Passive RADAR interrogation of passive cooperative targets: long range illumination of SAW delay lines using high power sources

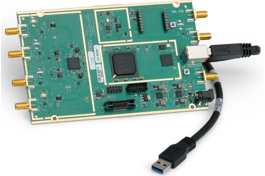
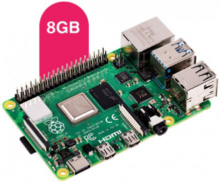

W. Crochot, `commons.wikipedia.org/`

J.-M Friedt, M. Paquit[1]

[1] now with AR Electronique

FEMTO-ST/Time & Frequency, Besançon, France

jmfriedt@femto-st.fr

`https://www.ettus.com/`
`https://www.kubii.fr/`

Slides at `http://jmfriedt.free.fr/sawsymposium2021.pdf`

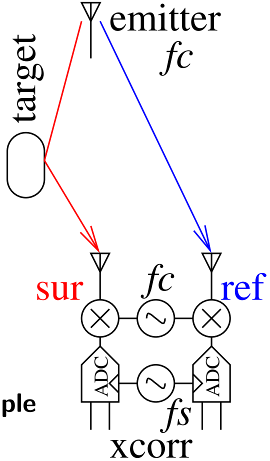
sequel to M. Paquit *& al.*, *Long range passive RADAR interrogation of subsurface acoustic passive wireless sensors using terrestrial television signals*, IEEE Sensors **20** (13) 7156–7160 (2020)

Passive bistatic RADAR (PBR)

- Passive RADAR: using existing electromagnetic sources for RAdiofrequency Detection And Ranging (time delay and Doppler shift for target velocity)
- Popular with universities and amateurs: no need to be allowed to emit a strong signal ($P_R \propto P_E/d^4$)
- Range resolution solely determined by bandwidth Δf $\Delta R = c/(2\Delta f) \Rightarrow \Delta f \nearrow \Rightarrow \Delta R \searrow$
- Beamwidth $\simeq$ azimuth resolution determined by antenna size wrt λ
- Sythetic Aperture RADAR: move transmitting and/or receiving antenna to simulate a large aperture and hence improved azimuth resolution

Demonstrated using Ettus Research E312 or [1] B210 [2] [3] SDR platforms using frequency stacking.

Need for two coherent (same LO, same sampling rate) channels to sample reference and surveillance signals



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[1] S.T. Peters *& al.*, *In Situ Demonstration of a Passive Radio Sounding Approach Using the Sun for Echo Detection*, IEEE Trans. Geosci. and Remote Sensing **56** (12) 7338 (Dec. 2018)

[2] S. Prager *& al.*, *Ultrawideband Synthesis for High-Range-Resolution Software-Defined Radar*, IEEE Trans. Instrum. Meas. **69** 3789-–3803 (2020)

[3] O. Toker *& al.*, *A Synthetic Wide-Bandwidth Radar System Using Software Defined Radios*, 7th International Electronic Conference on Sensors and Applications (15–30 November 2020)

Passive wireless cooperative target

- Design considerations
  - separate relevant signal from clutter: delay echo by at least 1 μs
  - compact: avoid 100 m coaxial cable to delay by 1 μs two-way trip
  - sensing capability: delay dependence with physical environment

  $\Rightarrow$ acoustic delay line since most non-cooperative sources will be wideband ($\neq$ resonator)
- Deployment scenario: passive wireless sensor buried in concrete/soil and periodically probed
- Challenge: radiofrequency emission **regulations**

Use existing high power broadband sources to illuminate SAW delay line and short range reception of the signal

SAW delay line as cooperative target for non-cooperative source PBR measurement [4]

