Wideband measurement strategies: from RADAR to passive wireless sensors ... and how passive wireless sensors were/are used by intelligence agencies.

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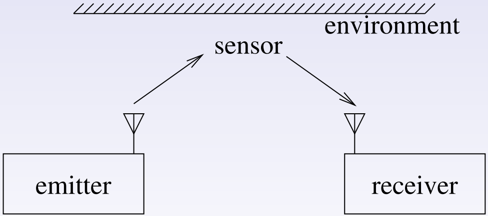
January 31, 2016

Introduction

- Passive transducers acting as RADAR cooperative targets for sensing purposes
- No local energy source, impossible to detect unless remotely powered
- "High" bandwidth measurement ($>$ 16 kHz for voice reconstruction)



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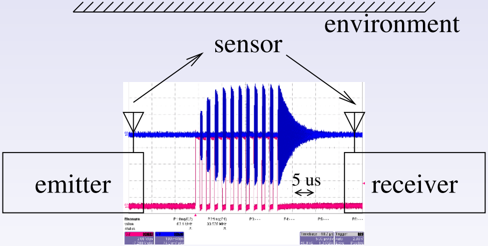

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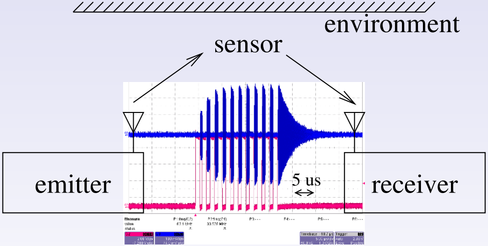

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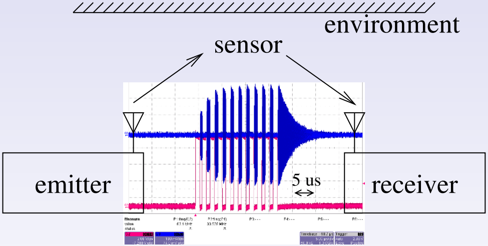

1. How to introduce a dedicated signature from a cooperative target ?
2. How to add a sensing capability ?
3. How to separate the emitted signal from the returned signal ?

Historical background: RADAR cooperative targets

1. target whose backscattered signal is representative of its state (identification, measurement)
2. active targets: radar beacons (racon), IFF
3. passive targets: buried dielectric reflectors, Lüneberg spheres
4. this work: use of radiofrequency transducers based on surface acoustic wave propagation (RF filters)

H. Stockman, *Communication by means of reflected power* Proc. IRE **36** (Oct. 1948) pp.1196–1204

(picture from `http://geogdata.csun.edu/~aether/pdf/volume_05a/rosol.pdf`)

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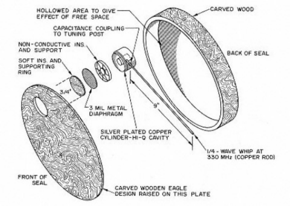

A. Glinsky, *Theremin: Ether Music And Espionage*, University of Illinois Press (2005)
P. Wright & P. Greengrass, *Spycatcher* (1987), pp.14–17

⇒ MI5 SATYR

http://madmikesamerica.com/2010/08/the-thing-and-the-curious-life-of-leon-theremin/thing2/

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J. Appelbaum, J. Horchert & C. Stöcker, *Shopping for Spy Gear: Catalog Advertises NSA Toolbox*, Der Spiegel (12/29/2013) `http://leaksource.info/2013/12/30/nsas-ant-division-catalog-of-exploits-for-nearly`

TOP SECRET//COMINT//REL TO USA, FVEY

CTX4000

ANT Product Data

(TS//SI//REL TO USA,FVEY) The CTX4000 is a portable continuous wave (CW) radar unit. It can be used to illuminate a target system to recover different off net information. Primary uses include VAGRANT and DROPMIRE collection.

8 Jul 2008

(TS//SI//REL TO USA,FVEY) The CTX4000 provides the means to collect signals that otherwise would not be collectable, or would be extremely difficult to collect and process. It provides the following features:

- Frequency Range: 1 - 2 GHz.
- Bandwidth: Up to 45 MHz
- Output Power: User adjustable up to 2 W using the internal amplifier; external amplifiers make it possible to go up to 1 kW.
- Phase adjustment with front panel knob
- User-selectable high- and low-pass filters.
- Remote controllable
- Outputs:
- Transmit antenna
- I & Q video outputs
- DC bias for an external pre-amp on the Receive input connector
- Inputs:
  - External oscillator
  - Receive antenna

Unit Cost: N/A

Status: unit is operational. However, it is reaching the end of its service life. It is scheduled to be replaced by PHOTOANGLO starting in September 2008.

POC: [redacted], S32243, [redacted], [redacted]@nsa.ic.gov

Derived From: NSA/CSSM 1-52
Dated: 20070108
Declassify On: 20320108

TOP SECRET//COMINT//REL TO USA, FVEY

SURLYSPAWN

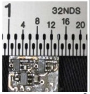
ANT Product Data

(TS//SI//REL TO USA,FVEY) Data RF retro-reflector. Provides return modulated with target data (keyboard, low data rate digital device) when illuminated with radar.

07 Apr 200

(U) Capabilities

(TS//SI//REL TO USA,FVEY) SURLYSPAWN has the capability to gather keystrokes without requiring any software running on the targeted system. It also only requires that the targeted system be touched once. The retro-reflector is compatible with both USB and PS/2 keyboards. The simplicity of the design allows the form factor to be tailored for specific operational requirements. Future capabilities will include laptop keyboards.



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G. Poteat, *Stealth, countermeasures and ELINT, 1960–1975 (U)* (2014)

“we received the radar’s signal and fed it into a variable delay line before transmitting the signal back to the radar. By smoothly varying the length of the delay line, we could simulate the false target’s range and speed. ... we could now simulate an aircraft of any radar cross section ”

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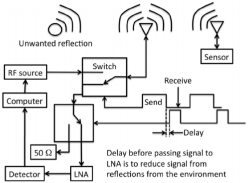
D. J. Thomson, D. Card, and G. E. Bridges, *RF Cavity Passive Wireless Sensors With Time-Domain Gating-Based Interrogation for SHM of Civil Structures*, IEEE Sensors Journal . **9** (11) (Nov. 2009), pp.1430-1438

Fig. 1. Passive RFCSs are mounted on or embedded within structures. A sensor with antenna is pictured in the upper left-hand corner. The sensor is approximately 90 mm in length. The sensor is interrogated using a pulse/echo technique. The sensor is passive and does not require any local power, such as a battery.



