Outline

Motivations (why)

Positioning & synchronizing (what)

The measurement system (how we did it)

Serendipity and lessons learned (some expected and unexpected consequences)

Engineering Systems for Positioning and synchronizing and other amenities

Paolo Carbone - University of Perugia - Italy

September 3, 2013

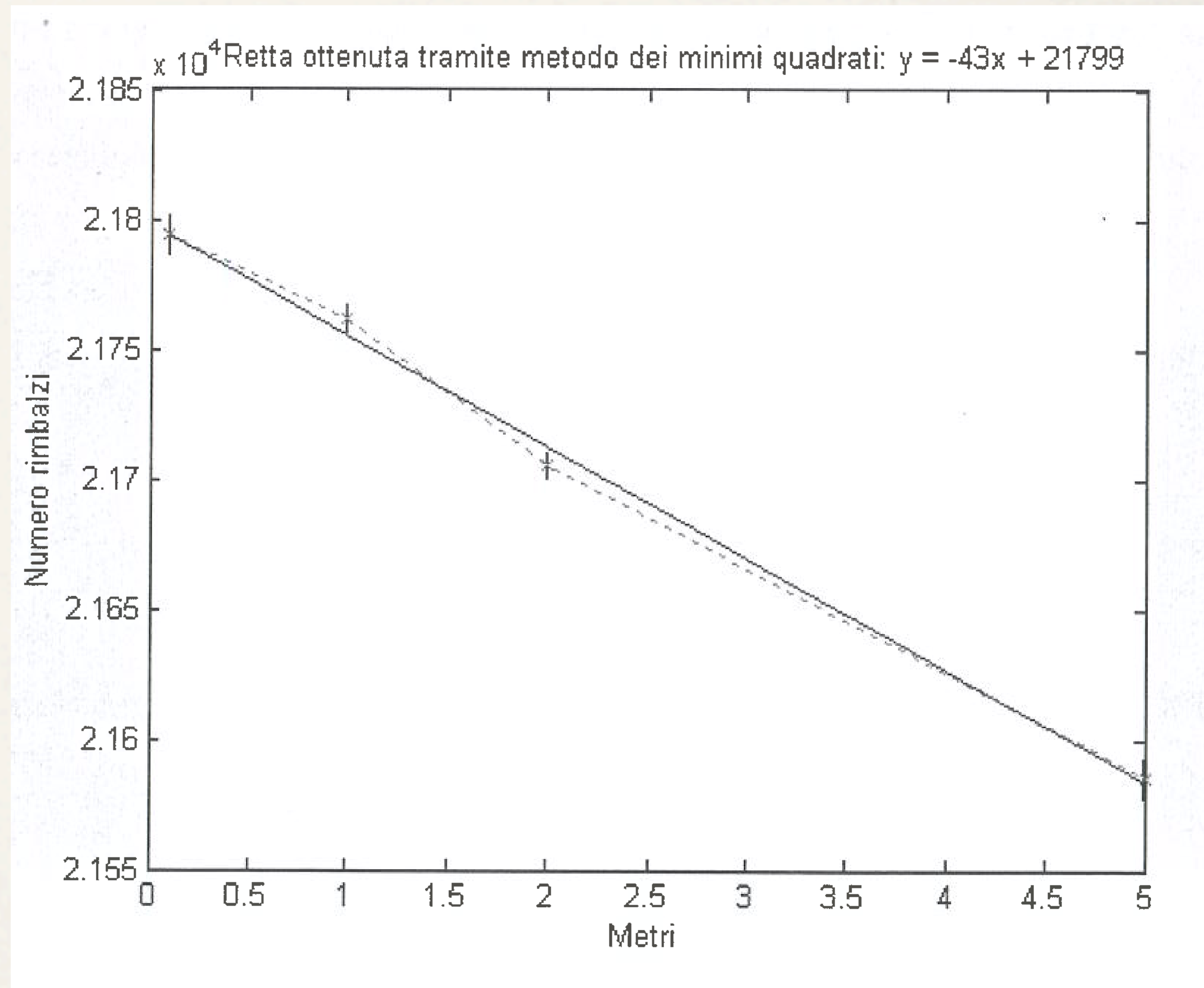
Blue sky research

- Characterization of communication networks

- Student's project: measure length of a cable between two nodes of a sensor network

Ping-pong approach of data packets
Count the number of bounces in 0.25s
COTS uC: max error < 20cm over 5 m

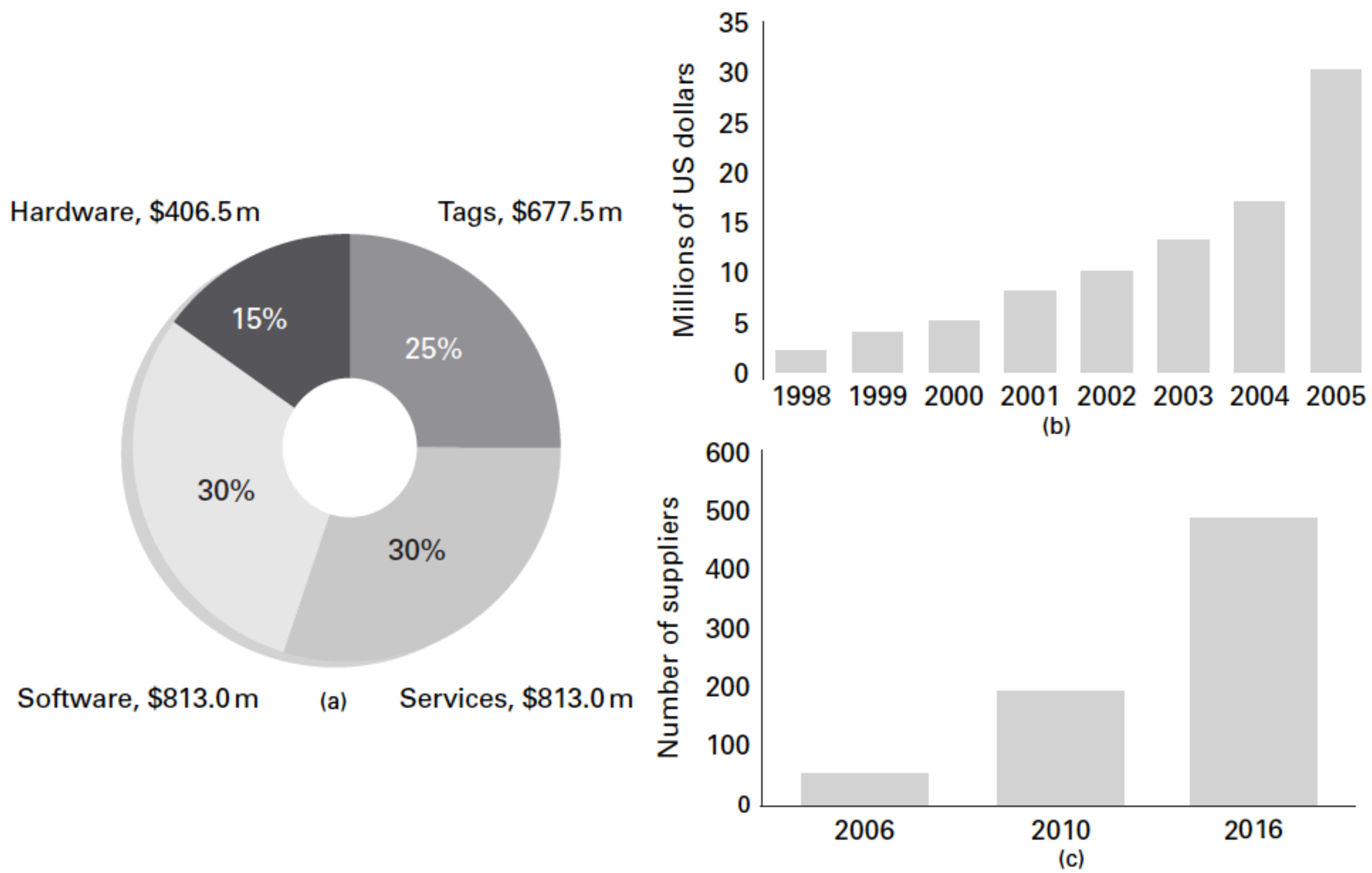
Cable in water ....
Cable around your body ...
Ranging in sensor networks?



Ranging and positioning in sensor network systems

- Ample scenario of ubiquitous computing and location-aware computing
- request for seamless localization capabilities inside and outside buildings
- Applications in areas such: emergency, safety, security, tracking, logistics, personal navigation, gaming, military, commerce
- Standardization driver: IEEE 802.15.4a-2007: Wireless Medium Access Control (MAC) and Physical Layer (PHY) Specifications for Low-Rate Wireless Personal Area Networks (WPANs)
- GPS does not provide useful information in closed environments and urban canyons
- Sister problem: network node synchronization

… driven by market needs



(a) Share of spendings on RTLS in 2016 in millions of US dollars. (b) Global market on RTLS in millions of US dollars, from 1998 to 2005. (c) Trend in number of significant suppliers into parts of the RTLS value chain in 2006, 2010 and 2016 (After [9]).

