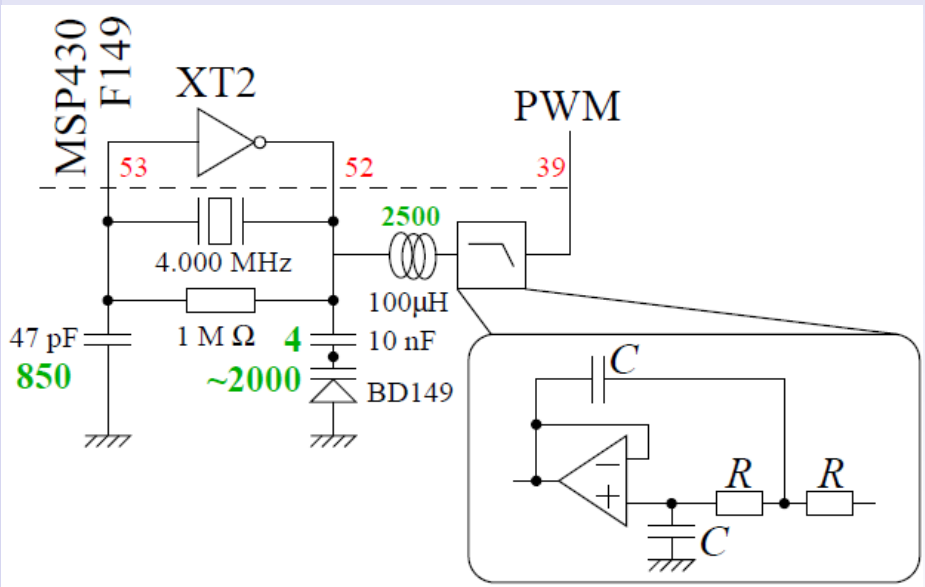


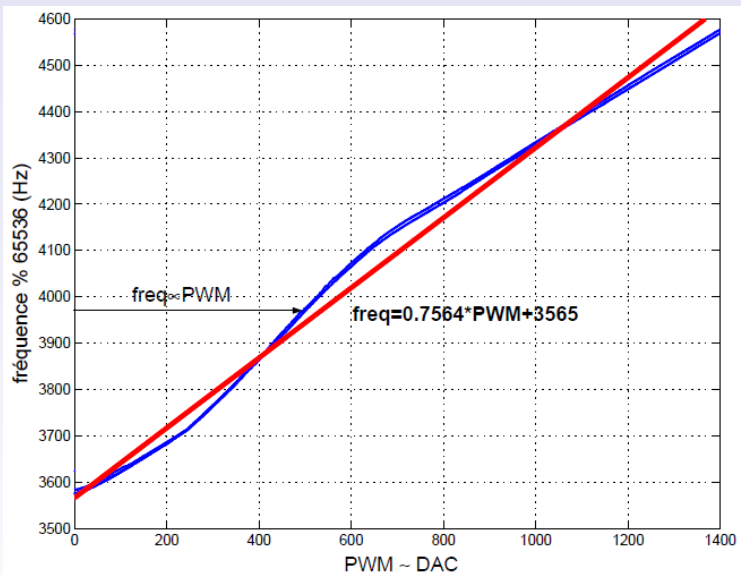



# GPS disciplined oscillator

- Acoustics (electromechanical resonators) provides high short term stability ($< 10$ s) but long term drift due to aging and temperature depenence.
- GPS is basically a combination of information gathered from atomic clocks onboard satellites, beamed to Earth using a radiofrequency link. The time information is provided to the user as the 1 PPS output [12].




[12] J.-M. Friedt, A. Masse, F. Bassignot, *Les microcontroleurs MSP430 pour les applications faibles consommations – asservissement d'un oscillateur sur le GPS*, GNU/Linux Magazine France 98, Octobre 2007, `jmfriedt.free.fr/lm_msp430.pdf`

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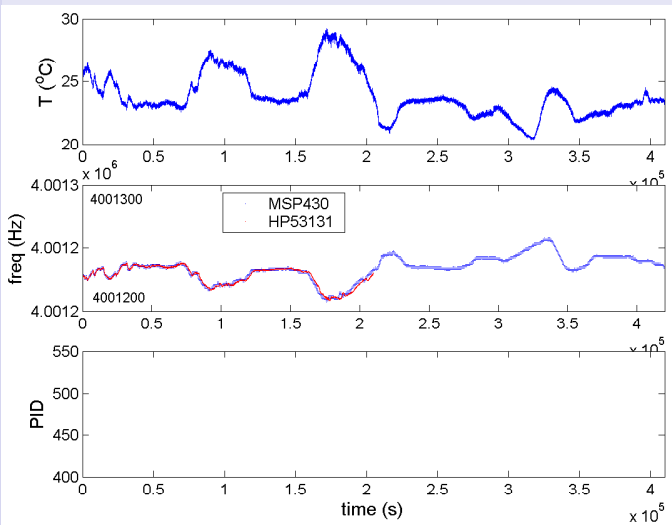


The 10 K temperature variation would have yielded 40 Hz variation, while the GPS disciplined oscillator variation (peak to peak) is less than 5 Hz. Temperature variations are visible on the control signal.