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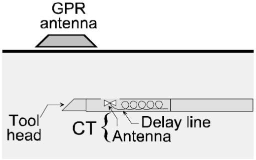
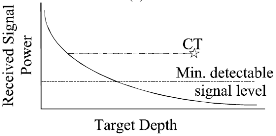
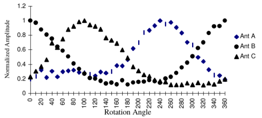


(a)





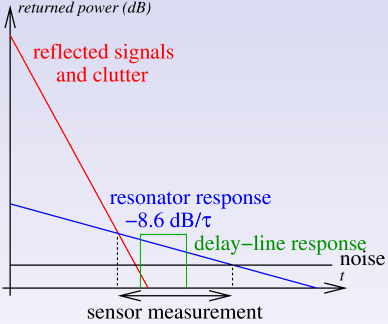
(b)

Figure 3. Normalized response at different rotation angles for (a) the two-CT configuration and (b) the three-CT configuration.

C.T. Allen, S. Kun, R.G Plumb, *The use of ground-penetrating radar with a cooperative target*, IEEE Transactions on Geoscience and Remote Sensing, **36** (5) (Sept. 1998) pp. 1821– 1825

Development strategy

- Electromagnetic to **acoustic** wave conversion for **shrinking sensor size**: 300 m/μs $\rightarrow$ 3000 m/s (piezoelectric substrate)
- **Delay line** for delayed echo (1 μs=1.5 mm acoustic path) [1]
- **Resonators** for energy storage and slow release [2]
- $20\log_{10}(e) = 8.6$ and exponential decay of an unloading resonator is $\exp(-t/\tau)$ with $\tau = Q/(\pi \cdot f_0)$
- Rising frequency for **shrinking antenna size**: λ (m) $= 300/f$ (MHz)

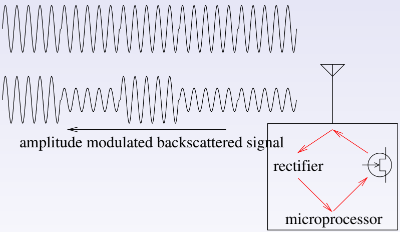


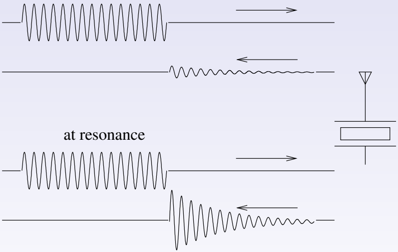
[1] L. Reindl *& al.*, *Theory and application of passive SAW radio transponders as sensors.*, IEEE Trans. Ultrasonics, Ferroelectrics, and Frequency Control **45** (5), 1281–1292 (1998)

[2] https://www.isa.org/participate-in-a-technical-division/communications-division/dielectric-resonators

RFID v.s linear transducers

RFID	linear transducers
rectifier for powering the microcontroller = diodes	linear transduction process (piezoelectric, dielectric resonator loading)
near field coupling	far field interrogation
backscattered signal modulation	delayed echo
periodic bit sampling	frequency sweep or Fourier transform of returned signal





S. Preradovic & N.C. Karmakar, *Multiresonator-Based Chipless RFID Barcode of the Future*, Springer (2012)

"Chipless RFID" !

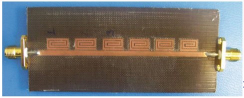
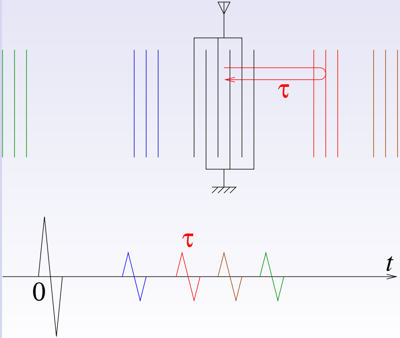


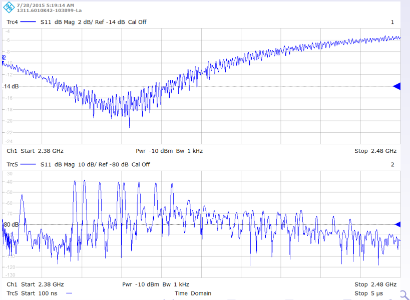
Fig. 3.27 Photograph of 6-bit multiresonator on Taconic TLX-0

Delay line design

1. interdigitated electrodes patterned on a piezoelectric substrate and connected to the antenna generate a radiofrequency **acoustic pulse**
2. the acoustic pulse, confined to the substrate surface, propagates at a few km/s ($\ll$ 300 m/μs),
3. electrodes patterned on the acoustic path act as **mirrors**
4. echos are returned to the RADAR with a delay dependent on **acoustic velocity** ($\propto$ T, σ ...)

Drawback: electromechanical conversion efficiency (a few % at most)





How to use a transducer for measurement ?