… an old problem

- compass (around 1000) and astrolabe, quadrant, sextant since 17th century
- navigation using the sun and the stars
- radar (half of 20th century)

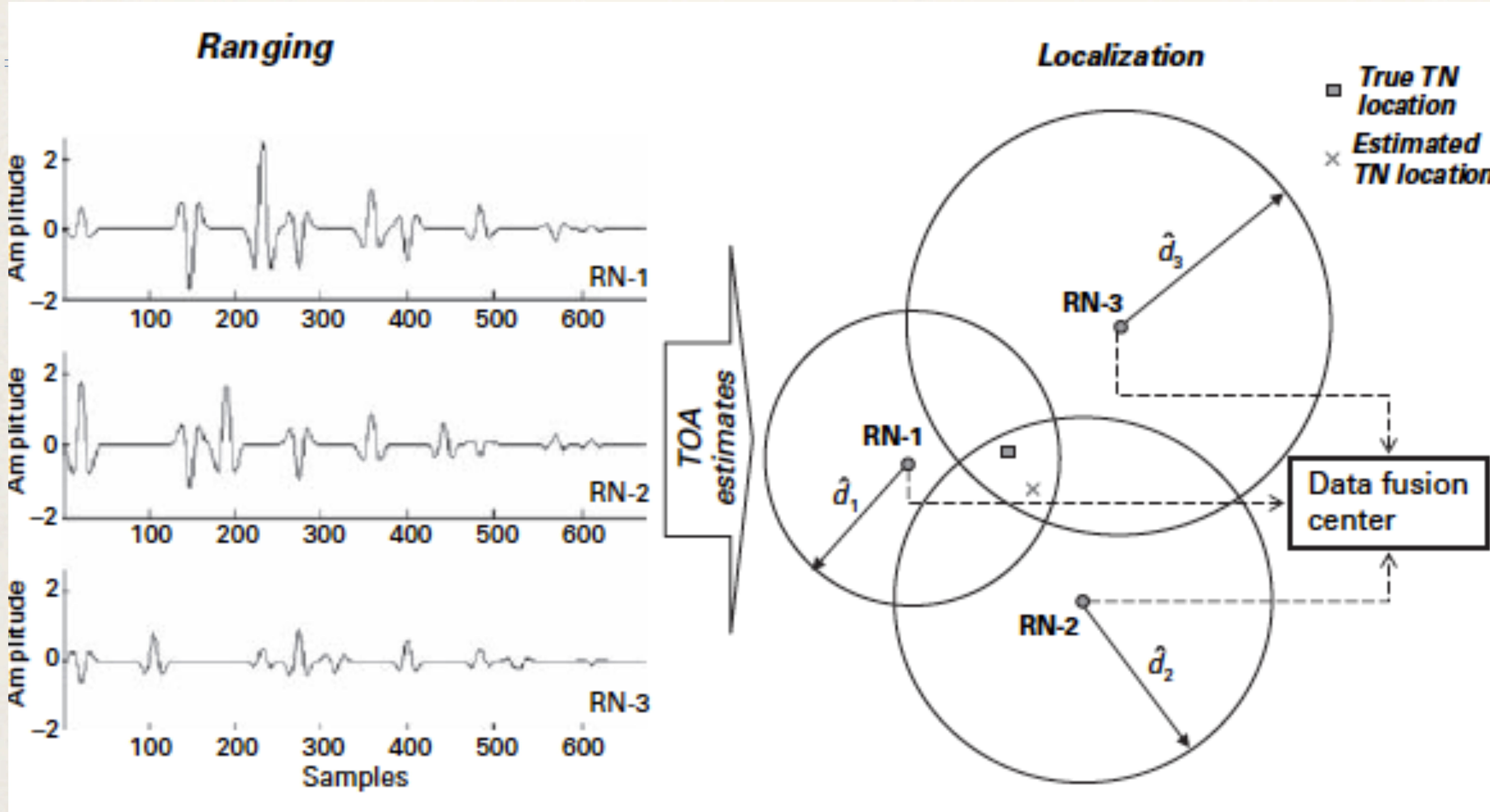
Requirements and possible technologies

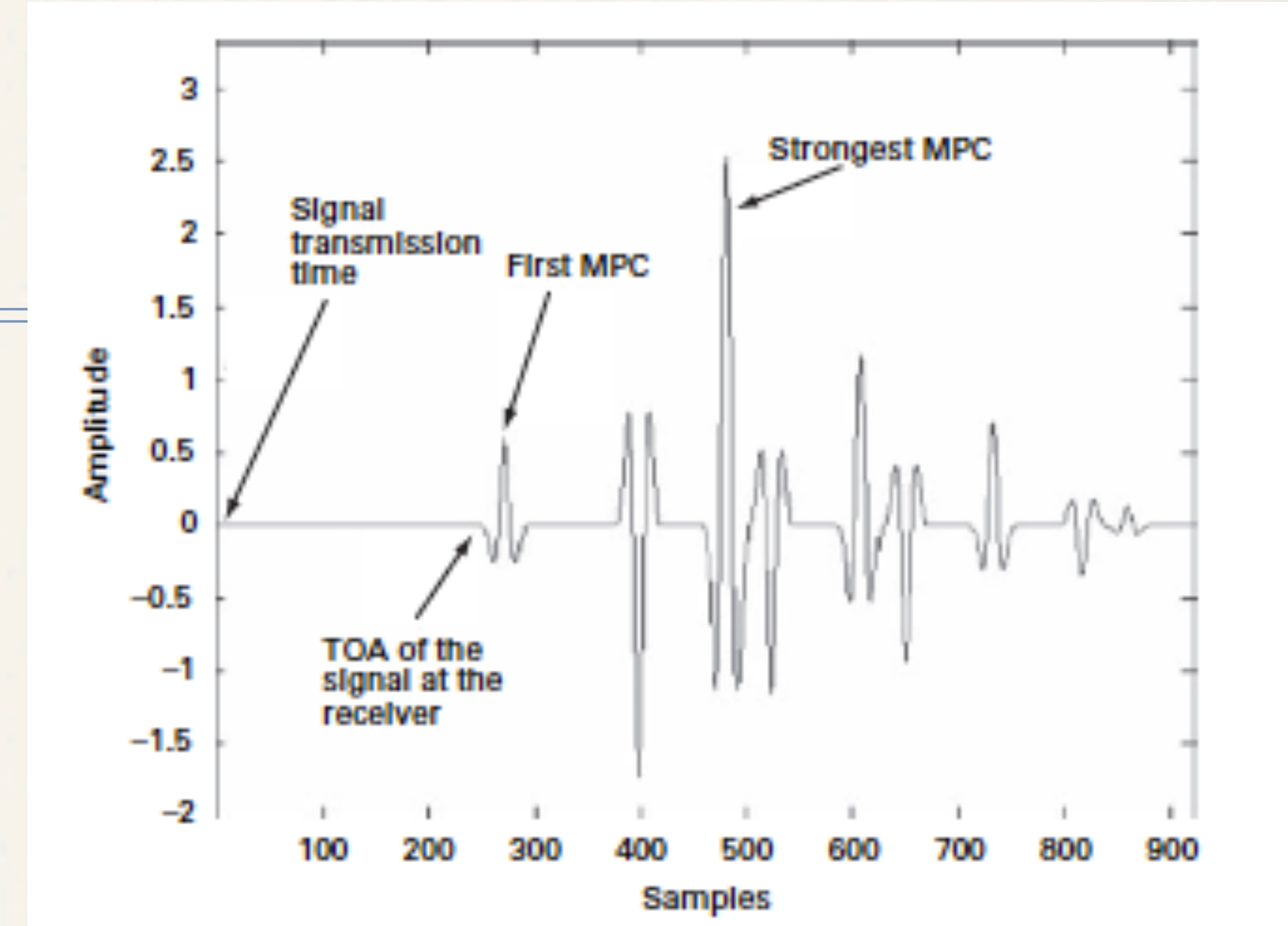
Ultrasound
• Optical/visual systems (infrared, laser, cameras)
• Inertial navigation
• RFID
• Wi-Fi
• UWB
• ZigBee
Hybridization of technologies

