Software Defined Radio based scientific instrumentation using SDR frontends and oscilloscopes for fast measurements

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References at http://jmfriedt.free.fr

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Basics on RF instruments

What kind of instruments can be addressed by SDR ? (non exaustive)

- spectrum analyzers: measures the spectral components of a source
- (vector) network analyzers (coherent emitter & receiver): measures the spectral response of a Device Under Test [1]
- lock in detectors [2] [3] : typically narrow bandwidth detection of a signal modulated at a known frequency [4] [5]
- basic physics [6] [7], scanning probe microscopes

[1] http://pavel-demin.github.io/red-pitaya-notes/vna/

[2] G.A. Stimpson, M.S. Skilbeck, R.L. Patel, B.L. Green & G.W. Morley, *An open-source high-frequency lock-in amplifier*, Rev. Sci. Instrum. **90**, 094701 (2019)

[3] A. Tourigny-Plante & *al.*, *An open and flexible digital phase-locked loop for optical metrology*, Rev. Sci. Instrum. **89**, 093103 (2018)

[4] P. Mahnke, *Characterization of a commercial software defined radio as high frequency lock-in amplifier for FM spectroscopy*, Rev. Sci. Instrum. **89** 013113 (2018)

[5] J.A. Sherman & R. Jördens, *Oscillator metrology with software defined radio*, Rev. Sci. Instrum. **87** (5) 054711 (2016)

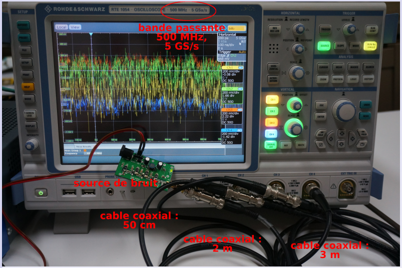
[6] C.J. Hasselwander, Z. Cao, W.A. Grissom *gr-MRI: A software package for magnetic resonance imaging using software defined radios*, J. Magnetic Resonance **270** 47–55 (September 2016)

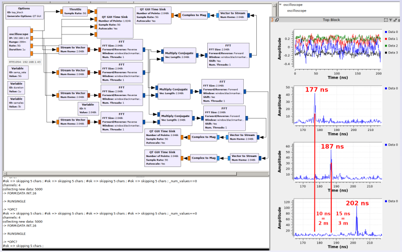
[7] F.F Balakirev *& al.*, *Resonant ultrasound spectroscopy: the essential toolbox*, Rev. Sci. Instrum. **90**, 121401 (2019) for a Redpitaya based instrument

Oscilloscope as radiofrequency frontend

Applications: large bandwidth, **no need for continuous datastreams**

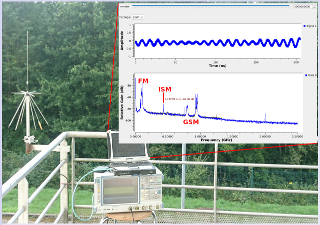
- Example: time-of-flight (reflectometry) measurement

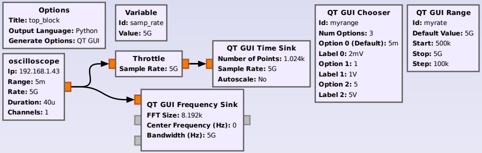




- Range resolution is $\Delta R = c/(2B)$ with B the signal bandwidth
- $B = 1$ GHz $\Rightarrow \Delta R = 15$ cm
- $B = 5$ GHz $\Rightarrow \Delta R = 3$ cm
- here "white" (broadband) noise source feeds a "broadband" load (RG58 coax cable)
- range as cross-correlation maximum position