Intrinsic material property

- acoustic velocity with temperature, stress: $c(T,\sigma)=\sqrt{\frac{E}{\rho}}$
- boundary condition (gravimetric sensor):
  sensitivity $\simeq$ (attached mass)/(moving mass)
  $\Rightarrow$ for a given layer thickness, dependent on λ & wave confinement
- a dielectric resonator resonance frequency is
  $f_{TE01}\simeq\frac{34}{a\sqrt{\varepsilon_r}}\left(\frac{a}{L}+3.45\right)$ GHz (a radius, L length in mm) [3] $\Rightarrow$
  dilatation ($df_{TE01}\simeq\frac{34}{\sqrt{\varepsilon_r}}\frac{dL}{L^2}$) and permettivity effect

Extrinsic transducer property

- varying load on a 2-port device (acoustic coupling between port connected to antenna and port connected to sensor): resistor (strain gauge), capacitor (moisture), light sensitive diode [4]
- disturbing the fringing electrical field [5]

[3] D. Kafjez & P. Guillon, *Dielectric resonators, 2nd Ed*, Noble (1998), p.3

[4] http://www.google.com/patents/US8339219

[5] K. Stroganov, V. Pashchenko, V. Kalinin, V. Plessky, *Passive Wireless SAW - MEMS Pressure sensor/Microphone, Proc 2014 EFTF*

Application examples

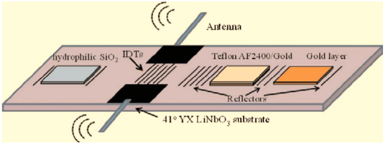


Fig. 1 Schematic of wireless chemical sensor system.

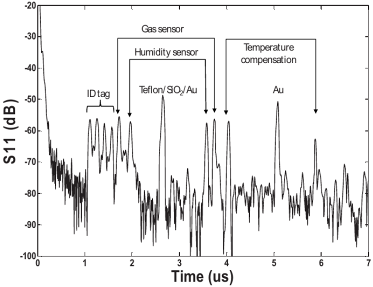


Fig. 6 Measured S_{11} parameter in the time domain of the fabricated gas sensor with no gas infusion.

[6]

IEEE SENSORS JOURNAL, VOL. 9, NO. 11, NOVEMBER 2009

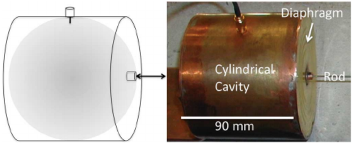


Fig. 13. Displacement sensor employing a corrugated diaphragm on one end with a rod attached. As the rod is displaced, the diaphragm is displaced causing the cavity to change dimension and hence shift the resonant frequency. The cavity is 100 mm in diameter. An SMA connector-wire probe is used to couple signals in and out of the cavity.

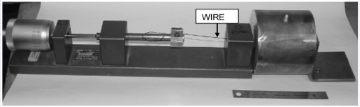
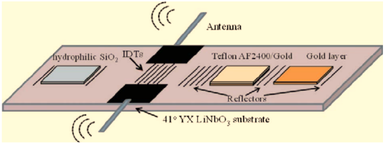


Fig. 14. Displacement sensor was mounted on a displacement test fixture, and a wire rod was attached to the front of the displacement sensor. Using the micrometer, the diaphragm of the displacement sensor was translated in 0.1 mm increments. At each increment the resonant frequency of the cavity was determined using the servo method described.

[6] Wang & al., *Wireless surface acoustic wave chemical sensor for simultaneous measurement of CO_2 and humidity*, J. Micro/Nanolith. MEMS MOEMS **8** (3) (2009)

Application examples



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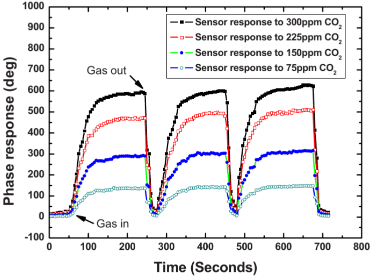
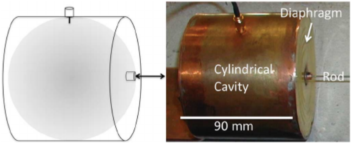


Fig. 7 Sensor response profile obtained from three consecutive 200-sec on/off exposures to different CO_2 concentrations at room temperature.
6

IEEE SENSORS JOURNAL, VOL. 9, NO. 11, NOVEMBER 2009



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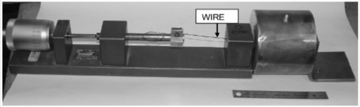

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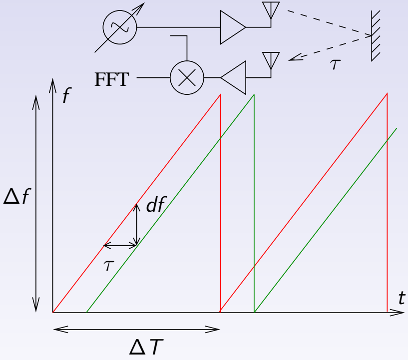
[6] D.J. Thomson & al., *RF Cavity Passive Wireless Sensors With Time-Domain Gating-Based Interrogation for SHM of Civil Structures*, IEEE Sensors **9** (11), 2009

RADAR measurement

- Challenge of RADAR measurement: detect weak backscattered signal while the strong emitted signal makes the receiver blind
- **Objective:** differentiate the returned signal from the emitted signal (isolation)

- Frequency domain: sweeping the emitted frequency so the returned signal at $t+\tau$ is at a different frequency than the emitted signal at time $t+\tau$: beat signal at $df = \frac{\Delta T}{\Delta f}\cdot\tau$
- Doppler RADAR: only velocity of target induces frequency shift, no sweep (CW)
- Time domain: separate emission and reception



G. L. Charvat, *Small and Short Range RADAR Systems*, CRC Press (2014)

In all cases: spatial (temporal) resolution given by the inverse of the **bandwidth** ($\Delta R = c/(2\Delta f)$)

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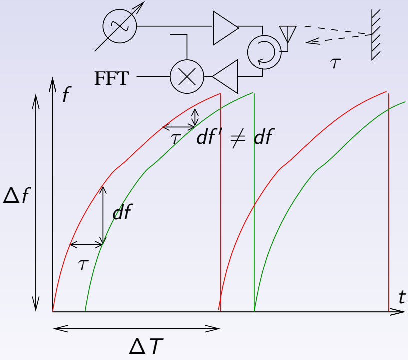

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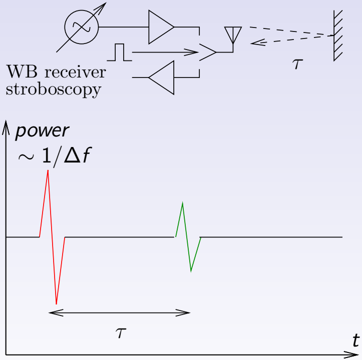