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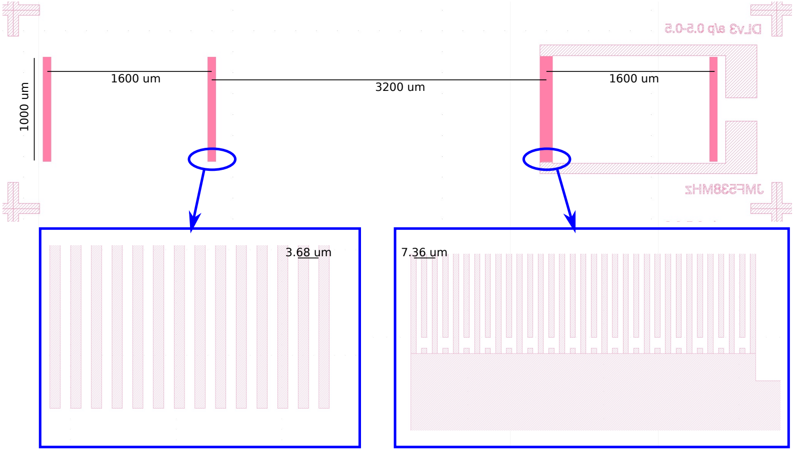
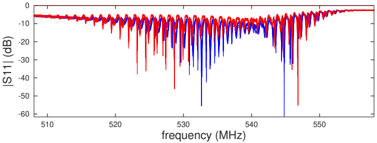
[4] M. Paquit *& al.*, *Long range passive RADAR interrogation of subsurface acoustic passive wireless sensors using terrestrial television signals*, IEEE Sensors **20** (13) 7156–7160 (2020)

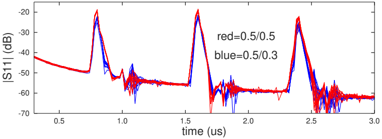
Reflective delay line layout



128° LNO: $K^2 \simeq 5.7\%$: sensor bandwidth $\simeq$ 31 MHz @ 538 MHz, $1/K^2$ finger pairs[5] in inter-digitated transducer (IDT)

- YXl/128° LNO
- 50% or 70% metallization ratio
- aperture=1000 μm
- floating potential …
- … reflective mirrors
- delays T, 2T, 3T (T=870 ns)
- chip size: 7200 μm×1800 μm
- 20 dB time-domain insertion losses





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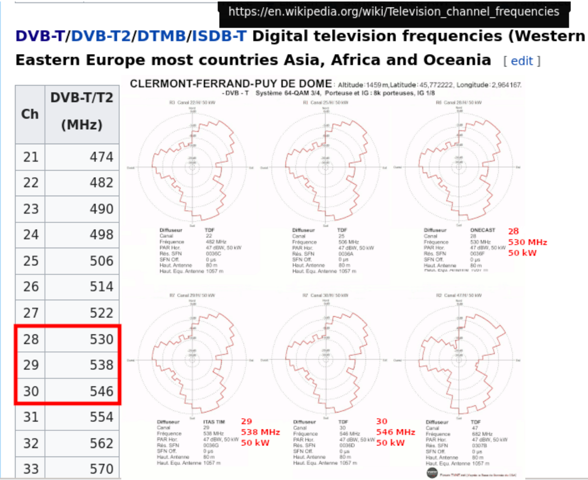
[5] D. Morgan, *Surface Acoustic Wave Filters – With Applications to Electronic Communications and Signal Processing, 2nd Ed.*, Academic Press (2007), pp.158–160, & teaching by V. Plessky

Digital Video Broadcast-Terrestrial non-cooperative source

Static emitter (e.g. DVB-T or GSM tower), static or moving receiver(s)

- 128° LNO: $K^2 \simeq 5.7\%$: sensor bandwidth $\simeq 31$ MHz
- DVB-T 8 MHz wide channels but ...
- ... Clermont Ferrand (45.7726 N, 2.9644 E) transmits DVB-T on three **adjacent channels** (European 28, 29 and 30) centered on 530, 536 and 546 MHz.
- 11.8 km range to the 1465 m high emitter

- One 6-element directional Yagi-Uda antenna towards reference signal and a dipole in close contact to the surface holding the sensor connected to a dipole antenna (cf Ground Penetrating RADAR layout)



https://en.wikipedia.org/wiki/Television_channel_frequencies

DVB-T/DVB-T2/DTMB/ISDB-T Digital television frequencies (Western Eastern Europe most countries Asia, Africa and Oceania [edit]

Ch	DVB-T/T2 (MHz)
21	474
22	482
23	490
24	498
25	506
26	514
27	522
28	530
29	538
30	546
31	554
32	562
33	570

CLERMONT-FERRAND-PUY DE DOME: Altitude: 1459 m, Latitude: 45,772222, Longitude: 2,964167.
- DVB - T Système 64-QAM 3/4, Porteuse et IG : 8k porteuses, IG 1/8