Oscilloscope as radiofrequency frontend





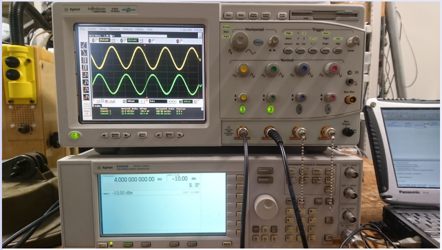
- plotting spectra does not require continuous stream
- mapping all transmissions from f_s/N to $f_s/2 = 2.5$ GHz: broadband spectrum analyzer
- lower frequency limited by FFT length: $N = 8192 \Rightarrow 0.6$ MHz
- *but* poor dynamic range (72 dB @ 12 bit ADC): ratio of strongest to weakest signal

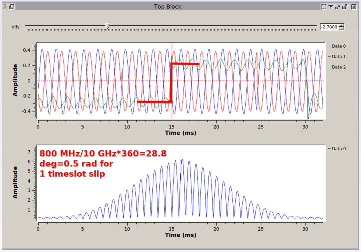
Oscilloscope as radiofrequency frontend

Dedicated `gr-oscilloscope`[8] source block communicating through Ethernet (VXI11)

User configurable (callback function in GNU Radio 3.8)

- oscilloscope IP address
- sample rate (bandwidth)
- measurement duration (number of samples)





- detect transient events hardly visible on a single screen capture (loss of 1 sample between channels)

[8] `https://github.com/jmfriedt/gr-oscilloscope38`

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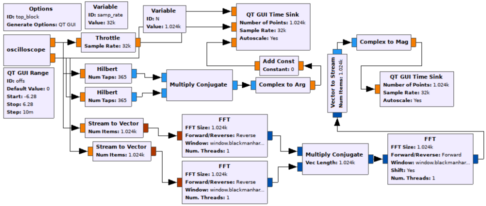

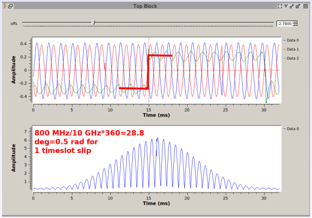

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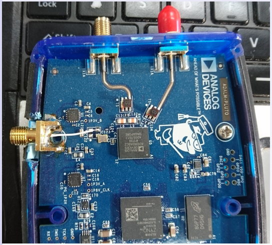
Oscilloscope → dedicated frontends

4-channel 70-6000 MHz lock in detector ?

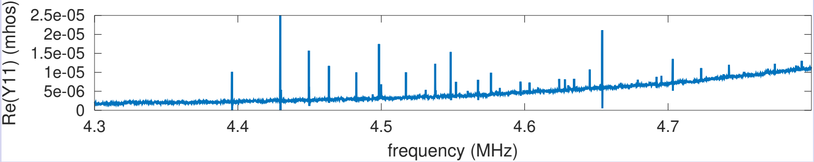


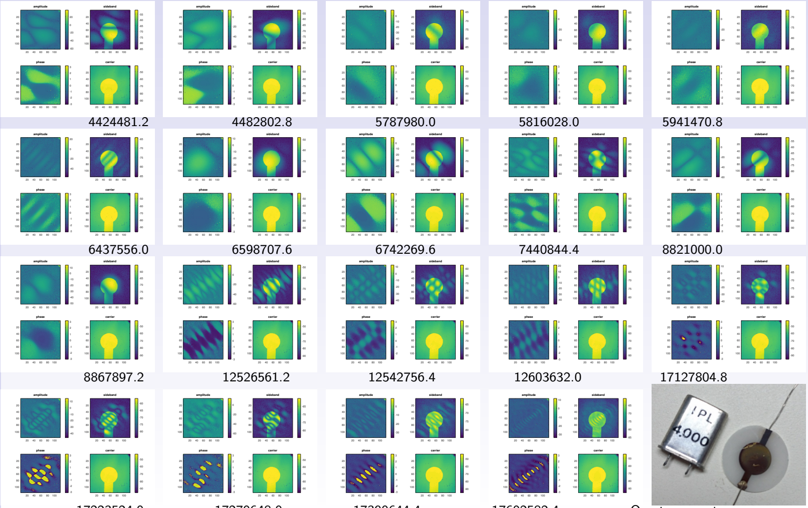
Externally clocked ADI PlutoSDR

Benefit of SDR (beyond cost) with respect to laboratory instruments ?