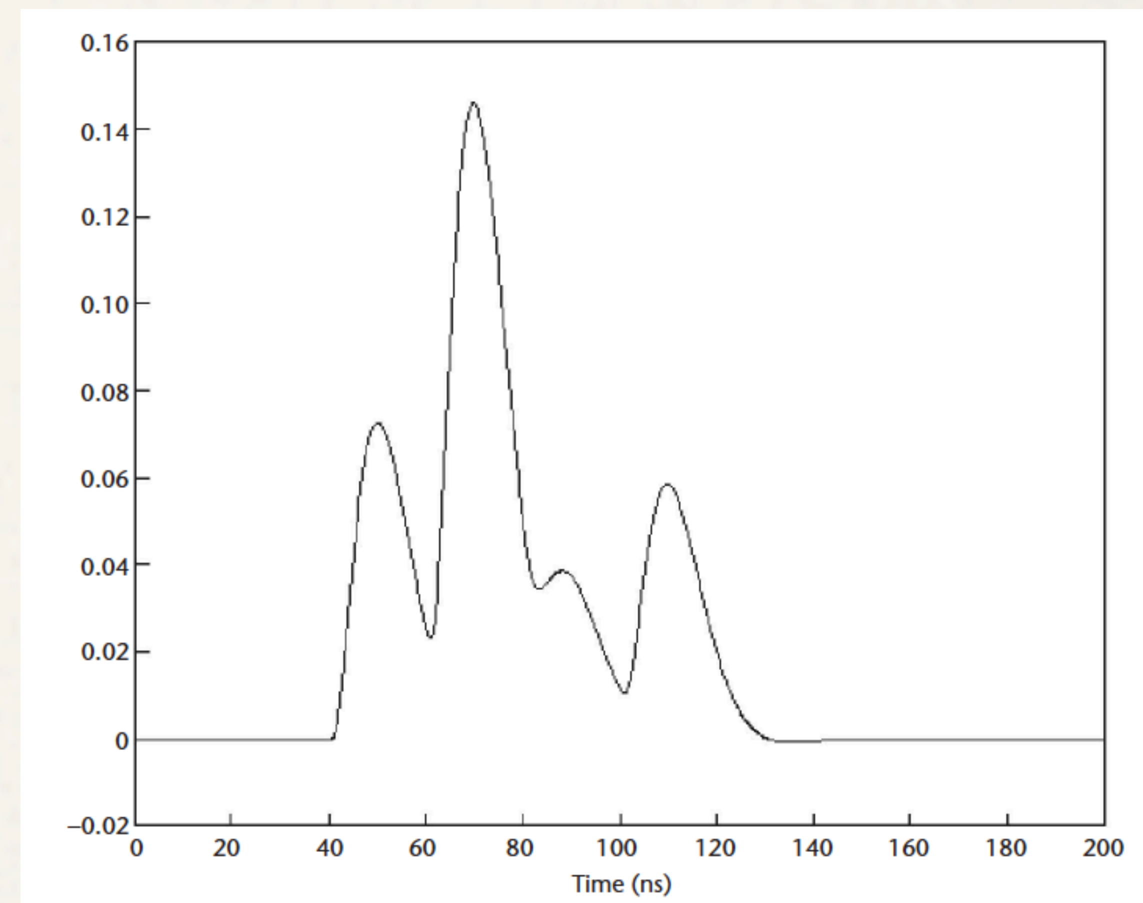
Table 1.2. Accuracy requirements of potential localization applications (After [8]).

Applications	Accuracy
Automated handling	0.5 cm
Route-guidance for blind	1 cm
In-building survey	1 cm
Tool positioning	1 cm
In-building robot guidance	8 cm
Formation flying	10 cm
Recreation and toys	10 cm
Urban canyon (off-road)	30 cm
Urban canyon (marine)	50 cm
Incidence tracking/guidance	80 cm
Urban canyon (other)	80 cm
Exhibit commentary	1 m
Goods and item tracking	1 m
Hazard warnings	1 m
Pedestrian route guidance	1 m
In-building tracking (other)	1 m
In-building worker tracking	1 m
Urban canyon (rail)	1 m
Precision landing	1 m
Access control	3 m
Location-based services	3 m
Public services tracking	3 m
Docking	5 m
Parolee tracking	10 m
Local information	30 m
Train / air / bus information	30 m
Advertising	100 m

Measurement model







- Shadowing, *multipath* and NLOS effects influence measurement context
- UWB: very few full realizations described in literature

Measurement methods

A triangulation problem

TOA - synchronization issues between M/S and clock granularity
TDOA - synchronized slaves
RTT - synchronization not needed
AOA - requires directional antennas

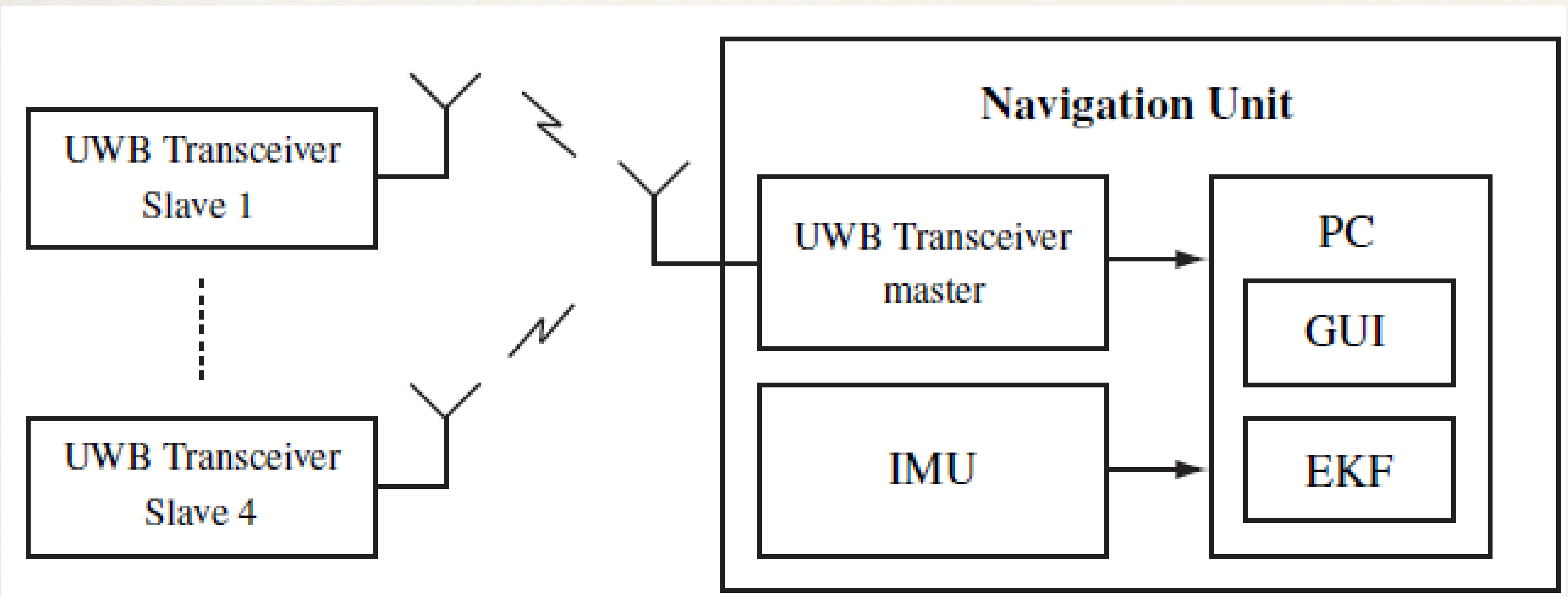
fingerprinting (RSSI), video, tagging, pattern matching