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Software defined radio

- Time gating: no need to record signal before sensor response + focus on sensor response
- Flexibility in sensor response tracking: digital version of the lock-in amplifier

BUT

- need to synchronize emission and reception
- low A/D resolution reduces interrogation range
- dedicated hardware (DDS + switch + power detector)
- *low* bandwidth of the DVB-T receiver (2.7 MHz $\Rightarrow \Delta R \sim 56$ m)

Low cost targets [7] to play with:

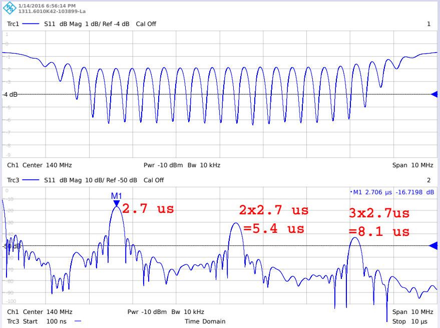
- TV dish receiver **dielectric resonator**
- **SAW [8] resonator** – narrowband device
- **SAW filters** – must be selected to match emitter spectrum

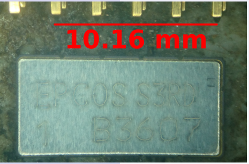
[7] M. Ossman, *The NSA Playset: RF Retroreflectors*, DEF CON 22, available at `https://www.youtube.com/watch?v=mAai6dRAtFo`, and `http://www.nsaplayset.org/`

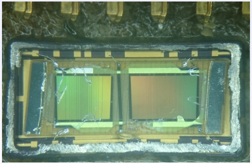
[8] Surface Acoustic Wave

Experimental demonstration

1. A SAW filter delays the incoming electromagnetic signal by 2.7 μs and multiples $\Rightarrow$ pulse repetition rate 100 kHz
2. pulse duration: 2 μs to separate echos and improve SNR of 2.7 MS/s DVB-T receiver signal (5-6 samples/pulse)







TDK/Epcos B3607 140 MHz filter (5 euros on Ebay) network analyzer characterization: top S_{11} (freq. domain), bottom S_{11} (time domain)

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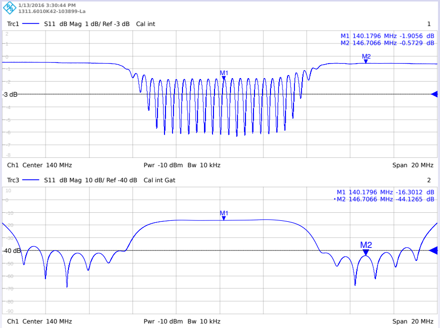

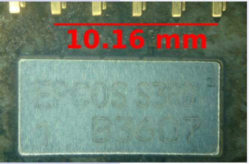

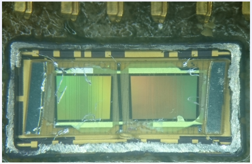

TDK/Epcos B3607 140 MHz filter (5 euros on Ebay) network analyzer characterization: top S_{11}, bottom time-gated between 2 and 3 μs

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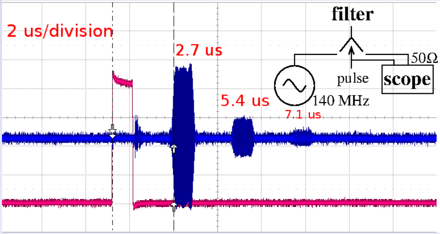
2. pulse duration: 2 μs to separate echos and improve SNR of 2.7 MS/s DVB-T receiver signal (5-6 samples/pulse)
3. open v.s 50 Ω load



signal reflected from the filter (impulse response)

Experimental demonstration

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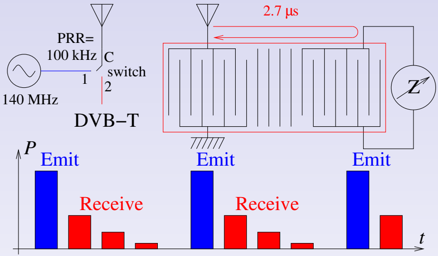
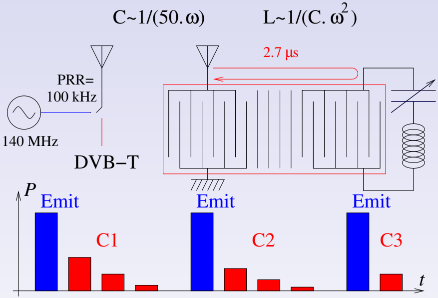
2. pulse duration: 2 μs to separate echos and improve SNR of 2.7 MS/s DVB-T receiver signal (5-6 samples/pulse)
3. variable capacitor (10-100 pF) selected to induce a 50 Ω load at operating pulsation ω, and inductor (56 nH) to cancel the imaginary component



MAX2606 VCO as source, Hittite switch, R820T2 receiver, PWM output of Atmega32U4 for switching

Experimental demonstration

1. A SAW filter delays the incoming electromagnetic signal by 2.7 μs and multiples $\Rightarrow$ pulse repetition rate 100 kHz
2. pulse duration: 2 μs to separate echos and improve SNR of 2.7 MS/s DVB-T receiver signal (5-6 samples/pulse)
3. the digital signal to be observed controls a FET (BF996S) which connects the filter to a 50 Ω load



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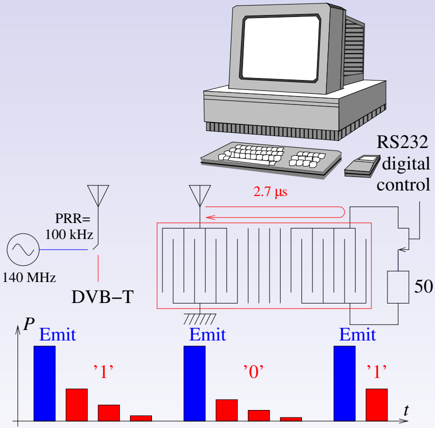