- **communication bandwidth**,
- pre-processing close to the data source
- **flexibility**
- control of the instrument (e.g. feed external frequency reference)
- easily deployed on long term experiments without colleagues “borrowing” running hardware

Acoustic field mapping of a bulk acoustic quartz resonator



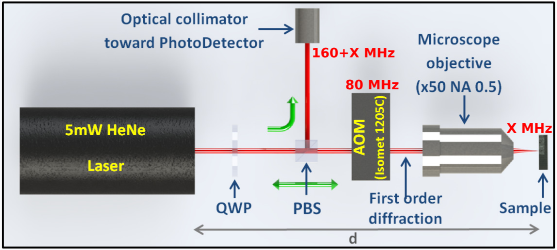


Quartz resonators

Optical probe for acoustic field mapping

Scanning probe microscopy:

- A scalar measurement system measures a local property of the sample
- The sample is raster scanned to map the physical quantity (conductivity, topography, magnetic field ...)
- Michelson interferometer: measuring out-of-plane displacement (sub-nm accuracy)
- Heterodyne approach ⇒ radiofrequency phase and magnitude measurement to get rid of static (slow) phase variations

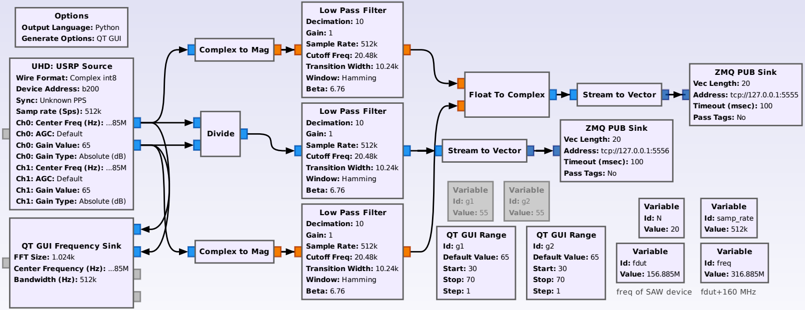


Double pass through 80 MHz acousto-optic modulator + sample vibration @ X MHz ⇒ detect radiofrequency signal at **160+X MHz**

Courtesy of D. Teyssieux ($X \in [5..1500]$ MHz)

Positioner control (GNU Radio)

- GNU Radio for radiofrequency signal acquisition and (continuous) streaming (to keep phase condition between channels)
- Dedicated antenna steering/positioner control software (e.g. GNU/Octave)
- 0-MQ UDP-like (`publish-subscribe`) communication



1 B210 → two spectrum analyzers (top 0-MQ stream) and one lock-in detector (bottom stream: ratio of I/Q is phase difference)

Positioner control (GNU/Octave)

GNU/Octave 0-MQ data collection + instrument control (functional even for large datasets when `total_length` $\gg 10^4$ bytes