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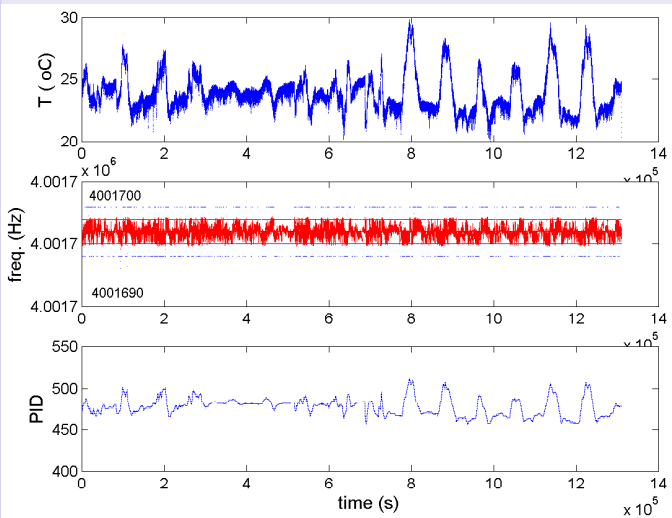


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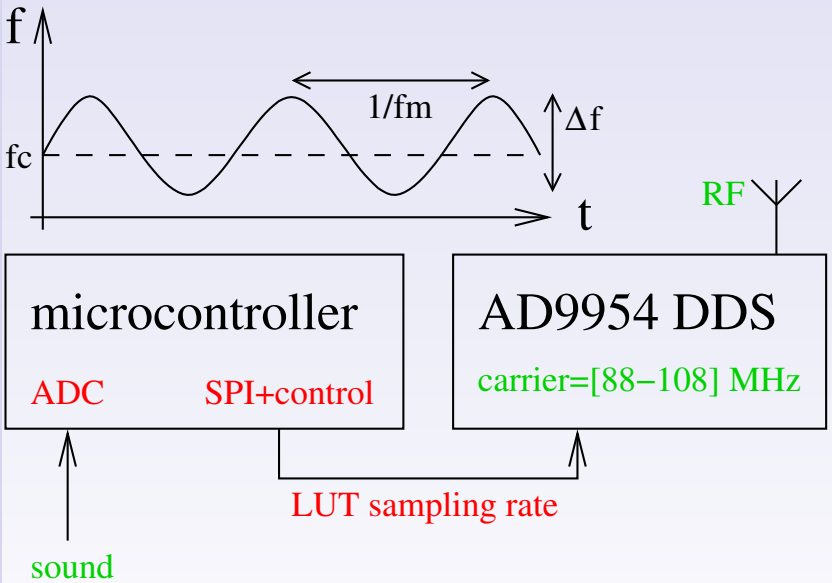
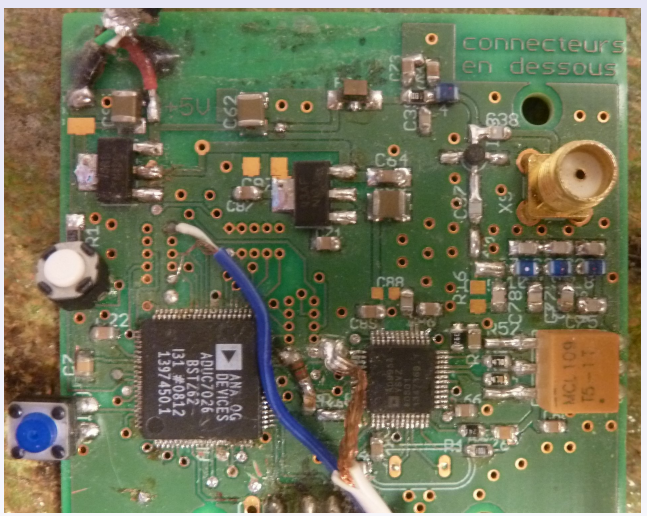
# Two-chip digital FM emitter

- Frequency modulation = vary the frequency of the emitted carrier $\omega_c$ at a rate proportional to the input signal (excursion and modulation frequency) $signal(t) = A \times \sin\left(\omega_c t - \frac{\Delta f}{f_m}\sin(\omega_m t)\right)$
- AD9954 provides a look-up table (LUT) with the (radio)frequencies to be emitted ⇒ a microcontroller [13] samples the input signal, programs the LUT *sampling rate* while the carrier frequency is fixed




[13] J.-M Friedt, É. Carry, *Développement sur processeur à base de cœur ARM7 sous GNU/Linux*, GNU/Linux Magazine France 117 (Juin 2009), pp.40-59, `jmfriedt.free.fr/lm_arm.pdf`

# Conclusion

- Software approach for flexibility and hardware cost reduction (single hardware for multiple uses)
- Exclusively open-source tools, here running under GNU/Linux, but now often available for proprietary operating systems
- Wide (and increasing) availability of radiofrequency components in (cheap) consumer electronics
- Understanding the detailed behaviour of these components allows for diverting from their original purpose

**Beyond radiofrequency**: embedded digital electronics (microcontroller), game console & organizers (iPod), routers

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