Monitoring the ionosphere altitude variation with a sound card: software defined radio processing of DCF-77 signals

J.-M Friedt, E. Rubiola, C. Eustache

February 4, 2017

Why ?

Only when certain events recur in accordance with rules or regularities, as is the case with **repeatable experiments, can our observations be tested – in principle – by anyone**. We do not take even our own observations quite seriously, or accept them as scientific observations, until we have repeated and tested them. Only by such repetitions can we convince ourselves that we are not dealing with a mere isolated "coincidence", but with events which, on account of their regularity and reproducibility, are in principle inter-subjectively testable.

K. Popper, *The Logic of Scientific Discovery*, (1935) p.23

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An open-source GNSS software receiver allows to have full access to the signal processing and to **make add-ons to the source code** in order to obtain the desired GNSS reflectometry processing.

L. Lestarquit *& al.*, *Reflectometry With an Open-Source Software GNSS Receiver: Use Case With Carrier Phase Altimetry*, IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing (2016)

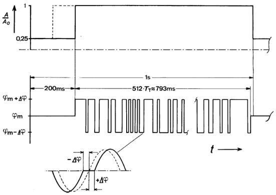
DCF-77 modulation schemes

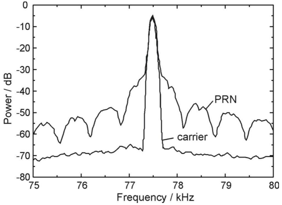
Radiofrequency wave $s(t) = A(t) \cdot \cos(\omega \cdot t + \varphi(t))$

$\Rightarrow$ carrier frequency (Cs, from PTB), amplitude (1 s), phase modulation

Modulation and Coding

Pseudo random noise phase shift keying of the carrier





Carrier, amplitude modulation and PRN are phase synchronous.

Phase deviation ± 14.3°

Chiprate 645.83 cps corresponding to 1.55 ms per chip

Can we use this information to measure the delay between air (bouncing off the ionosphere) and surface waves ?

[0] A. Bauch, *Time Dissemination II*, EFTS2016

Ionosphere altitude

type of phase variation deduced and the sort of heights estimated are sketched in Fig. 1a. Note that the "phase height" starts to change about 10–15 min before ground sunrise at the path midpoint, and varies continuously over the day being minimum near mid-day. There is some asymmetry in the daily variation in that evening changes are slower than morning changes, and this asymmetry is most marked in winter, but the asymmetry is not an outstanding feature of the record.

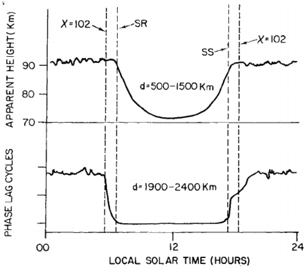


Fig. 1. Sketch of diurnal variation of "phase height" of reflection for l.f. radio waves propagated to the distances marked.

When l.f. waves are propagated to greater distances (about 200 km) the sky wave predominates and the ground wave becomes too small to be observable. If the stability of the oscillator at the transmitter and that of a reference oscillator at the receiver are very good it is possible to measure the daily phase variation of the received field,[2] and in fact, on some occasions, to establish whether the reflection height on a particular day was higher or lower than it was on the previous few days.

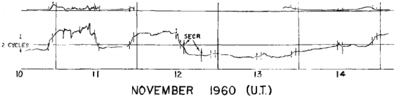
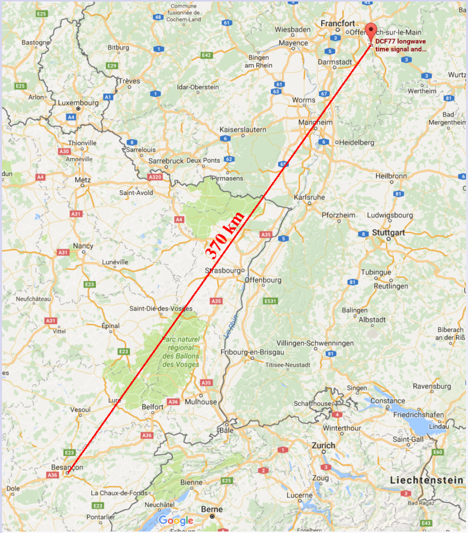


Fig. 7. Phase and amplitude of 80 kc/s transmissions between Ottawa and Churchill recorded during the great PCD of November 12, 1960. The short vertical lines mark the times when the solar zenith angles are 102 degrees, and 90 degrees 50 minutes (ground sunrise and sunset) at the path point. The lines with the caption SECR mark the times when a sudden increase in (ground level) cosmic rays were observed at Ottawa and Churchill.