Puy du Dôme DVB-T emitter characteristics

Digital Video Broadcast-Terrestrial non-cooperative source

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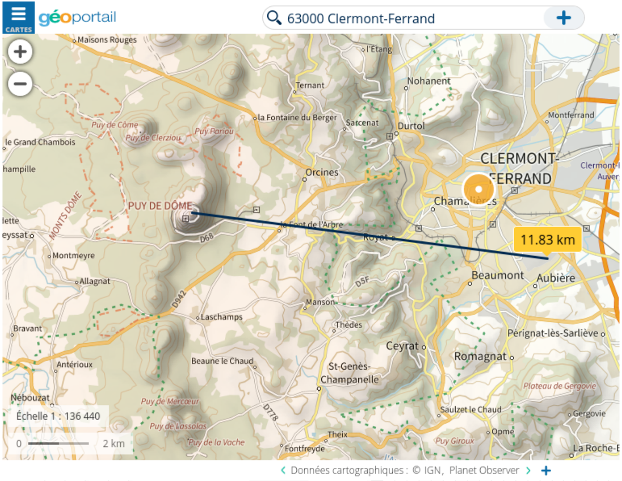


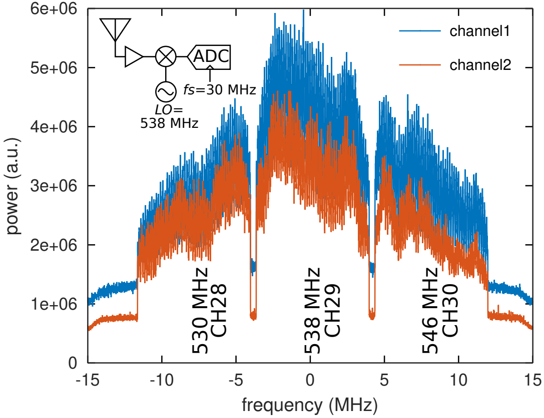
Geographical settings

- One 6-element directional Yagi-Uda antenna towards reference signal and a dipole in close contact to the surface holding the sensor connected to a dipole antenna (cf Ground Penetrating RADAR layout)

Hardware for radiofrequency signal reception

- SDR: bandwidth challenge
- USB3 on RPi4 for maximum transfer bandwidth + avoid the Ethernet/USB sharing bottleneck of RPi3
- single channel B210 measurement: 56 Msamples/s ...
- ... streamed to 8 GB RAM Raspberry Pi 4 (RPi 4) and stored to RAMdisk.
- Custom software [6] for transferring **8-bit data** (Over The Wire (otw) format) and storing 8-bit IQ samples to file
- RPi4 6 GB/56 MS/s IQ bytes=57 second records
- RPi4 6 GB/2×30 MS/s IQ bytes=53 seconds
- AD9361 radiofrequency frontend local oscillator $\in [70 : 6000]$ MHz
- Baseband spectrum displays the three channels ⟶
- Switch the RPi4 to “performance” (1.5 GHz clock rate) mode:

```
echo performance > /sys/devices/system/cpu/cpu0/cpufreq/scaling_governor
```



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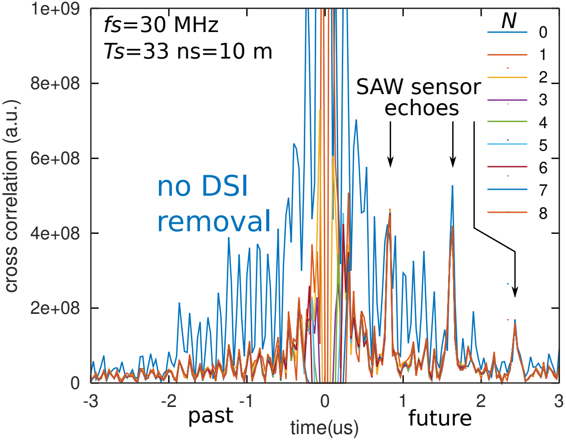
[6] https://github.com/jmfriedt/sentinel1_pbr/