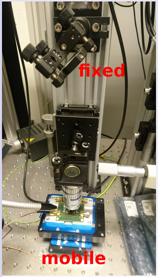
```
pkg load zeromq
pkg load instrument-control
total_length=20;

s1 = serial("/dev/ttyUSB0");            % Open port
set(s1, 'baudrate', 115200);  % communication speed
set(s1, 'bytesize', 8);                 % 8 bit data

vector=zeros(total_length,1);
p=1; m=1;                 % initialize array indices
srl_write(s1,"SVO 1 1\n");             % servo on (X)
srl_write(s1,"SVO 2 1\n");             % servo on (Y)

dx=0.01           % measurement parameters (in mm)
xmin=3.8
xmax=4.6
dy=0.001
ymin=-8.9
ymax=-1.9

table_delay=0.015;                     % in second(s)

for x=xmin:2*dx:xmax
  str=['MOV 2 ',num2str(x),"\n"];srl_write(s1,str);
  pause(table_delay);
  for y=ymin:dy:ymax
    str=['MOV 1 ',num2str(y),"\n"];srl_write(s1,str);
    pause(table_delay);
    sock1 = zmq_socket(ZMQ_SUB); % socket-connect-opt-close
    sock2 = zmq_socket(ZMQ_SUB); %                 = 130 us
    zmq_connect   (sock1,"tcp://127.0.0.1:5555");
    zmq_setsockopt(sock1, ZMQ_SUBSCRIBE, "");
    zmq_connect   (sock2,"tcp://127.0.0.1:5556");
    zmq_setsockopt(sock2, ZMQ_SUBSCRIBE, "");
    total=1;
    while (total<total_length)
      recv=zmq_recv(sock1, total_length*8, 0);
      value=typecast(recv,"single complex"); % char ->float
      if (total+length(value)-1<total_length)
         vector(total:total+length(value)-1)=value;
      else
         vector(total:end)=value(1:total_length-total+1);
      end
      total=total+length(value);
    end
    mesure1(m,p)=mean(vector);
[...]
    zmq_close (sock1);
    zmq_close (sock2);
  end
```

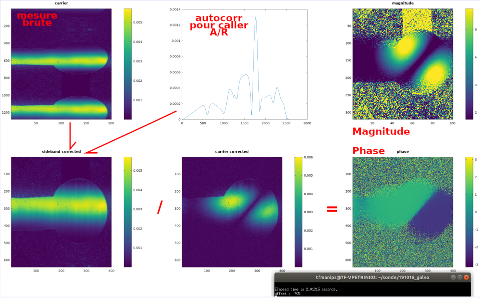
For each position (x, y), collect 20 RF samples from both channels (magnitude and ratio) and save their mean value ...

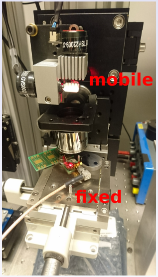
Optical probe for acoustic field mapping

Raster scanning a laser beam to map the out-of-plane acoustic field of piezoelectric devices

$\underbrace{\text{General purpose instrument}}_{1\text{ s/S}=3\text{ h}/100\times 100\text{ samples}} \rightarrow \underbrace{\text{Software Defined Radio}}_{10\text{ ms/S}=15\text{ min}/10^4\text{ S}} \rightarrow \underbrace{\text{Beam scanning}}_{8\ \mu\text{s/pt}=2\text{ s}/600\times 400\text{ S}}$

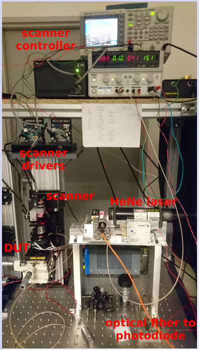


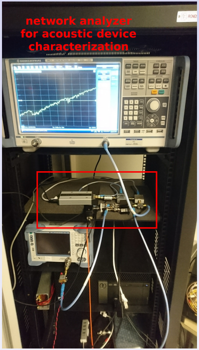


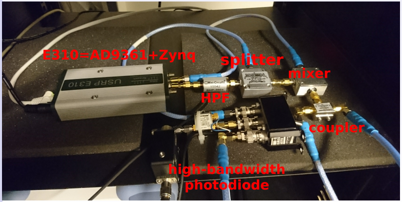


- Removes positioner stabilization time by scanning the laser beam
- Heterodyne approach ⇒ radiofrequency phase and magnitude measurement