J.S. Belrose, *The oblique reflecion of CW low-frequency radio waves from the ionosphere*, in W.T. Blackband, *Propagation of Radio Waves at Frequencies below 300 kc/s* (1964), chapter 11.

[0] Sudden Ionospheric Disturbances (SID) monitoring station at `http://sidstation.loudet.org/data-en.xhtml`

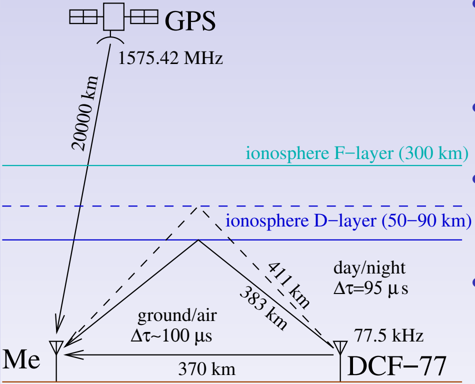
DCF-77



- 50 kW emitter in Mainflingen, Germany, 370 km from Besançon
- Carrier referenced to Cs primary standard (PTB)
- used to synchronize radiofrequency-disciplined clocks
- 77.5 kHz: surface wave and air wave bouncing off the ionosphere

[0] A. Bauch, P. Hetzel & D. Piester, *Time and Frequency Dissemination with DCF77: From 1959 to 2009 and beyond*, PTB Mitteilungen **119** (3), 2009

DCF-77



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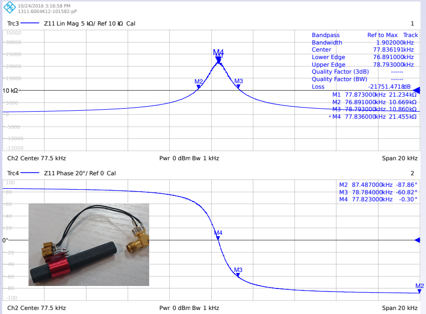
1: $c_{atm} = c_0/1.000338$

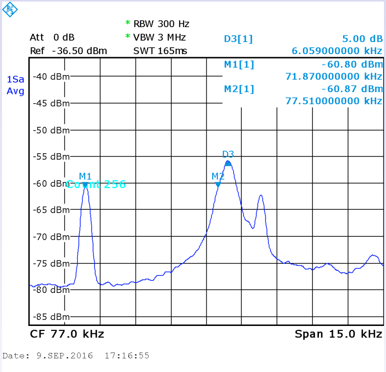
2: $c_{gnd} < c_{air}$: 0.5 μs @ 370 km

[0] C. Hargreaves, *ASF Measurement and Processing Techniques, to allow Harbour Navigation at High Accuracy with eLoran*, MSc Univ. of Nottingham (2010)

Short antenna impedance and quality factor

Coil + parallel capacitance for tuning antiresonance at operating frequency: $V = 2\pi\frac{A \cdot N \cdot E \cdot \cos(\vartheta)}{\lambda} \times \mathbf{Q}$





Z_{11} indoor

$\Rightarrow$ need to locate the antenna outdoor to get rid of lab-generated noise

$\Rightarrow$ need to introduce impedance converting circuit (antiresonance = maximize voltage with no current flow) + prevent Q degradation (http://www.qsl.net/dl4yhf/dcf77_osc/index.html)

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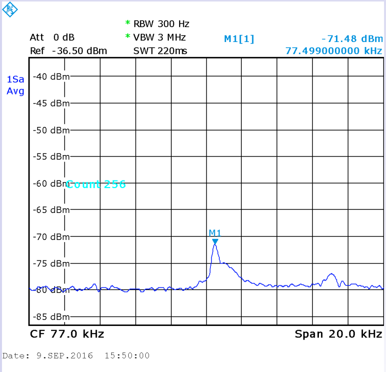