Signal extraction: direct signal interference (DSI) removal

- The surveillance channel receives the direct signal from the emitter as well
- The DVB-T is not exactly noise (autocorrelation=Dirac) but includes some repetitive structure in time and frequency (ambiguity function $\int s(t)s^*(t-\tau)\exp(j2\pi ft)\cdot dt$ = autocorrelation when Doppler shift is null)
- Identify direct signal from reference antenna and subtract from surveillance shifted n times, $n \in [0:N]$ with N large enough to remove multipath but small enough to keep target echoes
- weights identified as least square error solution[7]: assemble matrix of time-delayed copies of reference measurement, and pseudo-inverse to identify weight of each vector in surveillance: ⟶



```
Index1=-N;Index2=N;  % analyze delay N*dt, could be positive only
num_range_shift=(Index2-Index1+1);        % if ref channel is known
X1=zeros(nt,num_range_shift);
for kk=Index1:Index2                                % by W. Feng & al
   te=kk+abs(Index1)+1;
   if kk<=0 X1(:,te)=[signal_ref(0-kk+1:end);zeros(0-kk,1)];
        else X1(:,te)=[zeros(kk-1,1);signal_ref(1:end-kk+1)]; end
end
signal_meas=signal_meas-X1*(pinv(X1)*signal_meas); % least square
```

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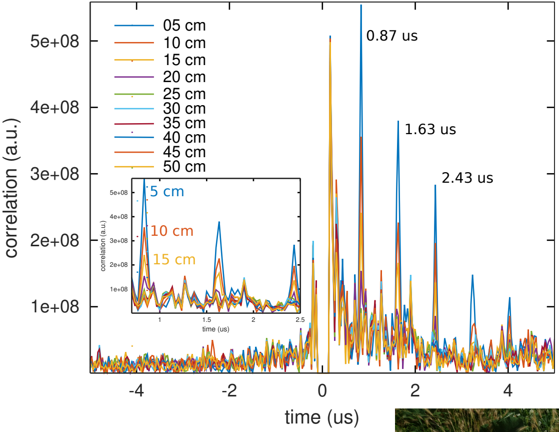
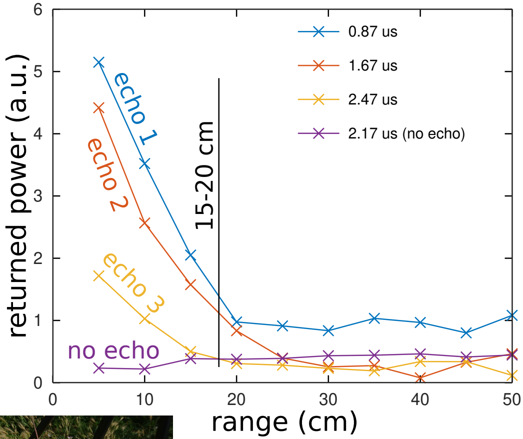
[7] W. Feng, J.-M. Friedt, G. Cherniak, Z. Hu, M. Sato, *Direct path interference suppression for short range passive bistatic SAR imaging based on atomic norm minimization and Vandermonde decomposition*, IET Radar, Sonar and Navigation (2019)

Measurement range assessment

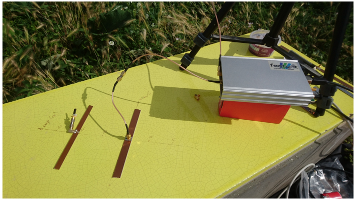




X: time delayed copies of *ref*

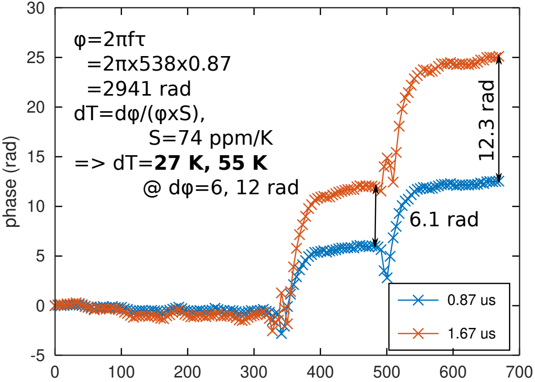
$$sur = sur - X\cdot\underbrace{\underbrace{(X^t\cdot X)^{-1}X)}_{pinv(X)}\cdot sur)}_{weights}$$

$$xcorr = iFFT[FFT(ref)\cdot FFT^*(sur)]$$

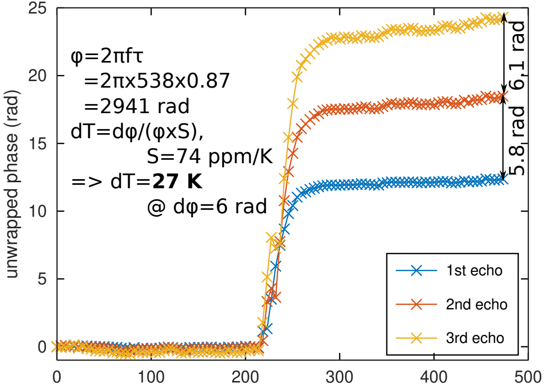


Temperature measurement

- Range from surveillance dipole to sensor dipole: 10 cm – lighter heating the sensor
- 128° LNO: ≃ 74 ppm/K