Optical probe for acoustic field mapping



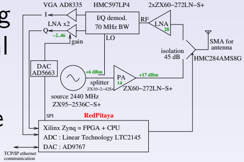


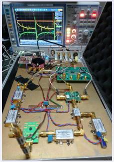


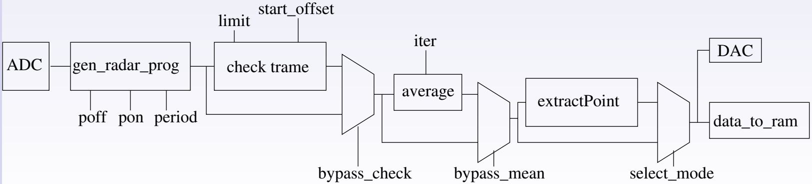
- Synchronize beam scanning with data acquisition: external trigger
- E310 dedicated firmware externally triggering data sampling and storage
- Replace one lock-in amplifier and two spectrum analyzers with a single E310
- Add **external trigger** to ADI E310 support (custom FPGA bitstream) with the additional support for Buildroot/u-boot
- see `https://github.com/oscimp/app/tree/master/e310/optical_probe`

Pulsed RADAR for cooperative target sensor measurement

- pulsed RADAR for high speed cooperative target sensor measurement
- pulse repetition rate defined by longest echo: 2.5 μs$\leftrightarrow$400 kS/s
- baseband pulse generation and data collection/transfer to CPU scheduled by a Redpitaya Zynq
- frequency transposition by switching 2.4 GHz LO (emission) and external I/Q detection (reception)
- application: high bandwidth remote (wireless) vibration measurement

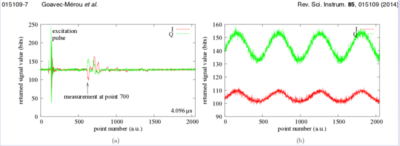


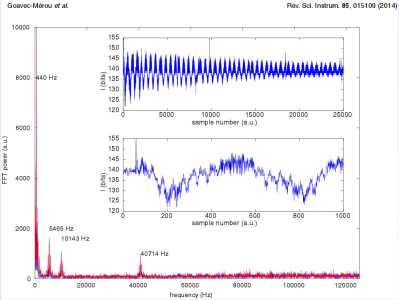


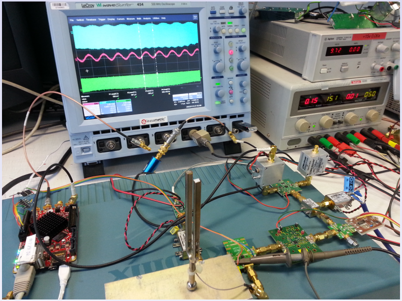


Pulsed RADAR for cooperative target sensor measurement [9]

4 μs maximum echo delay $\Rightarrow$ 250 kHz PRR $\Rightarrow$ analysis up to 125 kHz







G. Goavec-Merou & al., *Fast contactless vibrating structure characterization using real time FPGA-based digital signal processing: demonstrations with a passive wireless acoustic delay line probe and vision*, Rev. Sci. Instrum **85** (1) pp.015109 (2014)

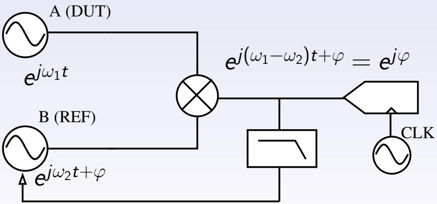
[9] https://github.com/oscimp/app/tree/master/redpitaya/pulsed_radar

Phase noise characterization

Short term **oscillator instabilitity** characterized as phase fluctuation in a 1 Hz band ⇒ normalize by measurement bandwidth B

$$S_\varphi(f) = \frac{\sigma_\varphi^2}{B} \text{ rad}^2/\text{Hz}$$

Mix a reference oscillator to the Device Under Test to cancel carrier and focus on phase (frequency) fluctuations near carrier at Fourier offset f