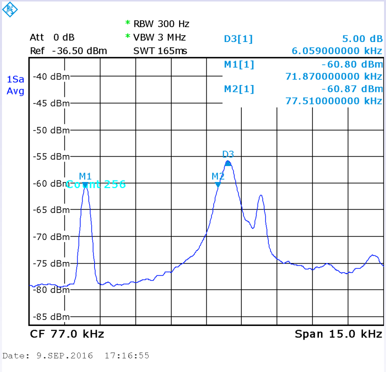

outdoor indoor

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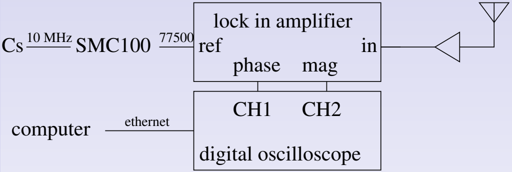
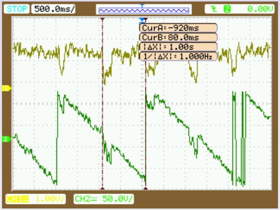
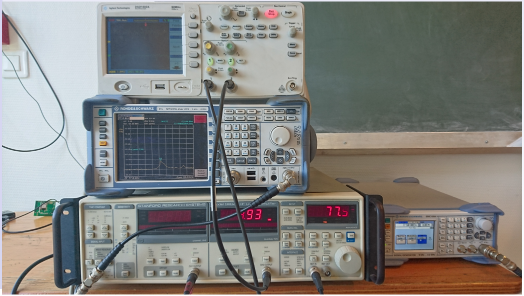
Lock-in + oscilloscope signal reception

Experiment1: phase of the carrier and amplitude modulation detection





Internal synthesizer quartz reference



- AM: 100 or 200 ms long amplitude drop at the beginning of each second
- φ: $\Delta\omega \cdot t + \varphi(t)$

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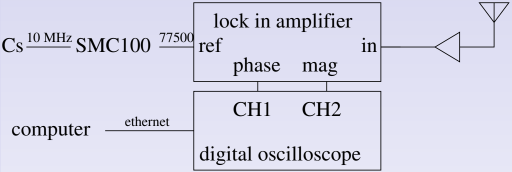
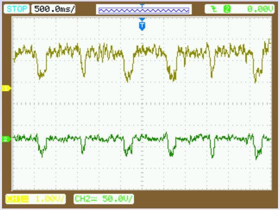
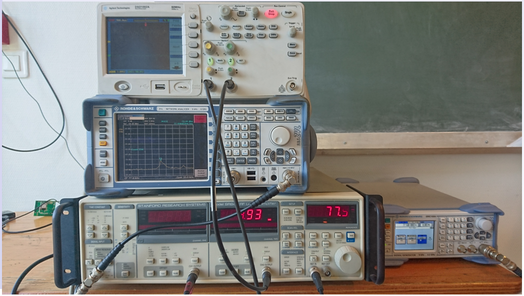




Synthesizer locked on Cs reference



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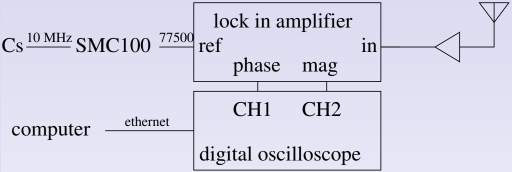
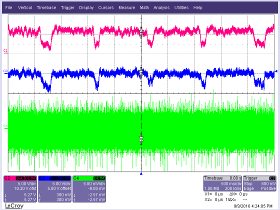
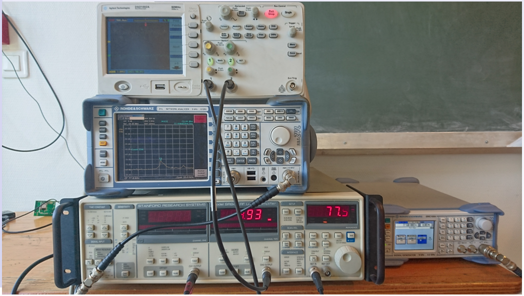




Amplitude+phase+raw data @ >200 kS/s



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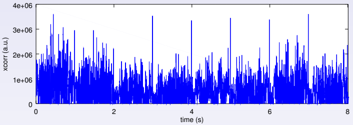
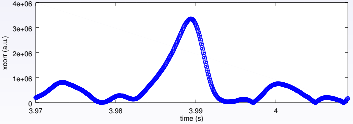
Phase-modulated spectrum spreading