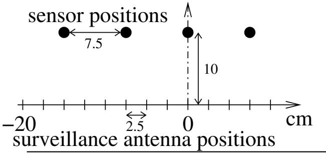
φ=2πfτ
=2πx538x0.87
=2941 rad
dT=dφ/(φxS),
S=74 ppm/K
=> dT=**27 K, 55 K**
@ dφ=6, 12 rad

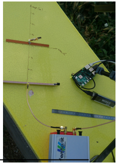


φ=2πfτ
=2πx538x0.87
=2941 rad
dT=dφ/(φxS),
S=74 ppm/K
=> dT=**27 K**
@ dφ=6 rad

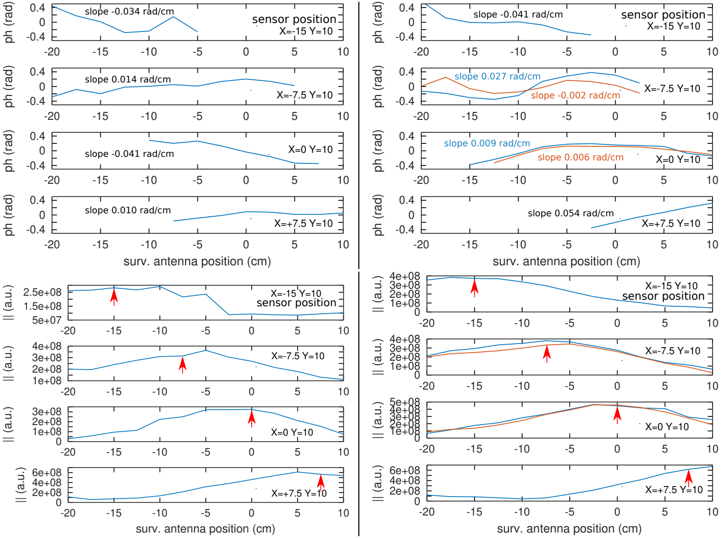
Spatial separation of sensors

- Matrix ($M \times N$) with M time-domain acquisitions for N surveillance antenna positions separated by $\Delta d < \lambda/2$
- Range compression: correlation along time axis (M items)
- Phase along azimuth: $\varphi = 2\pi \frac{\Delta d}{\lambda} \sin \vartheta_0$
- Synthetic aperture RADAR azimuth compression [8]: iFFT along surveillance antenna positions (N items)
- Here near field measurement: max(|returned power|) hints at sensor position along measurement line





Experiment1 Phase Experiment2



Magnitude

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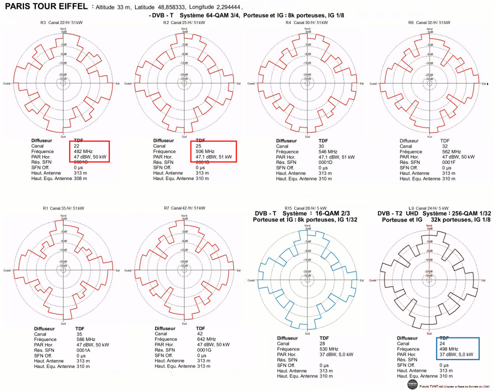
[8] W. Feng, J.-M Friedt, G. Goavec-Merou, M. Sato, *Passive radar delay and angle of arrival measurements of multiple acoustic delay lines used as passive sensors*, IEEE Sensors **19** (2) 594–602 (2019)

Same in Paris ... Eiffel tower, measurement 4.25 km away

- 50 kW at 482 and 506 MHz (32 MHz wide) and tentative
  5 kW @ 498 & 530 MHz



PARIS TOUR EIFFEL : Altitude 33 m, Latitude 48,858333, Longitude 2,294444.