Analog setup: feedback loop to cancel offset between REF and DUT

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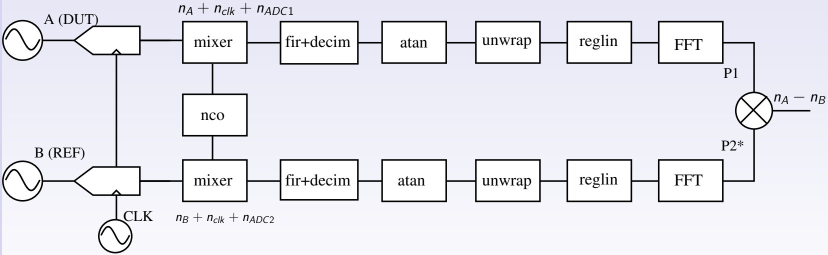
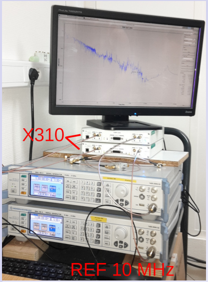
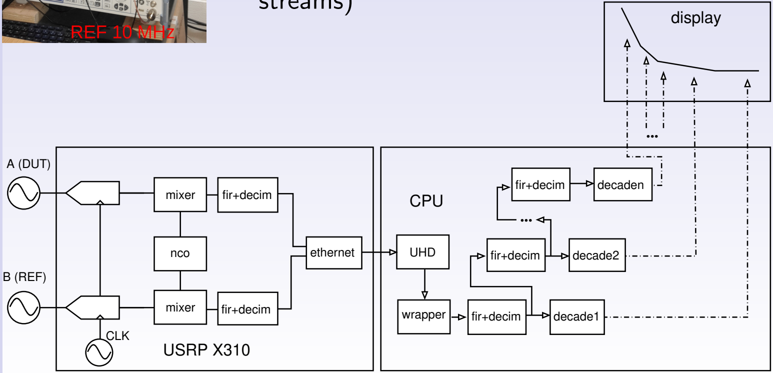


Digital setup propagating unwrapped phase

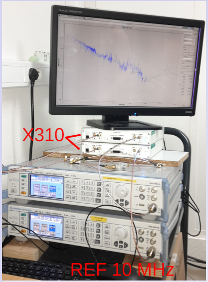
Digital setup implementation



- Two X310 fitted with BasicRX (baseband) direct sampling boards (no transposition)
- Could be implemented with a single X310 if each channel measurement could be streamed ($\neq$ two complex streams)



Digital setup implementation



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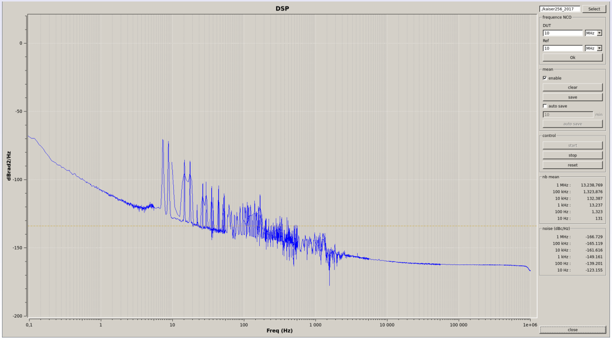

Conclusion

Using SDR beyond (digital) radiofrequency communication

- using[10] readily available hardware
- high bandwidth communication and broadband measurement
- possibly discontinuous data transfer if measurement bandwidth ≫ communication bandwidth
- detailed control on the hardware setup and the frequency source feeding the various processing stages

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- **European GNU Radio Days**: Poitiers (France), **June 22-23** ⟶
- Call for contribution: **April 1st 2020**
- Fee: free of charge
- Registration (mandatory): **May 1st**
- Keynote: gnss-sdr internals

[10] `https://github.com/jmfriedt/gr-oscilloscope38` and `https://github.com/oscimp/oscimpDigital`