- Phase demodulation cross-correlation peak: 120 periods at 77.5 kHz=1.55 ms/bit
- 700 Hz bandwidth needed for phase modulation processing
- 511 bit long PRN [1]: $x^9 + x^5 + 1$ in lfsr.dat
  00000100011000010011100101010110000110111110100110111001000101000010101101001111110110010010010110111111001001
  10101001100110000000110001100101000110100101111111010001011000111010110010110011110001111110111010000011010110
  11011101100000101101011111010101010000001010010101110010111011100000011100111010010011110101110101000100100 0
  01100111000010111101101100110100001110111100001111111110000011110111110001011100110010000010010100111011 01000
  1111001111100110110001010100100011100011011010101110001001100010001000000001
- interpolate the PRN sequence to match sampling rate, and cross-correlate

```
load lfsr.dat
np=192000/59*(120/77500); % fs*(Tprn/fDCF)
oldP=0;
for k=1:length(lfsr)
  P=round(k*np);
  if (lfsr(k)==1)
        ilfsr(oldP+1:P)=ones(P-oldP,1);
  else  ilfsr(oldP+1:P)=zeros(P-oldP,1);
  endif
  oldP=P;
end
yc=xcorr(xp-mean(xp),ilfsr-mean(ilfsr));
```

+ parabolic fit of $|xcorr()|$ max





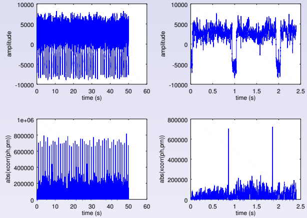
[1] https://www.ptb.de/cms/fileadmin/internet/fachabteilungen/abteilung_4/4.4_zeit_und_frequenz/pdf/5_1988_Hetzel_-_Proc_EFTF_88.pdf

Resolution gain by using phase rather than amplitude

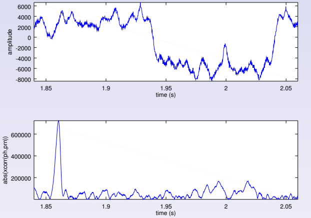
Oscilloscope: sampling rate=5 kHz, duration=50 s (250 ksamples=1.8 MB/chan/min)

record phase+amplitude ⇒ cross-correlate PRN and phase

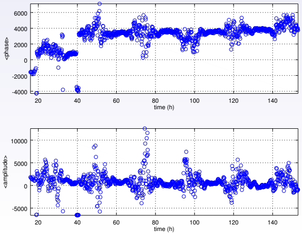
50-s acquisition



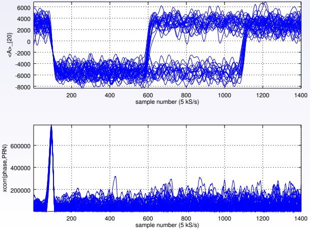
Zoom



Carrier phase

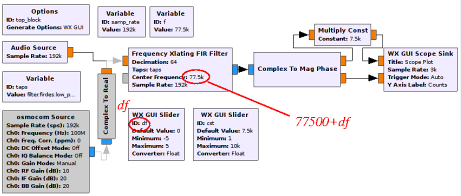


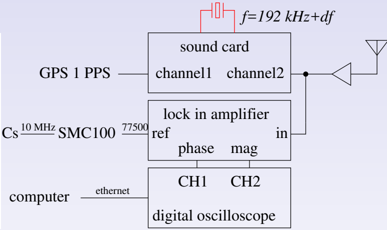
AM v.s PM cross-correlation



Full SDR solution using gnuradio [2]

- Frequency translation and low-pass filter (lockin): Xlating FIR Filter
- Once baseband is reached, decimate (low pass filter to prevent aliasing and 1 in N) – here N=59
- $(192000/\mathbf{59})/(77500/120) \simeq 5_{.0388}$: 5 samples/bit
- Sound card sampling frequency fluctuation ⇒ record GPS 1 PPS





- Sound card offset to nominal frequency: 1.15 Hz @ 77.5 kHz=15 ppm
- Lack of continuity of the GNURadio oscilloscope output when adding second (GPS) path ?

[2] dsPIC-based based DCF receiver: `http://www.marvellconsultants.com/DCF`

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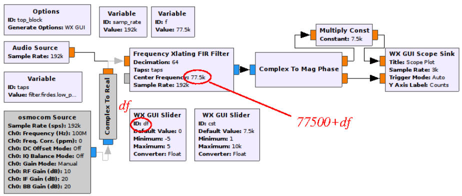