- DVB - T Système 64-QAM 3/4, Porteuse et IG : 8k porteuses, IG 1/8

	R3 Canal 22/H/ 51kW	R2 Canal 25/H/ 51kW	R4 Canal 30/H/ 51kW	R6 Canal 32/H/ 51kW	R1 Canal 35/H/ 51kW	R7 Canal 42/H/ 51kW
Diffuseur	**TDF**	**TDF**	**TDF**	TDF	**TDF**	**TDF**
Canal	22	25	30	32	35	42
Fréquence	482 MHz	506 MHz	546 MHz	562 MHz	586 MHz	642 MHz
PAR Hor.	47 dBW, 50 kW	47,1 dBW, 51 kW	47,1 dBW, 51 kW	47 dBW, 50 kW	47 dBW, 50 kW	47 dBW, 50 kW
Rés. SFN	0001C	0001B	0001D	0001F	0001A	0001G
SFN Off.	0 µs	0 µs	0 µs	0 µs	0 µs	0 µs
Haut. Antenne	313 m	313 m	313 m	313 m	313 m	313 m
Haut. Equ. Antenne	308 m	310 m	310 m	310 m	310 m	313 m

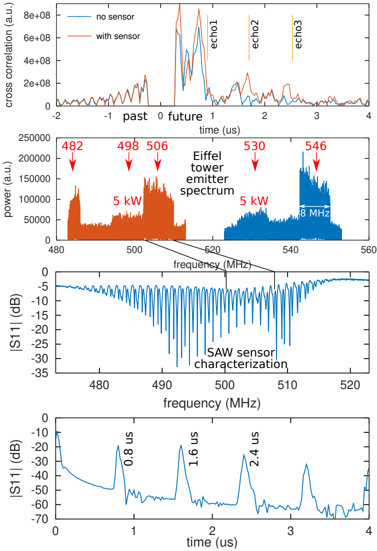
R15 Canal 28/H/ 5 kW
DVB - T Système : 16-QAM 2/3
Porteuse et IG : 8k porteuses, IG 1/32

L9 Canal 24/H/ 5 kW
DVB - T2 UHD Système : 256-QAM 1/32
Porteuse et IG 32k porteuses, IG 1/8

	R15 Canal 28/H/ 5 kW	L9 Canal 24/H/ 5 kW
Diffuseur	**TDF**	**TDF**
Canal	28	24
Fréquence	530 MHz	498 MHz
PAR Hor.	37 dBW, 5,0 kW	37 dBW, 5,0 kW
Rés. SFN		
SFN Off.	0 µs	0 µs
Haut. Antenne	313 m	313 m
Haut. Equ. Antenne	310 m	310 m

Forum TVNT.net (d'après la Base de Donnée du CSA)

Only a single channel in each 30-MHz wide band.



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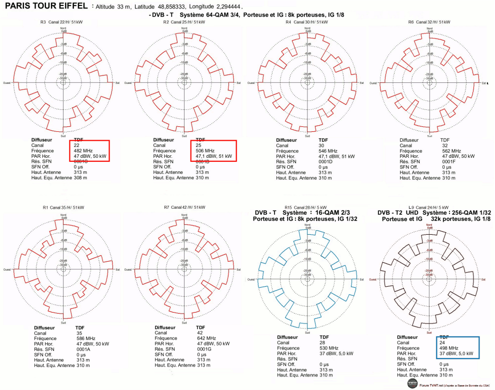
- 50 kW at 482 and 506 MHz (32 MHz wide) and tentative 5 kW @ 498 & 530 MHz



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R3 Canal 22 /H/ 51kW

Diffuseur	**TDF**
Canal	22
Fréquence	482 MHz
PAR Hor.	47 dBW, 50 kW
Rés. SFN	0001C
SFN Off.	0 µs
Haut. Antenne	313 m
Haut. Equ. Antenne	308 m

R2 Canal 25 /H/ 51kW

Diffuseur	**TDF**
Canal	25
Fréquence	506 MHz
PAR Hor.	47,1 dBW, 51 kW
Rés. SFN	0001B
SFN Off.	0 µs
Haut. Antenne	313 m
Haut. Equ. Antenne	310 m

R4 Canal 30 /H/ 51kW

Diffuseur	**TDF**
Canal	30
Fréquence	546 MHz
PAR Hor.	47,1 dBW, 51 kW
Rés. SFN	0001D
SFN Off.	0 µs
Haut. Antenne	313 m
Haut. Equ. Antenne	310 m