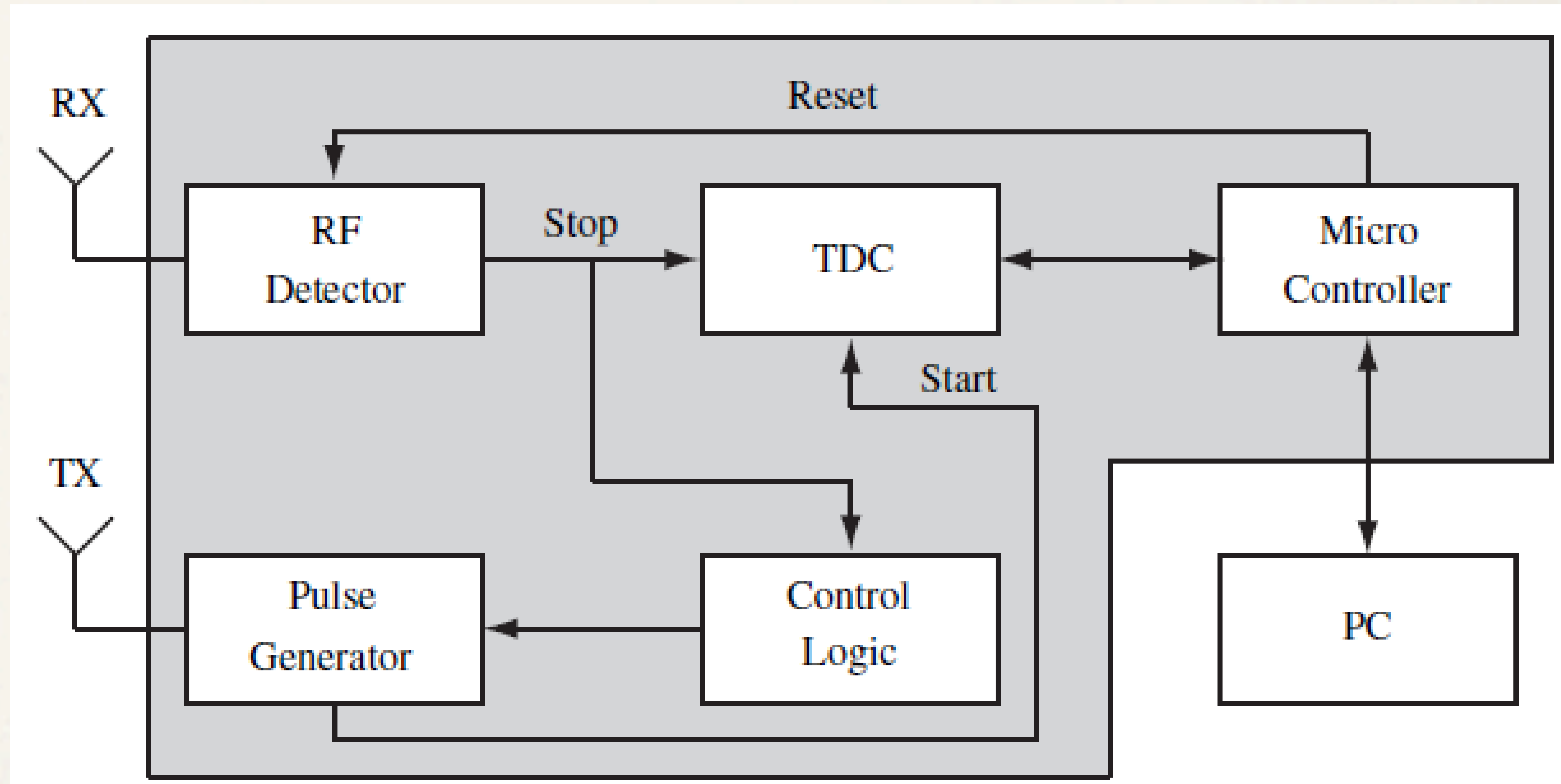
Many algorithms are applicable: NLS is the simplest one
(others being Extended *Kalman* filtering, particle filtering, ...)

The measurement system: a systems engineering challenge

- Really a ***systems engineering*** type of problem:
- Much of the technology is known: difficulties at interfacing and synchronizing operations
- Sensor network: several slave nodes at known positions and the master node
- Generation of very short-time pulses (<1 ns rise time)
- measurement short-time intervals (with <100 ps accuracy)
- synchronization and communication between nodes
- management of signals and application of signal processing

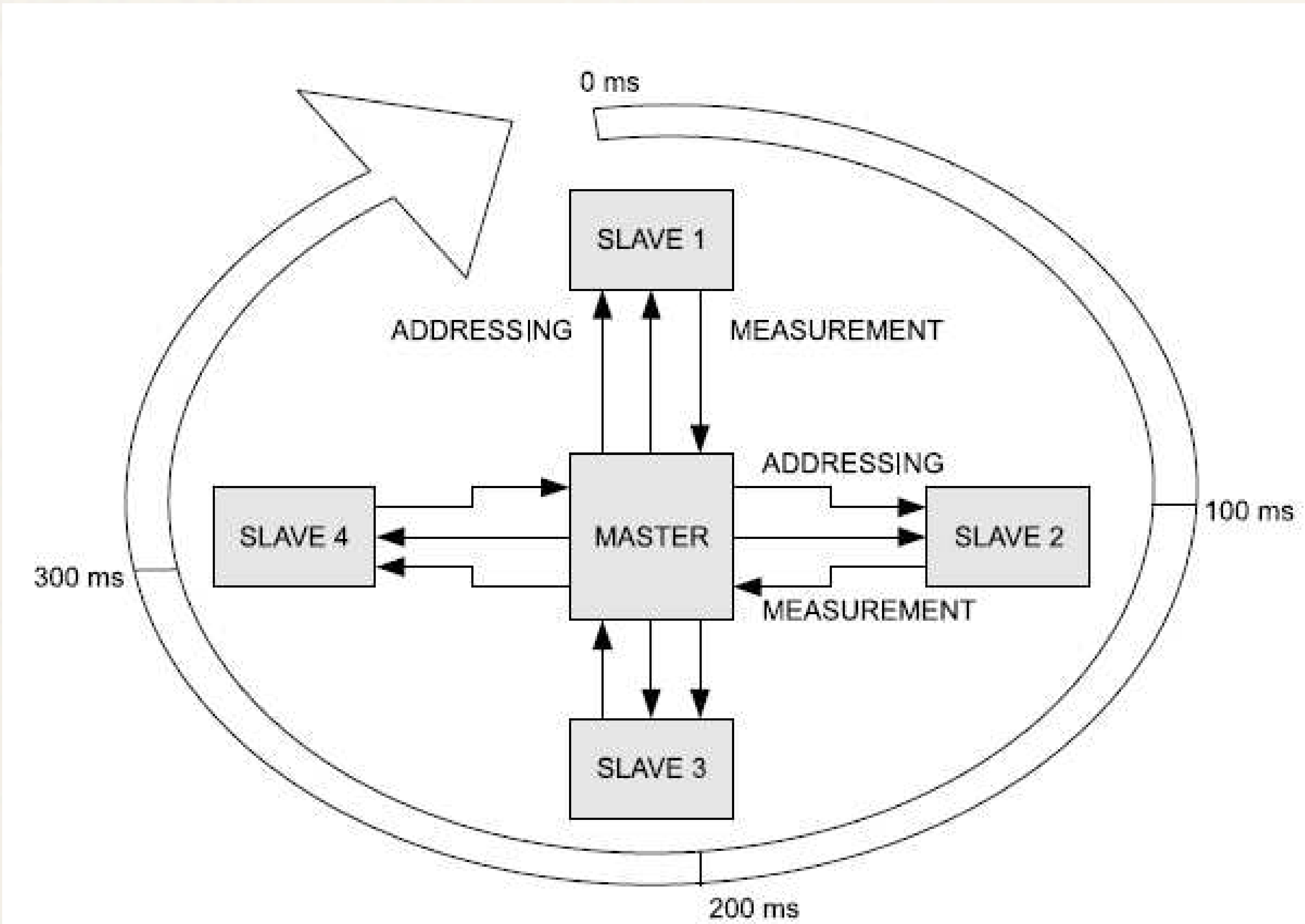
System overview





- System Architecture
- Master/slave units

System operations



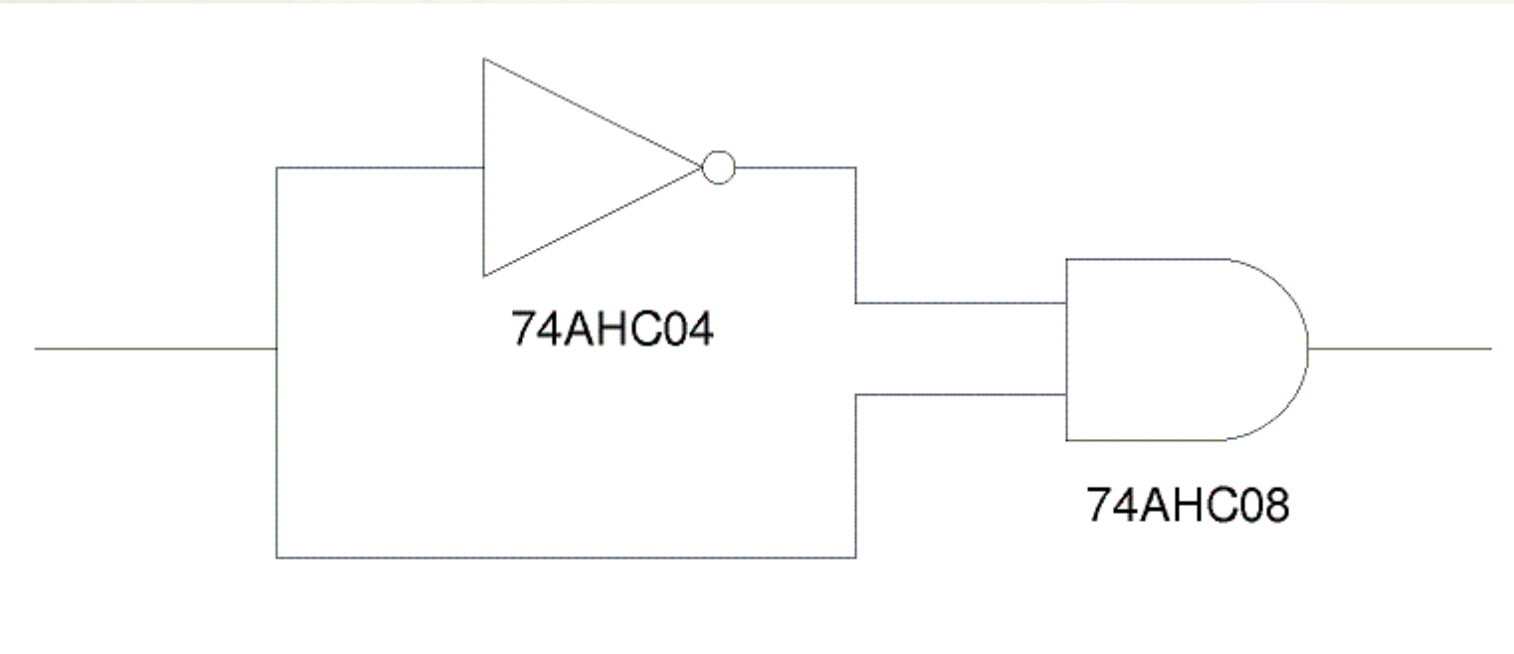
Round robin selection of slave device as transponders