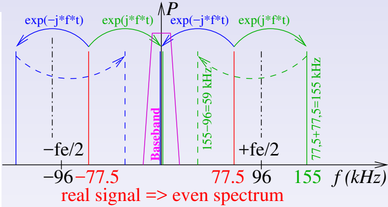

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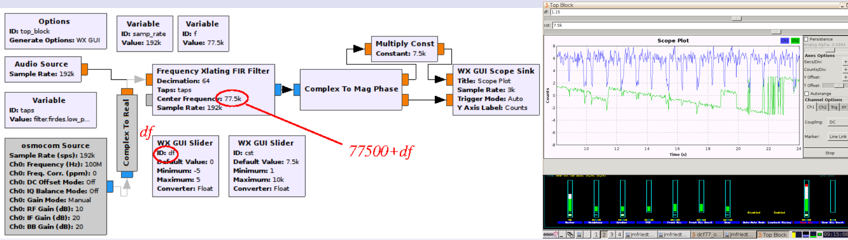

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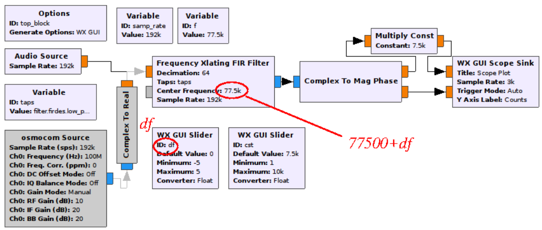

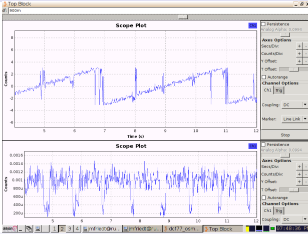

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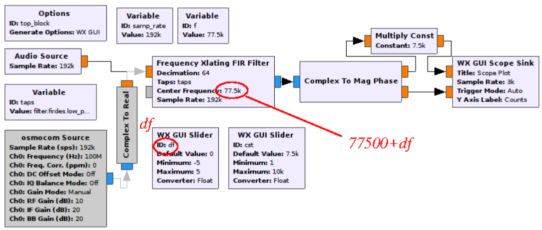

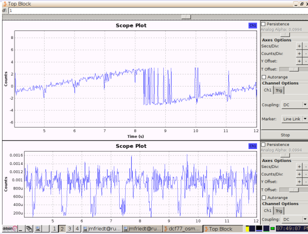

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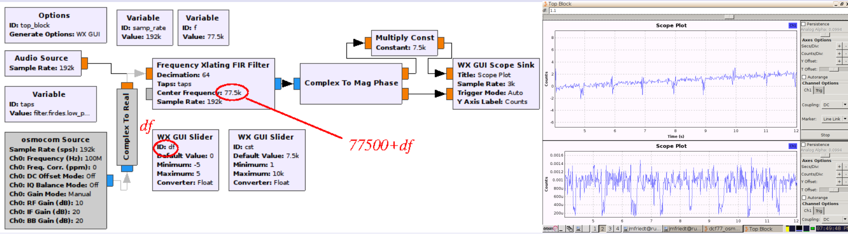

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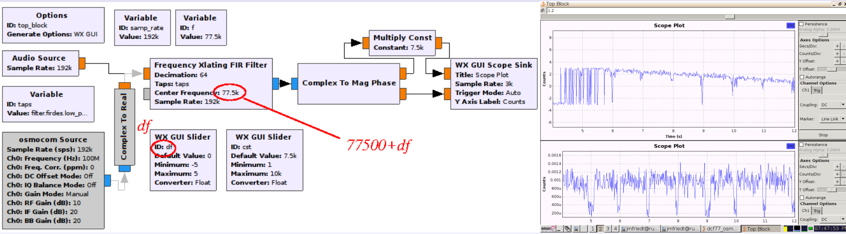

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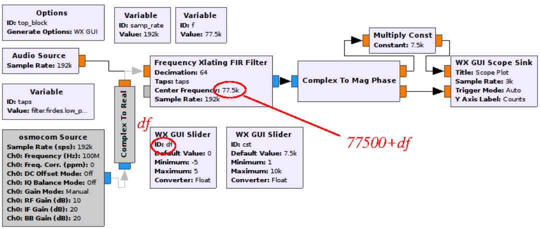

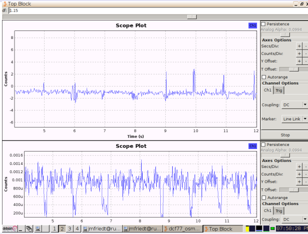

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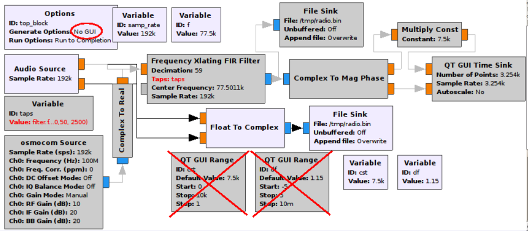
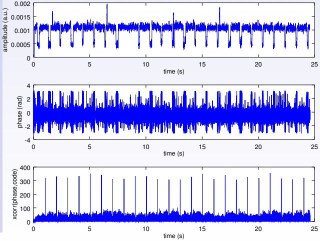
Sound card SDR