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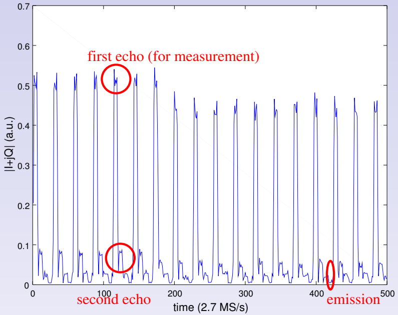
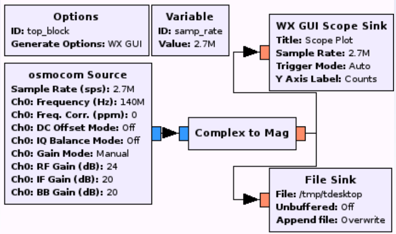
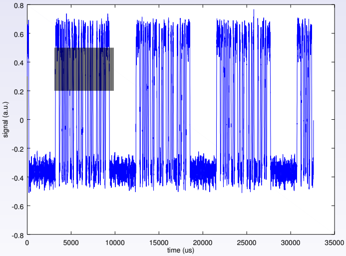
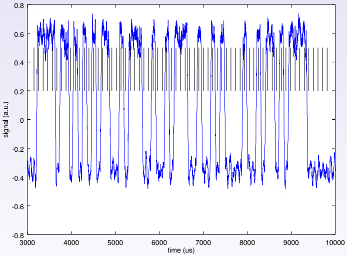




Demonstration using an acoustic filter

1. only keep the returned signal above a given threshold
2. 9600 baud $\Rightarrow$ 1/9600 s/symbol=104 μs/symbol (start, 8 bits, stop)
3. 10 pulses/bit and 5 samples/pulse $\Rightarrow$ 50 I/Q samples/RS232 bit
4. sliding average on 15 samples to keep sharp transitions from 1 to 0





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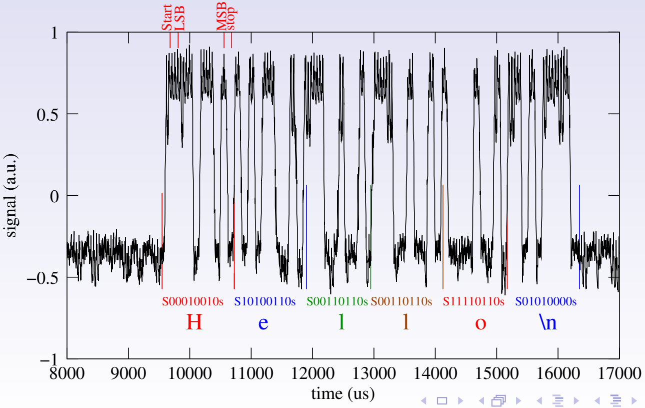
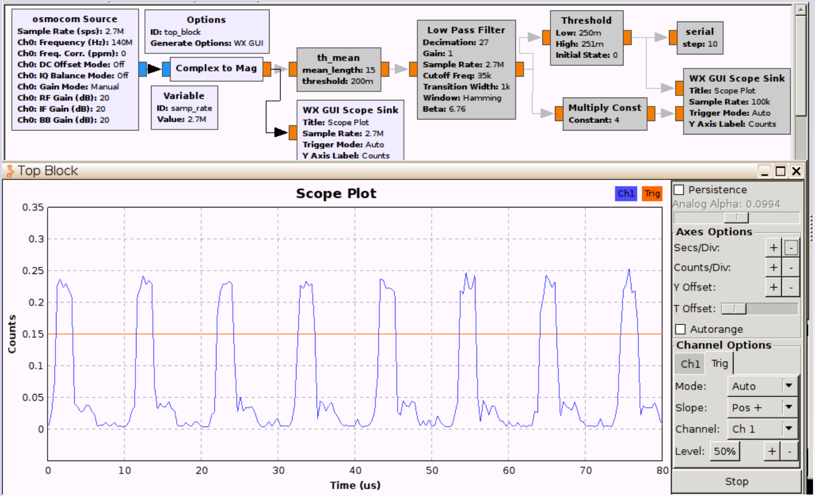


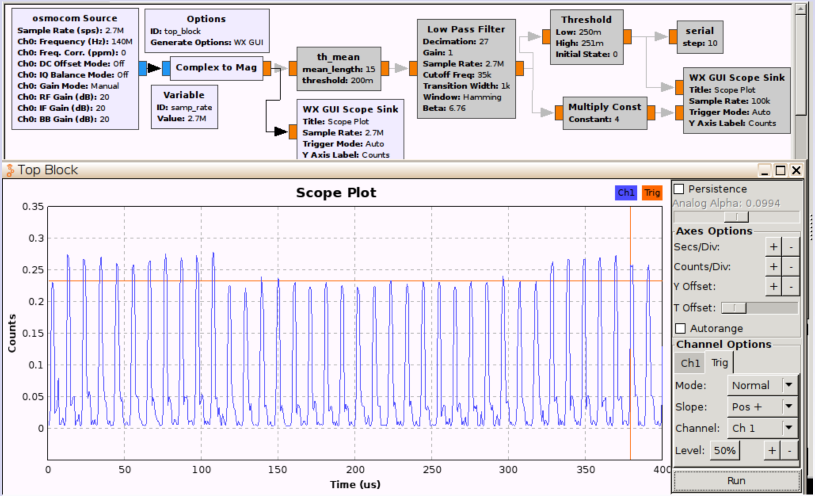
GNURadio real time decoding

Continuously recover the signal including emission and reception times (2.7 MS/s)