R6 Canal 32 /H/ 51kW

Diffuseur	TDF
Canal	32
Fréquence	562 MHz
PAR Hor.	47 dBW, 50 kW
Rés. SFN	0001F
SFN Off.	0 µs
Haut. Antenne	313 m
Haut. Equ. Antenne	310 m

R1 Canal 35 /H/ 51kW

Diffuseur	**TDF**
Canal	35
Fréquence	586 MHz
PAR Hor.	47 dBW, 50 kW
Rés. SFN	0001A
SFN Off.	0 µs
Haut. Antenne	313 m
Haut. Equ. Antenne	310 m

R7 Canal 42 /H/ 51kW

Diffuseur	**TDF**
Canal	42
Fréquence	642 MHz
PAR Hor.	47 dBW, 50 kW
Rés. SFN	0001G
SFN Off.	0 µs
Haut. Antenne	313 m
Haut. Equ. Antenne	313 m

R15 Canal 28 /H/ 5 kW

DVB - T Système : 16-QAM 2/3
Porteuse et IG : 8k porteuses, IG 1/32

Diffuseur	**TDF**
Canal	28
Fréquence	530 MHz
PAR Hor.	37 dBW, 5,0 kW
Rés. SFN	
SFN Off.	0 µs
Haut. Antenne	313 m
Haut. Equ. Antenne	310 m

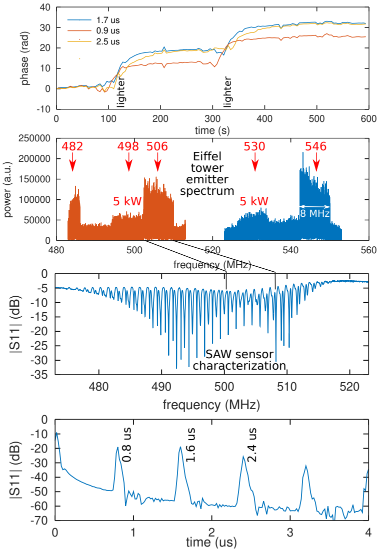
L9 Canal 24 /H/ 5 kW

DVB - T2 UHD Système : 256-QAM 1/32
Porteuse et IG 32k porteuses, IG 1/8

Diffuseur	**TDF**
Canal	24
Fréquence	498 MHz
PAR Hor.	37 dBW, 5,0 kW
Rés. SFN	
SFN Off.	0 µs
Haut. Antenne	313 m
Haut. Equ. Antenne	310 m

Forum TVNT.net (d'après la Base de Donnée du CSA)

Consistent temperature measurement @ 4.5 cm.



How does it compare with energy harvesting?

Series of investigations at Univ. of Tôkyô on rectenna for electromagnetic smog energy harvesting

- H. Nishimoto, Y. Kawahara, T. Asami, *Prototype Implementation of Ambient RF Energy Harvesting Wireless Sensor Networks*, IEEE Senseors conference (2010)
- R. Vyas, H. Nishimoto, M. Tentzeris, Y. Kawahara, T. Asami, *A battery-less, energy harvesting device for long range scavenging of wireless power from terrestrial TV broadcasts*, Proc. IEEE MTT-S International Microwave Symposium (2012)
- R.J. Vyas, B.B. Cook, Y. Kawahara, M. Tentzeris, *E-WEHP: A Batteryless Embedded Sensor-Platform Wirelessly Powered From Ambient Digital-TV Signals*, IEEE Trans. Microwave Theory and Techniques (2013) ⟶

6.3 km from Tôkyô Tower to Univ. of Tôkyô Hongo campus: -9 dBm resulting from -37 dBm integrated over 9 channels (54 MHz bandwidth) to power a MSP430 & PIC24F low-power microcontrollers + radiofrequency digital communication interface **but 60 s charge time**

This work: 77 dBm emitted at a range of 11.8 km ⇒ Free Space Propagation Loss leads to -31.5 dBm received power at SAW sensor with 20 dB loss ⇒ -51.5 dBm backscattered power and Free Space Propagation Loss to surveillance: -58.5 dBm received power ideally @ 10 cm = 266 μV_{RMS} **but** 1 MS correlation collected in **30 ms**