GNURadio is a python script generator, no need for a graphical interface

1. run periodically acquisition script
2. process resulting dataset using GNU Octave



⚠ Implementation using Octave of FIR+xcorr: $xcorr(a, b) \neq xcorr(b, a)$




```
x=read_complex_binary(filename);
dcf=real(x); gps=imag(x); fe=192e3;
time=[0:length(x)-1]'/fe;
dcf=dcf.*exp(j*2*pi*(77500)*time);
lpf=firls(250,[0 720 790 fe/2]*2/fe,[1 1 0 0]);
dcf=filter(lpf,1,dcf); x=dcf(1:59:end); fe=192000/59;

[yf,xf]=max(abs(fft(x-mean(x)))); xf=xf-length(x)-1;
df=-xf/length(x)*fe; lo=exp(j*2*pi*df*time); x=x.*lo;
xp0=mean(angle(x(1:3000)));x=x.*(-j*xp0); xp=angle(x);
yc=xcorr(xp-mean(xp),ilfsr-mean(ilfsr));
yc=yc(floor(length(yc)/2):end);
ggps=gps(1:59:end);
```

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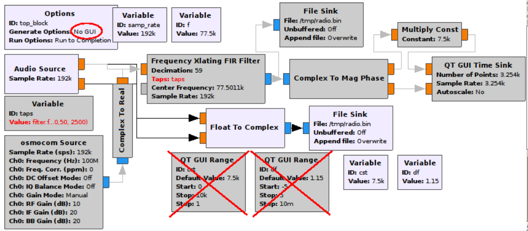
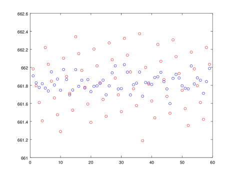
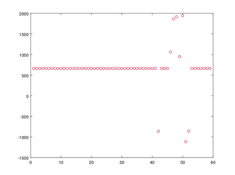
1. run periodically acquisition script
2. process resulting dataset using GNU Octave



1 minute acquisition (60 seconds),
red=xcorr max. to 1 PPS interval, blue=parabolic fit max. to 1 PPS

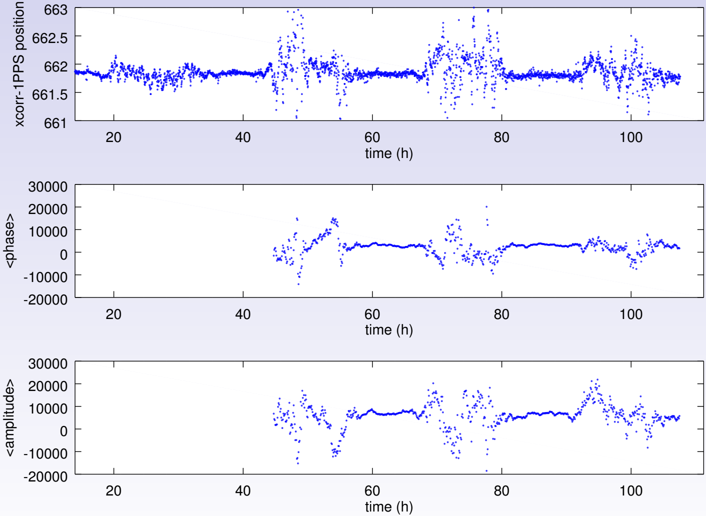




Getting rid of outliers: use median value + average of samples lying at median±5 a.u.

Cs v.s sound card+GPS

3-day measurement



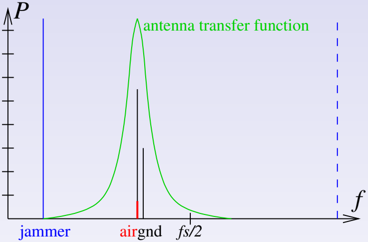
$\sigma_{xcorr-1PPS}(200 samples) = 0.03$ sample periods around time 60 h

192 kHz/59=3254 Hz=1/307 μs $\Rightarrow \sigma_{xcorr-1PPS} = 9.2$ μs$\sim$2.8 km

DVB-T v.s sound card

- Sampling frequency > 150 kHz (we only need up to 200 kS/s)
- Sampling resolution [2] : is 8 bit sufficient to detect air v.s ground wave ?