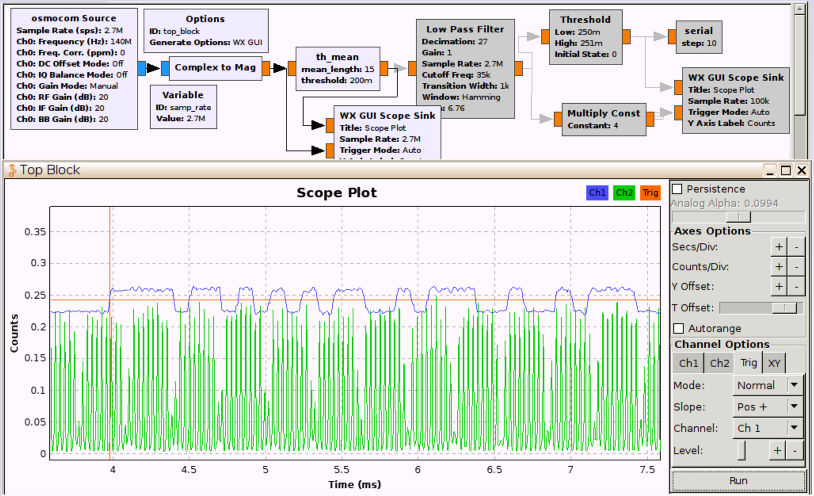
GNURadio real time decoding

Threshold defines the returned echo while low level is observed during emission



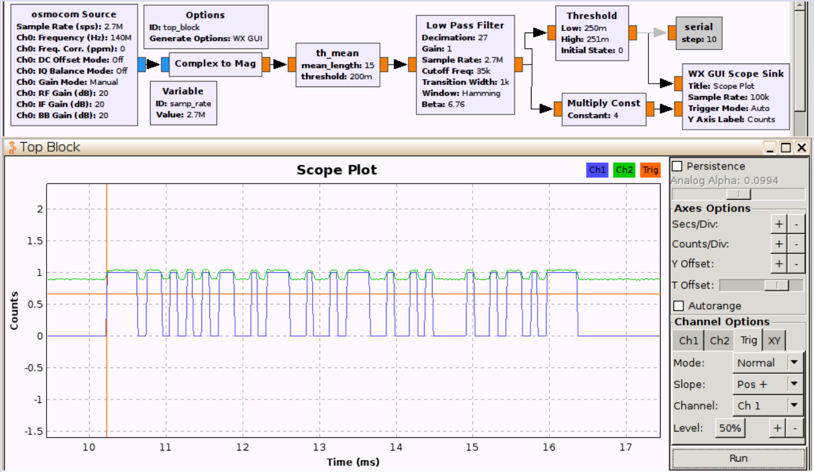
GNURadio real time decoding

Issue of **variable rate**: echoes don't always last the same duration
$\Rightarrow$ peak holder (green), with encoding signal visible



GNURadio real time decoding

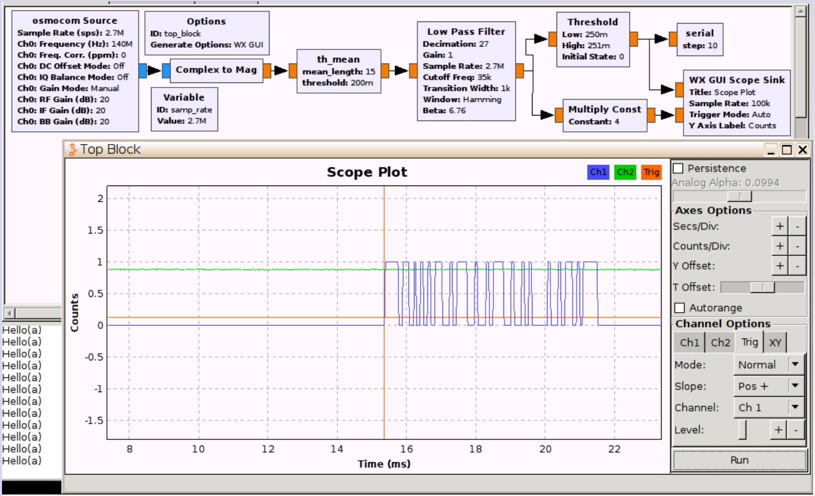
Threshold on the detected signal and low pass filtering for decimation (2700 $\rightarrow$100 kS/s) $\Rightarrow$ at 9600 bauds (104 μs/bit), 10 samples/bit
$\Rightarrow$ **decoding independent on PRR**[9]



[9] Pulse Repetition Rate

GNURadio real time decoding

Real time decoding of the recorded message (start – 8 bits – stop)



Membrane design

Membrane geometry [9]:

Radius $a = 1$ cm, **gap** $h = 50 \cdot 10^{-6}$ m $\Rightarrow C = \varepsilon_0 \varepsilon_r \frac{\pi \cdot a^2}{h} = 56$ pF

Tension load $N_0 = 2000$ N/m along circumference [10]

Pressure p_0**=1 Pa** (traffic on a busy roadway)

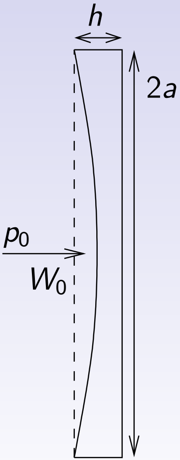
$\Rightarrow$ displacement W_0 at center of membrane by considering force equilibrium:

tension=pressure (assuming negligible membrane stiffness and inertia)

$p_0 \times \pi a^2 = 4\pi N_0 \times W_0 \Leftrightarrow W_0 = \frac{p_0 \cdot a^2}{4 N_0} = 125$ nm and

$$\boxed{\frac{\delta C}{C} = \frac{W_0}{h} = 0.25\% \text{ or } \delta C = 1 \text{ pF}}$$

($\times 10$ if N_0 divided by 10 since sound quality does not matter)



[9] Tradeoff between acoustic and RF characteristics: reentrant cavity design proposed in Report on Research on EASYCHAIR (1955) at `http://www.cryptomuseum.com/covert/bugs/ec/files/19550714_cia.pdf`

[10] `http://etd.dtu.dk/thesis/249608/Arnaud_DESSEIN.pdf`

Conclusion

- RADAR passive **cooperative targets for sensing** & tagging,
- need to separate emitted pulse from returned signal: frequency sweep (FMCW) or time gating (pulsed radar)
- Pulse Repetition Rate defined by echo delay, pulse length defined by recorder bandwidth $\Rightarrow$ make decoding **independent** on PRR
- need to **match** emitter, transducer and receiver **bandwidths**: the narrowest part defines the whole system bandwidth
- demonstrated with **acoustic filter** and PAL delay line (sensing principle ?)
- demonstrated response modulation by varying load under digital control (RS232) and recovering the signal from returned RF signal
- Demonstration using the Redpitaya for >500 kS/s refresh rate [11], now with `gnuradio` **support** in `buildroot`[12].