IEEE TRANSACTIONS ON MICROWAVE THEORY AND TECHNIQUES

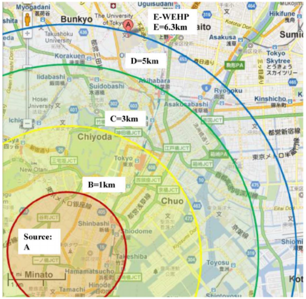


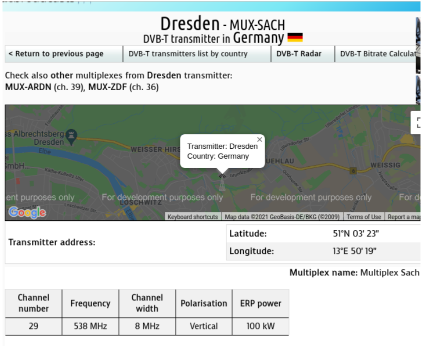
Fig. 3. Location of Tokyo TV broadcast source at A (35°39′31 N 139°44′44 E) with respect to E-WEHP at E (35.712704 N, 139.763277 E) 6.3 km away.

TABLE II
THEORETICAL AND MEASURED SINGLE-CARRIER AND CHANNEL POWER LEVELS USING E-WEHP ANTENNA (GAIN: 5–7.3 dBi)

TV Channel Freq. (MHz)		A P_{TX} Power kW	B 1km μW	C 3km μW	D 5km μW	E 6.3km μW	
						theory	meas
JOMX 512-518	1-tone	5	0.32	0.26	0.21	0.19	0.008
	Channel		37.3	30.3	24.5	22.1	0.93
JO-RX/CX/TX/EX/AX/AB/AK 518-560	1-tone	48	3.6-4.1	2.9-3.4	2.3-2.7	2.2-2.5	0.1-0.25
	Channel		419-478	338-396	268-315	256-291	11.7-29
JOUD 560-566	1-tone	19	1.37	1.08	0.86	0.78	0.032
	Channel		160	126	100	91	3.73

Conclusion

- Demonstration of long range (>10 km) powering of SAW delay line for short range (<20 cm) passive wireless transducer probing in the context of shallow buried sensors
- Embedded, COTS hardware for passive bistatic RADAR probing of cooperative targets
- Demonstration with VHF SAW reflective delay lines and DVB-T transmitters.
- Need for subtracting Direct Signal Interference to recover SAW sensor backscattered signal.



Dresden - MUX-SACH
DVB-T transmitter in **Germany**

Check also **other** multiplexes from **Dresden** transmitter:
MUX-ARDN (ch. 39), **MUX-ZDF** (ch. 36)

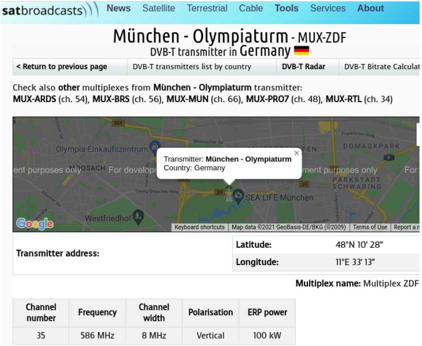
Transmitter: Dresden
Country: Germany

Transmitter address:	**Latitude:**	51°N 03' 23"
	Longitude:	13°E 50' 19"

Multiplex name: Multiplex Sach

Channel number	Frequency	Channel width	Polarisation	ERP power
29	538 MHz	8 MHz	Vertical	100 kW

S. Müller, `wikimedia.org`



München - Olympiaturm - MUX-ZDF
DVB-T transmitter in **Germany**

Check also **other** multiplexes from **München - Olympiaturm** transmitter:
MUX-ARDS (ch. 54), **MUX-BRS** (ch. 56), **MUX-MUN** (ch. 66), **MUX-PRO7** (ch. 48), **MUX-RTL** (ch. 34)

Transmitter: **München - Olympiaturm**
Country: Germany

Transmitter address:	**Latitude:**	48°N 10' 28"
	Longitude:	11°E 33' 13"

Multiplex name: Multiplex ZDF

Channel number	Frequency	Channel width	Polarisation	ERP power
35	586 MHz	8 MHz	Vertical	100 kW

Taxiarchos228, `wikimedia.org`

Applicable throughout Europe at least (example of German emitters: 100 kW EIRP) & China [9]

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[9] `http://www.com-tech.it/download/ChannelStructure.pdf`