$\boxed{SNR = 6.02 \cdot B + 1.76 + 10\log_{10}(f_s/(2 \cdot f_{max}))}$ with $B_{16\rightarrow 8}$ & $f_s\times = 10$



Problems:

- the zero-IF E4000 based DVB-T receivers are obsolete
- the newer R820T(2) based receivers use non-zero (3.57 MHz) IF [3]
  $\Rightarrow$ bypass RF frontend (capacitive decoupling of I-/Q-)
  $\Rightarrow$ make the RTL2832U believe it is operating at zero-IF

[2] J. Mitola, *Software Defined Radio Architecture*, John Wiley & Sons (2000), p.293

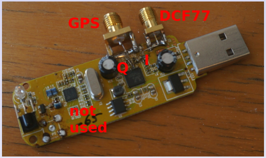
[3] `http://superkuh.com/rtlsdr.html`

DVB-T

1. hardware modification: I+=DCF77, Q+=GPS 1 PPS
2. software modification: `librtlsdr`[4] : `src/librtlsdr.c`, l.1580

```
[...]
found:
  fprintf(stderr,"dev tuner,%x-> %x\n",dev->tuner_type,
          RTLSDR_TUNER_E4000);
  dev->tuner_type=RTLSDR_TUNER_E4000;

  /* use the rtl clock value by default */
  dev->tun_xtal = dev->rtl_xtal;
```



3. replace gr-osmosdr source (complex=8 bytes/sample) with `rtl_sdr`
   1.92 MS/s during 1 minute=230 MB as char but 920 MB as float

```
#!/bin/sh
while true; do
  rtl_sdr -s 1920000 -n 115200000 /tmp/dvbt.bin
  nom=`date +%s`
  octave go.m > $nom.dat
  mv 1.eps ${nom}_1.eps;mv 2.eps ${nom}_2.eps;mv 3.eps ${nom}_3.eps
  sleep 10
done
```

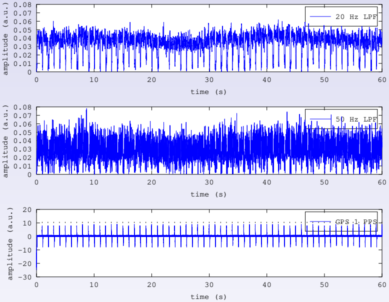
4. low-pass & decimate to reach 192 kHz, mix and low-pass+decimate:

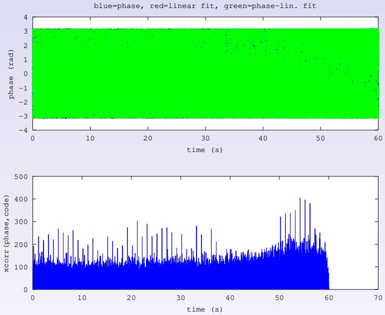
```
fs=1.92e6;
b=firls(128,[0 2e5 2.5e5 fs/2]*2/fs,[1 1 0 0]);      % 1.92 MHz/128=15 kHz res.
ddcf=filter(b,1,ddcf); ddcf=ddcf(1:10:end);fs=fs/10; % LPF/decim=192 kHz
time=[0:length(ddcf)-1]'/fs;
ddcf=ddcf.*exp(i*time*2*pi*77493);                   % frequency transposition
b=firls(128,[0 750 800 fs/2]*2/fs,[1 1 0 0]);        % LPF/decim
ddcf=filter(b,1,ddcf); ddcf=ddcf(1:59:end);fs=fs/59;% LPF/decim=3.254 kHz
time=[0:length(ddcf)-1]'/fs;
```

[4] https://github.com/steve-m/librtlsdr

DVB-T

Again, magnitude (AM) and phase (PM) demodulation functional, but now 1 PPS GPS signal identified with 520 ns resolution (10-fold improvement)