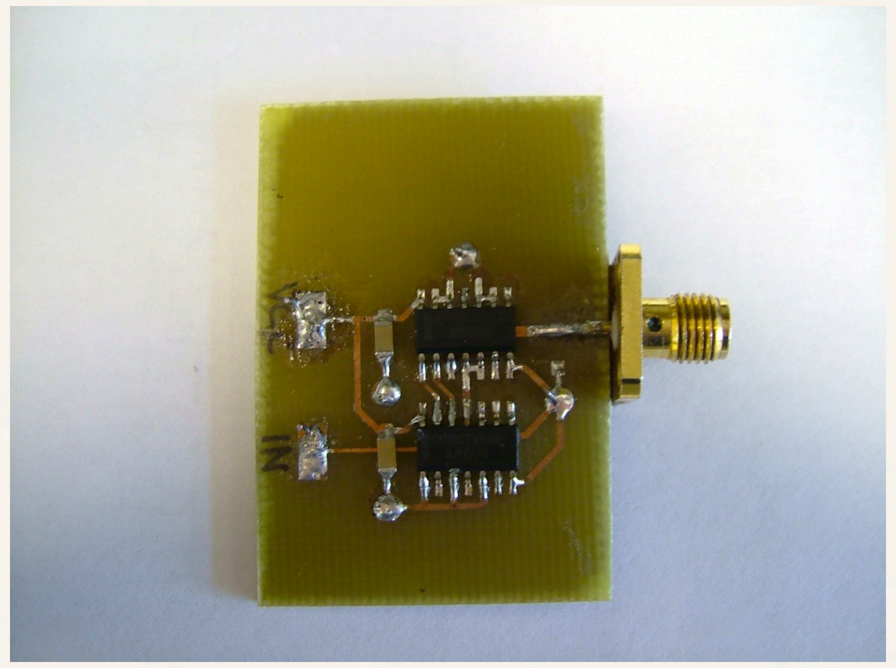
- One of the realized master unit prototypes

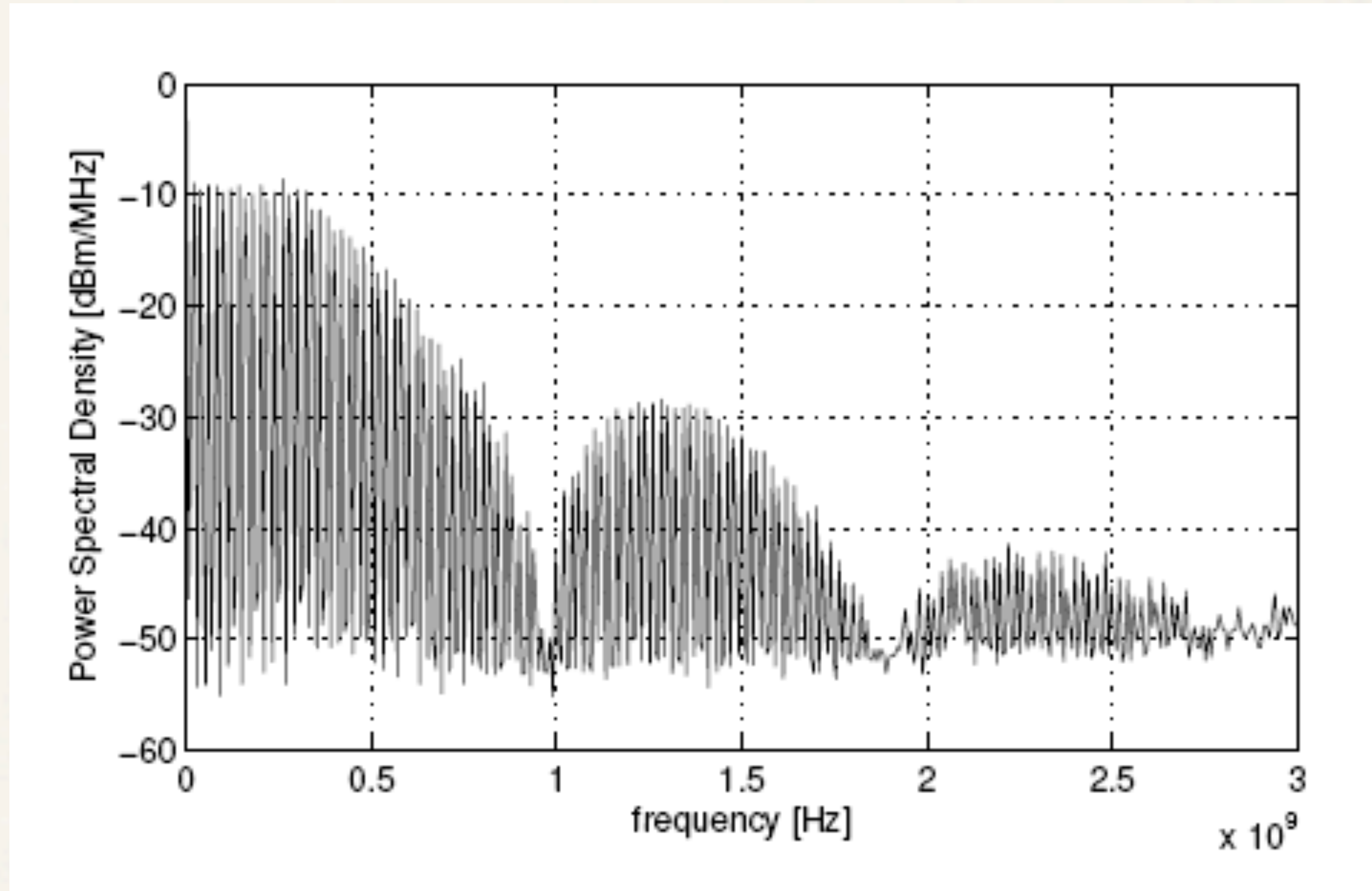
How we did it

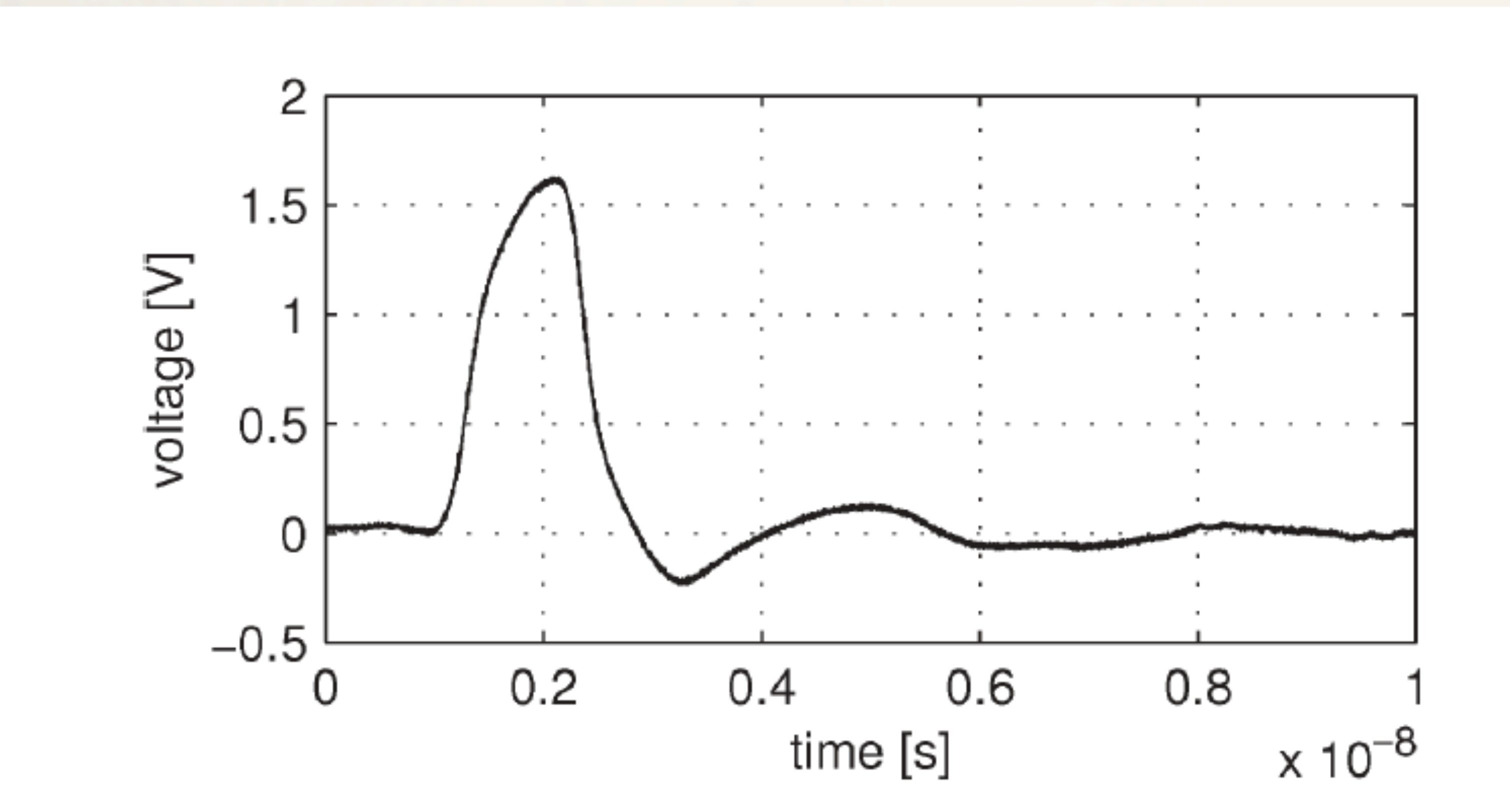
- Ultra wide-bandwidth pulses (UWB): relative bandwidth > 20% or absolute bandwidth > 500 MHz. Preferred because of:
- fine time resolution, < 1ns rise time
- robustness to *multipath*
- low power generation
- lab synthesis of UWB pulses: critical path in digital ports to generate short-delays and artificial glitches, step-recovery diode, avalanche diode