[11] G. Goavec-Mérou & 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), Jan. 2014, pp.015109

[12] https://github.com/trabucayre/redpitaya

Perspectives

5.8 The RF circuit method[13]

" Before low-noise field effect transistors were available, semiconductor technology was applied to condenser microphones in the form of the so-called radio-frequency circuit method, which requires only conventional transistors. With an RF circuit, the microphone capsule operates as an "active transducer" (see Section 2): It controls the frequency or phase of an RF oscillator or represents an impedance in an RF circuit that varies in cadence with the audio frequency."

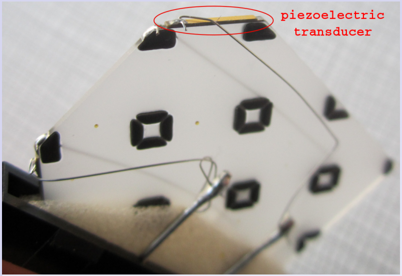
Perspectives:

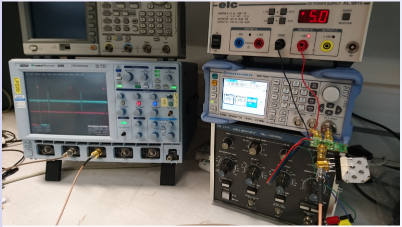
- identify a frequency source and filter for operating at **higher frequency**, yet keeping the long delay,
- demonstrate a **wireless** link (50 cm monopole) instead of simulated propagation losses with attenuator (FSPL≃70 dB @ 10 m 2-way),
- coherent approach for **phase** exploitation (instead of magnitude) requires shared clock between emitter and receiver.

Acknowledgements: V. Plessky, S. Ballandras, G. Martin, L. Reindl & T. Ostertag

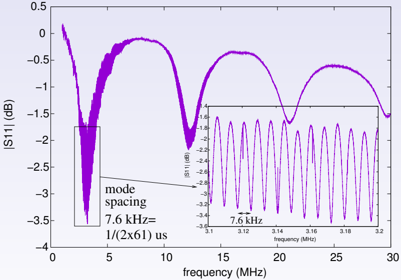
[13] G. Boré & S. Peus, *Microphones – Methods of Operation and Type Examples* (4th Ed.), (1999), p.43, initial release 1973, available at `http://www.neumann.com/downloadmanager/d.php?download=docu0002.PDF`

PAL delay line

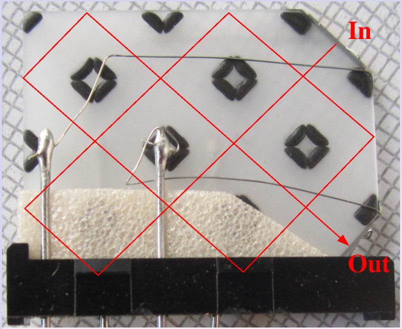


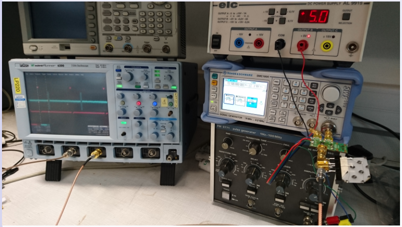


1. 61 μs delay (too large)
2. low operating frequency, 3.2 MHz fundamental frequency (too low)
3. fringes due to delayed signal interference ($c/(2d)$)

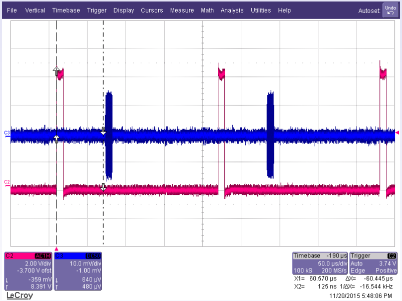


PAL delay line





1. 61 μs delay (too large)
2. low operating frequency, 3.2 MHz fundamental frequency (too low)
3. harmonic: here 12.2 MHz

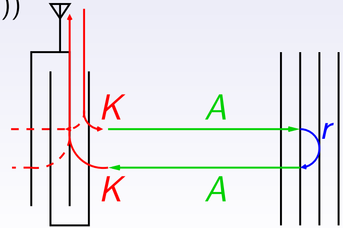


Link budget

For a given transmitted power, propagation range, antenna gains and receiver sensitivity, range is given by the target cross-section σ.

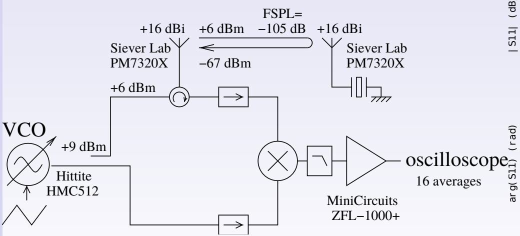
$$\frac{P_r}{P_t} = \frac{G^2\lambda^2\sigma\exp(-2\alpha R)}{(4\pi)^3R^4} \text{ (α for non-air media, eg soil)}$$

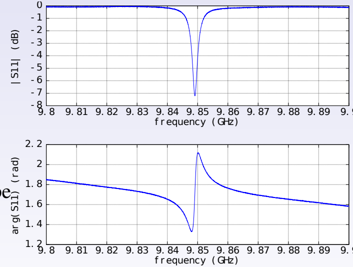
- notice the 4-th power of distance dependance
- delay lines: $\sigma \rightarrow (G')^2\lambda^2/(4\pi\cdot IL)$ with $IL = K^2\times A\times r$ with A att./λ (dB/μs$\propto f^2$, 0.14 dB/μs @ 300 MHz), r mirror reflection coef., $K^2 = 5.4\%$ for LNO-128, 4.8% for LTO-36. Classical **IL: 30 dB**, best case is $\simeq$ 20 dB.
- resonators: returned power$=1-|S_{11}|$ and $\min(S_{11}) < -10$ dB $\Rightarrow IL \simeq -0.5..-2$ dB **but** 8.7 dB/τ loss due to receiver delay (8.7=10$\cdot\log_{10}$(e))