AM (20 Hz LPF), AM (50 LPF), GPS   unwrapped phase, xcorr

Lower SNR ⇒ poorer cross-correlation peak location in time

DVB-T

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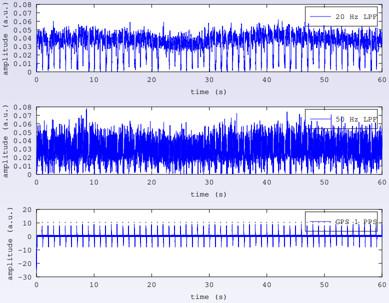
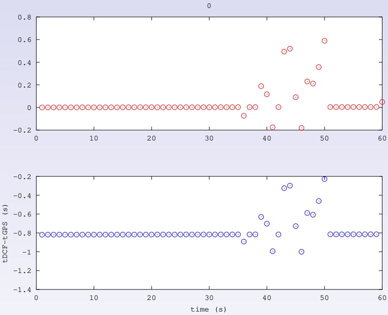




AM (20 Hz LPF), AM (50 LPF), GPS   GPS to DCF77 phase

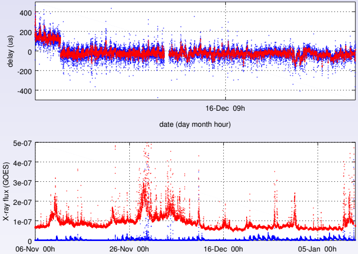
Lower SNR ⇒ poorer cross-correlation peak location in time

Monitoring the ionosphere altitude variation with a sound card: software defined radio processing of DCF-77 signals

J.-M Friedt *& al.*

Conclusion and perspectives

- Ability to receive DCF-77 using active antenna
- Ability to decode DCF-77 using a lock-in amplifier and decode phase modulation
- Ability to decode DCF-77 using SDR with signal acquired from sound card & DVB-T receiver (how come that $\Delta z \ll \frac{c}{2 \cdot B}$!)
- Consistent results between Cs+lockin or sound card+GPS



- Question: if ground wave is strongest, why does its phase vary with day/night ? (waveguide model)
- Question: separate ground and air wave (improve xcorr resolution) ?
- Microcontroller based sampling for high resolution 1 PPS timing

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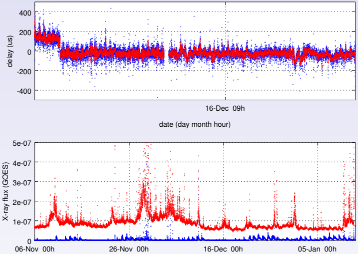

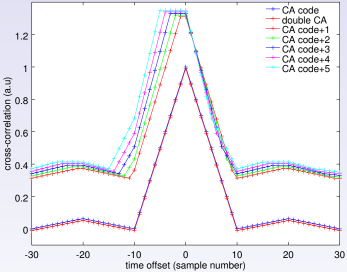

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1. P.-H. Kamp, *A Cheap SDR Loran-C frequency receiver* at `phk.freebsd.dk/AducLoran/AducLoran-0.3.pdf`
2. ARRL Antenna Handbook, Chapter5 (Small Loop Antennas), 18th Ed. (1997)
3. S.M.F. Raupach & G. Grosche, *Chirped Frequency Transfer: A Tool for Synchronization and Time Transfer*, IEEE Trans. Ultrasonics, Ferroelectrics, and Freq. Control **61** (6), June 2014 chirped freq time transfer.pdf
4. K. Davies, *Ionospheric Radio*, IET (1990)
5. P. Dolea *& al.*, *In-situ Measurements Regarding LF Radio Wave Propagation using DCF77 Time Signal Transmitter*, TELSIKS 2013
6. P. Hetzel, *Time dissemination via the LF transmitter DCF77 using a pseudo-random phase-shift keying of the carrier*, 2nd EFTF (1988)
7. A.D. Watt *& al.*, *Worldwide VLF Standard Frequency and Time Signal Broadcasting*, J. of Research of the National Bureau of Standards **65D** (6), 1961
8. W.T. Blackband, *Propagation of Radio Waves at Frequencies below 300 kc/s* (1964)
9. A. Bauch *& al.*, *Time and Frequency Dissemination with DCF77: From 1959 to 2009 and beyond*, PTB Mitteilungen **119** (3), 2009
10. J.R. Johler, *Propagation of the Low-Frequency Radio Signal*, Proc. IRE (1961)
11. D. Engeler, *Performance analysis and receiver architectures of DCF77 radio-controlled clocks*, IEEE Trans. on Ultrasonics, Ferroelectrics, and Freq. Control **59** (5), 2012
12. D. Piester, A. Bauch *& al.*, *Time and Frequency Broadcast With DCF77*, Proc. 43rd PTTI Systems and Appliocations Meeting (2012)

All references available on the Library Genesis, `gen.lib.rus.ec`