Critical path-based generation





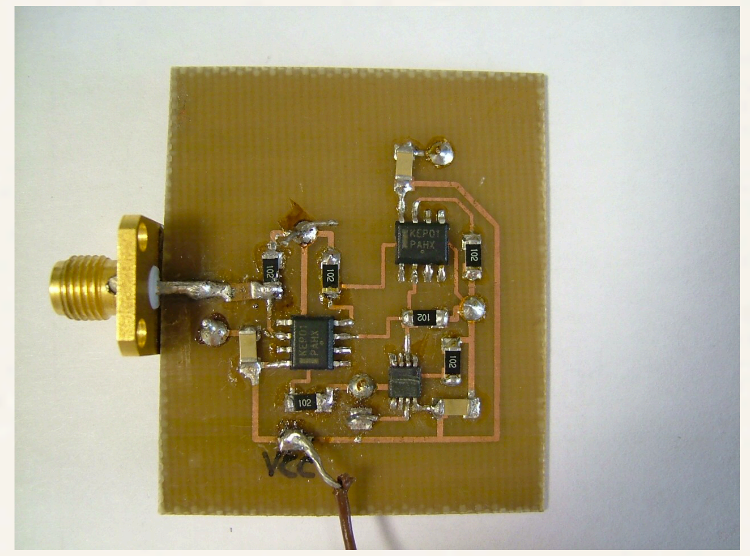


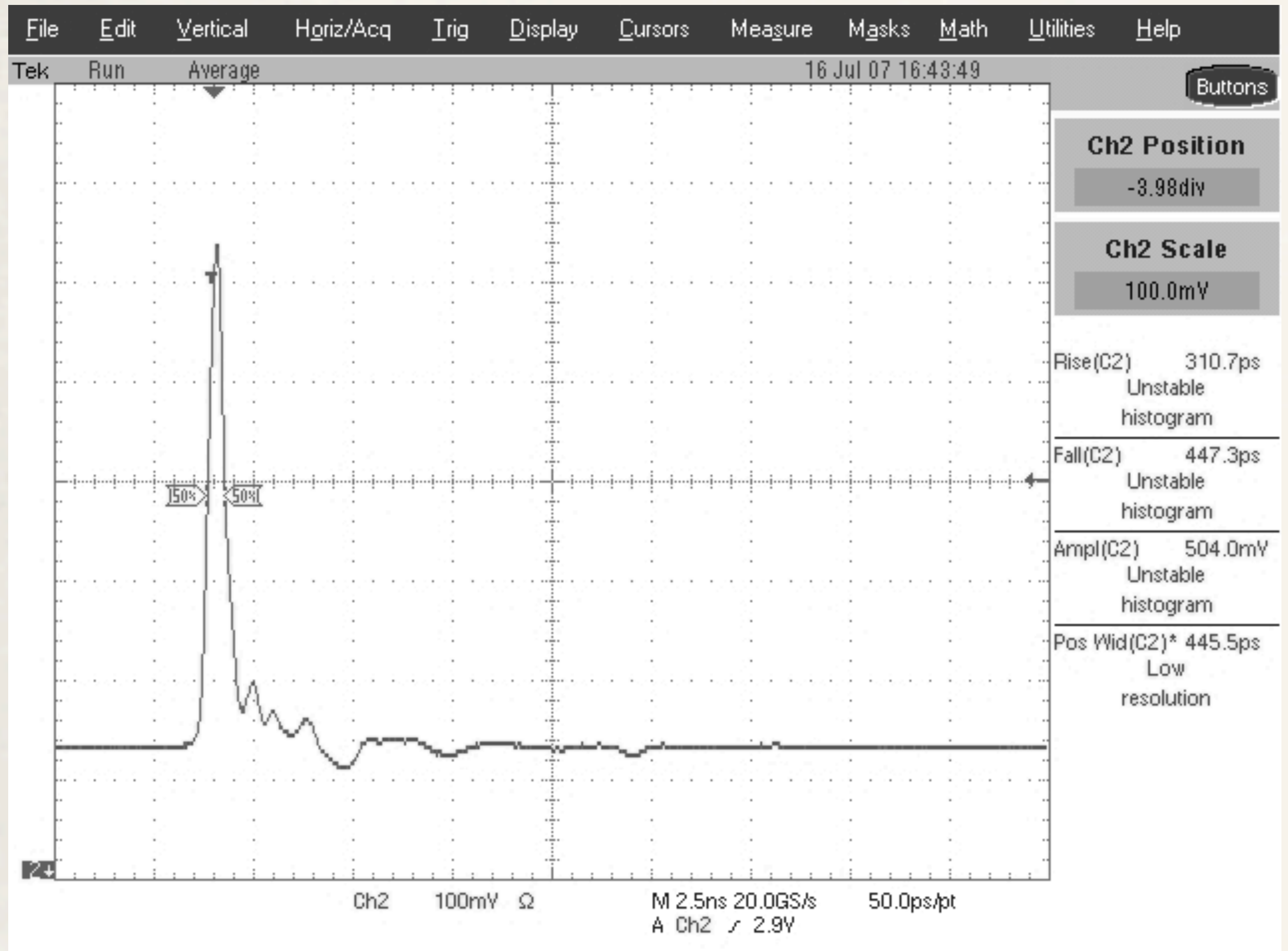


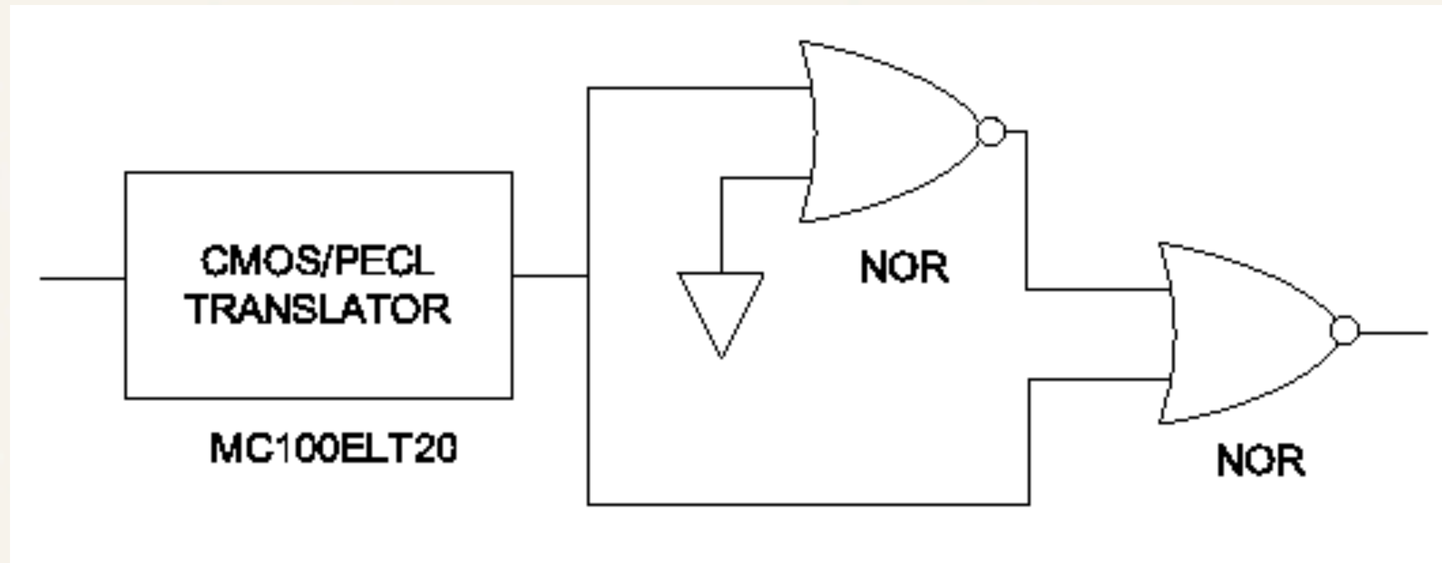
- resolution bandwidth 1MHz,
- PRF =2 MHz
- bandwidth @ -10 dB: 700 MHz