Dielectric resonator wireless interrogation

- Backscattered signal through farfield antenna impedance coupling [14]
- Returned signal requires fine tuning the VCO sweep rate
- Here demonstrated on 9.85 GHz resonator fitted in a resonant cavity
- $Q \simeq 10^4$ mandatory for long range measurement





[14] J.-M. Friedt *& al.*, *Probing a dielectric resonator acting as passive sensor through a wireless microwave link*, Rev. Sci. Instrum. **85** (9), pp. 024409RSI (2014)

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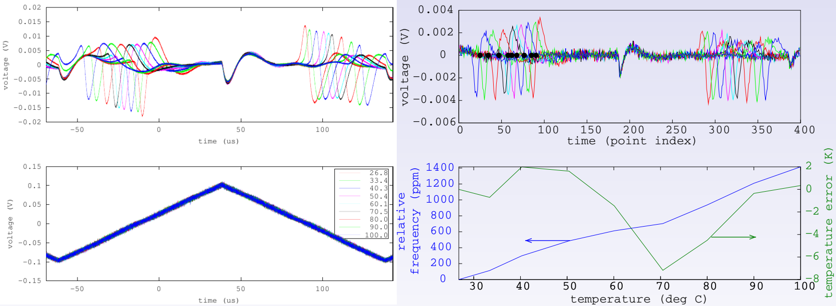

Using the derivate of the returned signal to convert the minimum to a zero-crossing condition

[14] J.-M. Friedt *& al.*, *Probing a dielectric resonator acting as passive sensor through a wireless microwave link*, Rev. Sci. Instrum. **85** (9), pp. 024409RSI (2014)

Membrane design++

Membrane geometry:
radius a,
thickness $h = 250 \cdot 10^{-6}$,
tension load N_0 along circumference,
Material (Mylar):
Young modulus $E \simeq 4-5$ GPa
Poisson ratio $\nu = 0.3$
Pressure $p_0 \Rightarrow$ displacement W_0 at center of membrane

$$D = E \cdot h^3/(12(1-\nu^2))$$

$$k = \sqrt{\frac{N_0 \cdot a^2}{D}}$$

$$P = \frac{p_0 \cdot a^4}{E \cdot h^4}$$

(from [15])

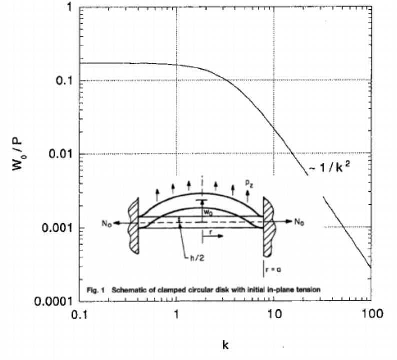

Fig. 2 Center deflection normalized by loading as a function of in-plane tension

Chart of W_0/P as a function of k

[15] M. Sheplak, J. Dugundji, *Large Deflections of Clamped Circular Plates Under Initial Tension and Transitions to Membrane Behavior*, J. Appl. Mech. (1998) **65**, 107–

GNU/Octave to GNURadio RS232 decoding

```
r=read_float_binary('Hellodesktop_2p7.bin');
k=find(r>0.4);
y=conv(r(k),ones(15,1)/15);y=y(7:end-7);     % sliding avg
plot(k(1:15000)/2.7,y(1:15000))
xlabel('time (us)');ylabel('signal (a.u.)')
for k=1:65
  line([k*1e6/9600+3045 k*1e6/9600+3045],[0.4 0.5]) % clk
end

s=0.47                                              % threshold
u=1;
for k=1:4500 % length(k)
 if (y(u)>=s) debut=1;u=u+75 % 1.5 baud=50+25 I/Q samples
  c=0;  % new char start bit (hi->lo transition) detected
  for l=0:7
   if (y(u)<s) printf('1');c=c+2^l; else printf('0'); end
   u=u+50;          % hardcoded baudrate: 5 samples/echo ...
  end               %                           ... & 10 echo/bit
  debut=0;
  printf(' %c\n',char(c))
 end
 u=u+1;
end
```

```
namespace gr {
  namespace theremin {
[...]
    serial_impl::serial_impl(int step) : sync_block("serial",
       gr::io_signature::make(1, 1, sizeof(float)),
       gr::io_signature::make(0, 0, 0)),_next_pos(0),
        _curr_char('\0'), _step(step), _nb_bits(0), _in_frame(0), test_pos(false), _total(0)
    {}
[...]
    void serial_impl::forecast (int noutput_items, gr_vector_int &ninput_items_required)
    {}
#define HIGH_STATE 1
#define LOW_STATE 0
    int serial_impl::work(int noutput_items, gr_vector_const_void_star &input_items,
                          gr_vector_void_star &output_items)
    {const float *in = (const float *) input_items[0];
     volatile long i = _next_pos;
     int start_step = _step + (_step>>1);
     unsigned char bit;

     while (i < noutput_items) {
       bit = (unsigned char)in[i] ^ 1;
       if (_in_frame == 0) {         /* not in a frame : search for start bit falling edge */
         if (bit == LOW_STATE) {
           _in_frame = 1;     /* 1/2 period for start bit + 1 period = middle of first bit */
           i += start_step; _total += start_step;
         } else { i++; _total ++;}
       } else {
         if (_nb_bits >= 8) {                                                   /* stop bit */
           if ((_curr_char>31)&&(_curr_char))
             printf("%c", (unsigned char)_curr_char);
           else printf("(%x)\n", (unsigned char)_curr_char);
             _curr_char = '\0'; _nb_bits = 0; _next_pos = 0; _in_frame = 0;
         } else {_curr_char|= (bit<<_nb_bits);_nb_bits++;i +=_step;_total+=_step;} // add bit
       }
     }
     if (_in_frame == 1) _next_pos = i - noutput_items;  /* if trame is on multiple buffer */
     consume_each (noutput_items);
     return noutput_items;
    }
  } /* namespace theremin */
} /* namespace gr */
```