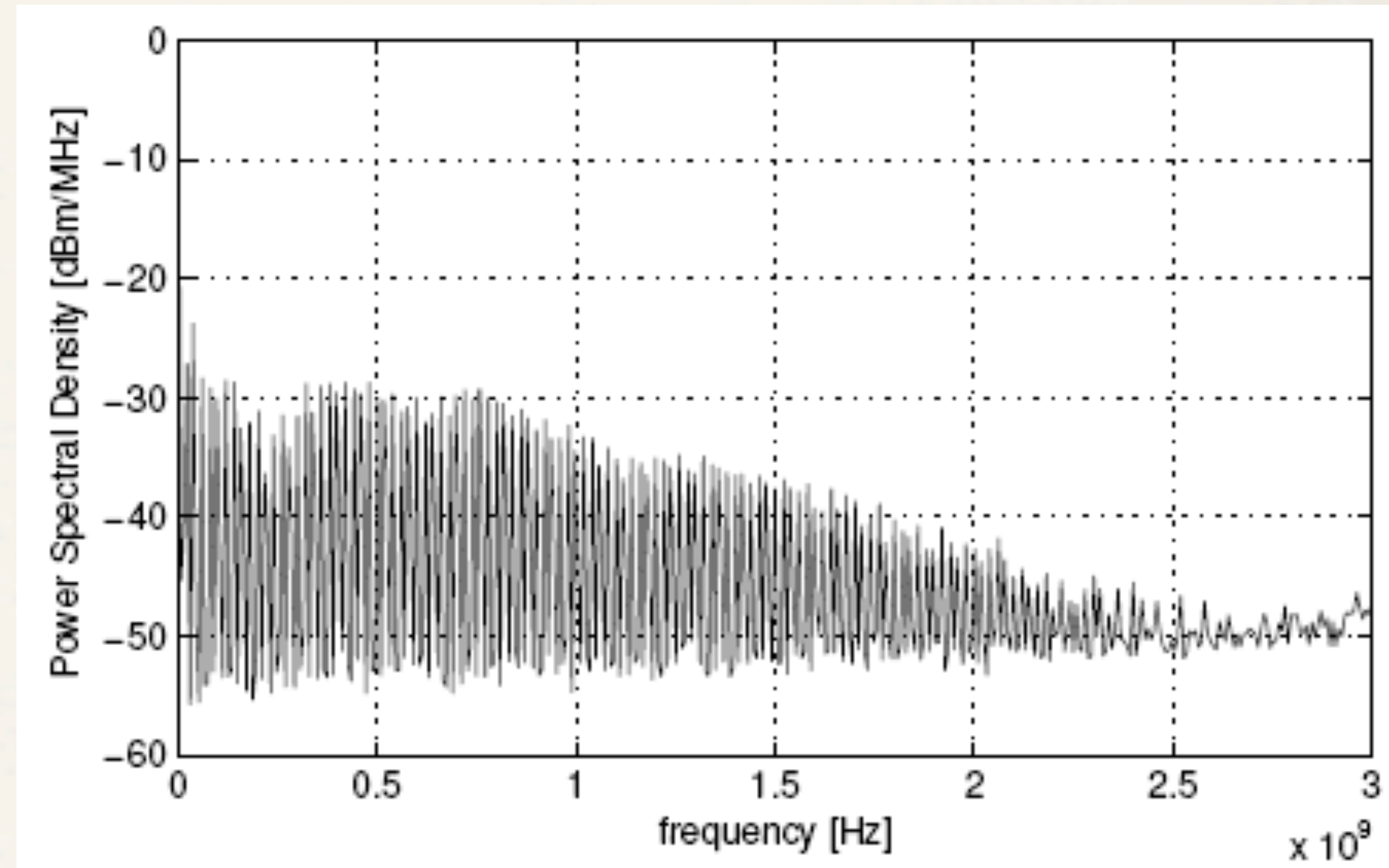
- DSO 20 GSa/s - 6 GHz, tr = 585 ps

ECL-based generator





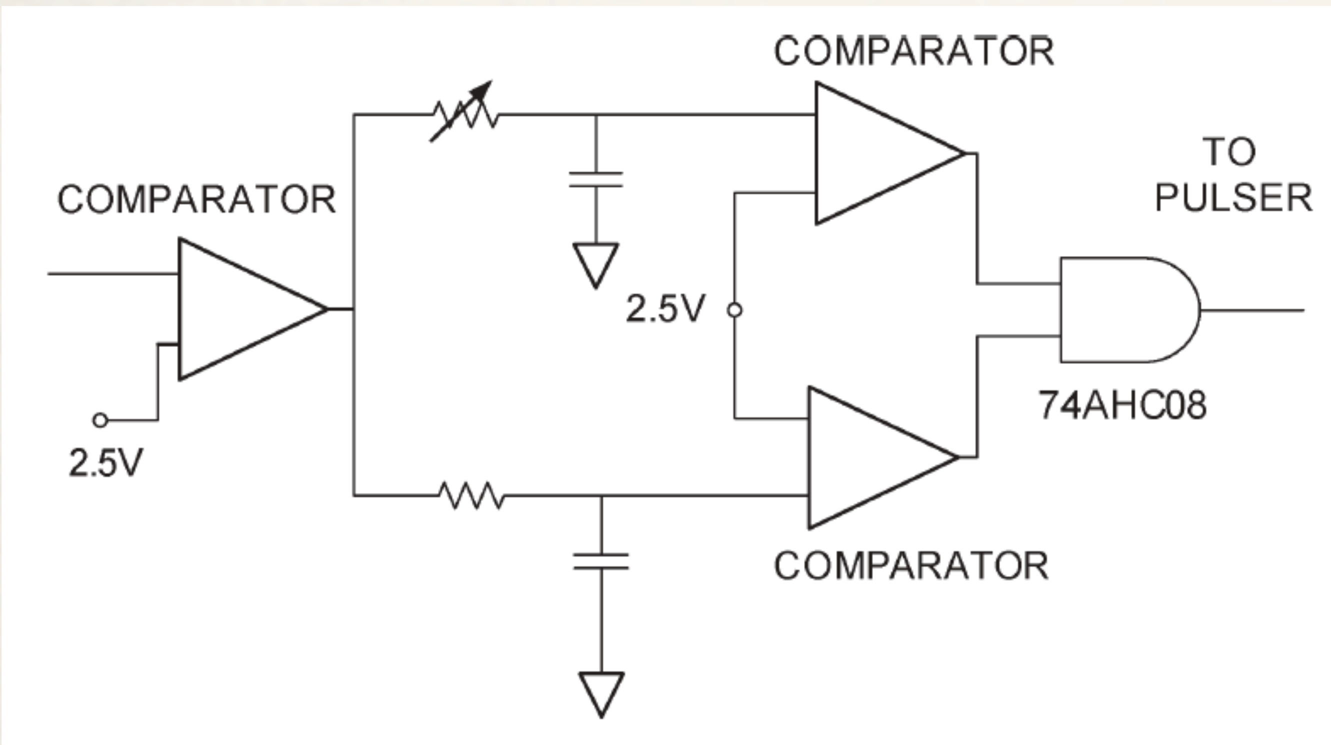


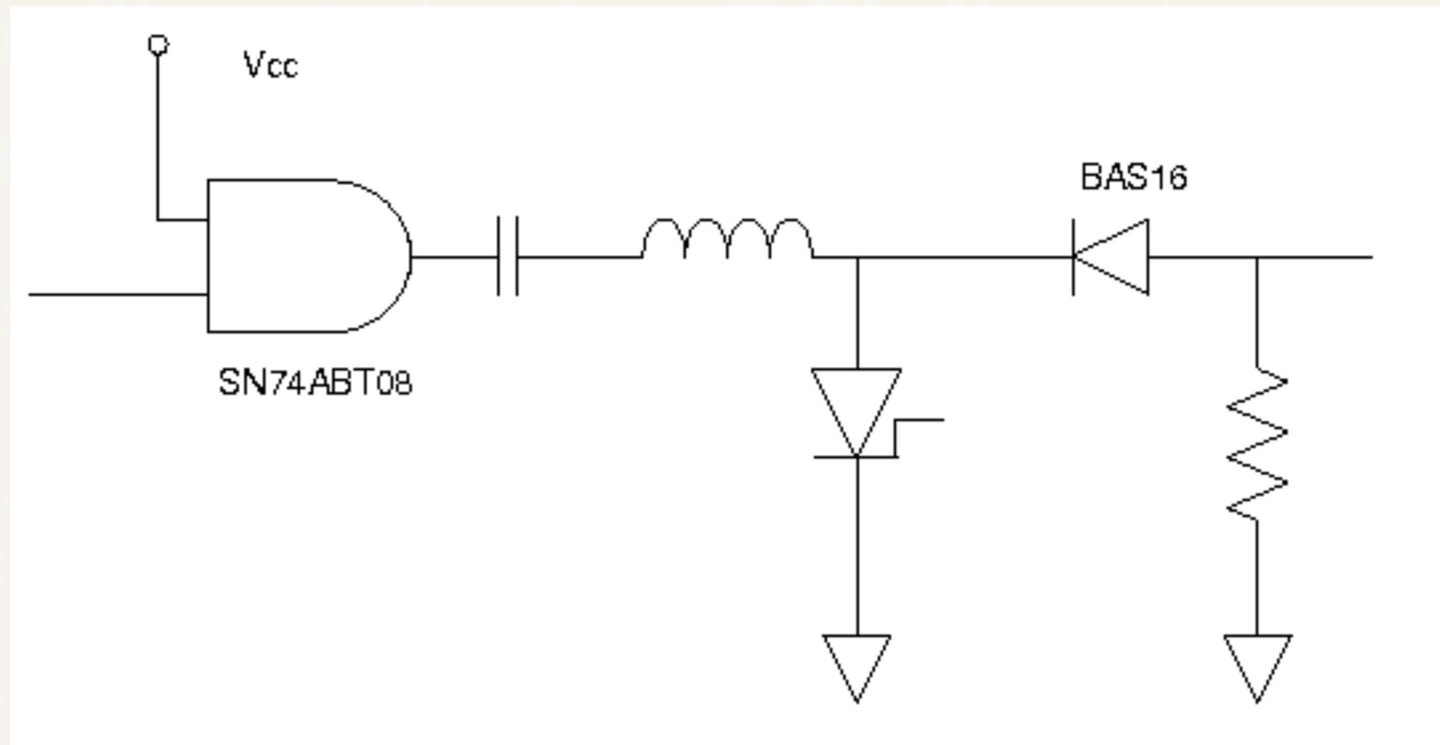


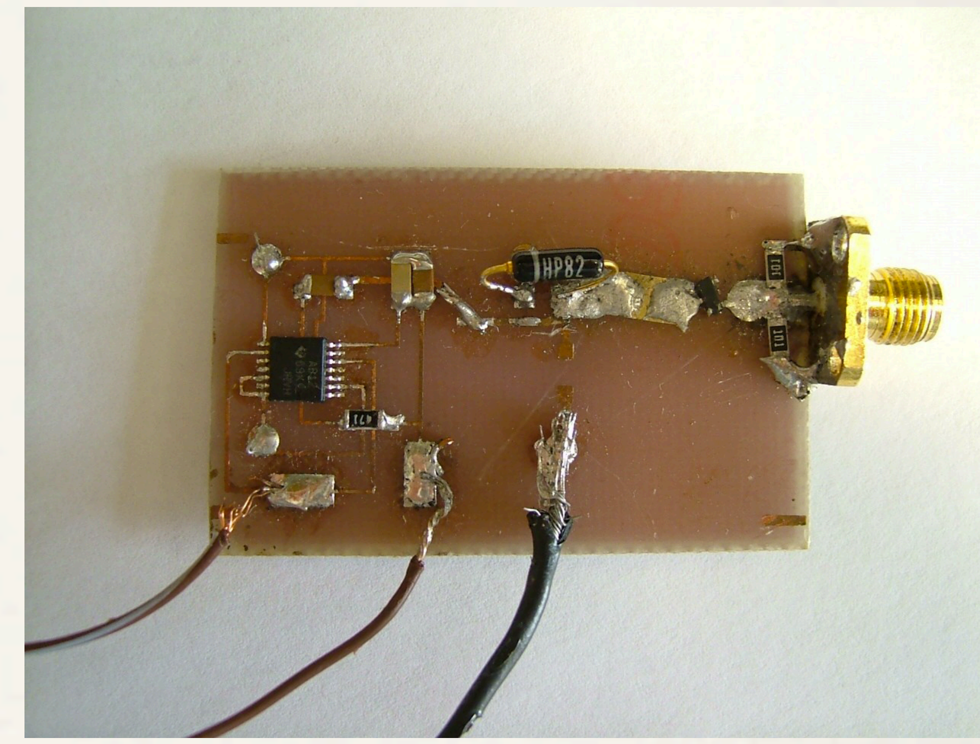
- DSO 20 GSa/s - 6 GHz, tr = 310 ps, 500 mV

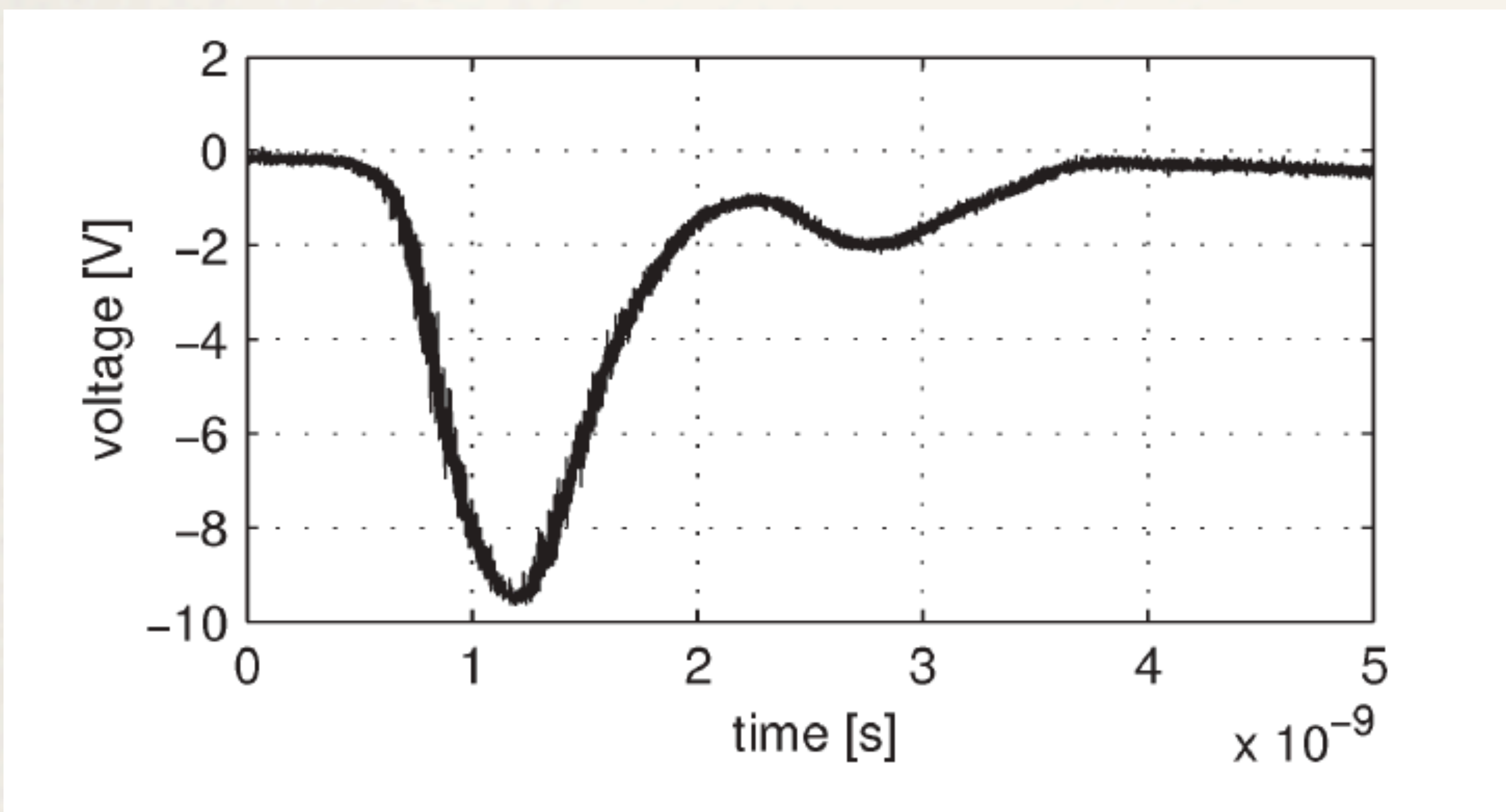
- resolution bandwidth 1MHz,
- PRF =2 MHz
- bandwidth @ -10 dB: 1300 MHz

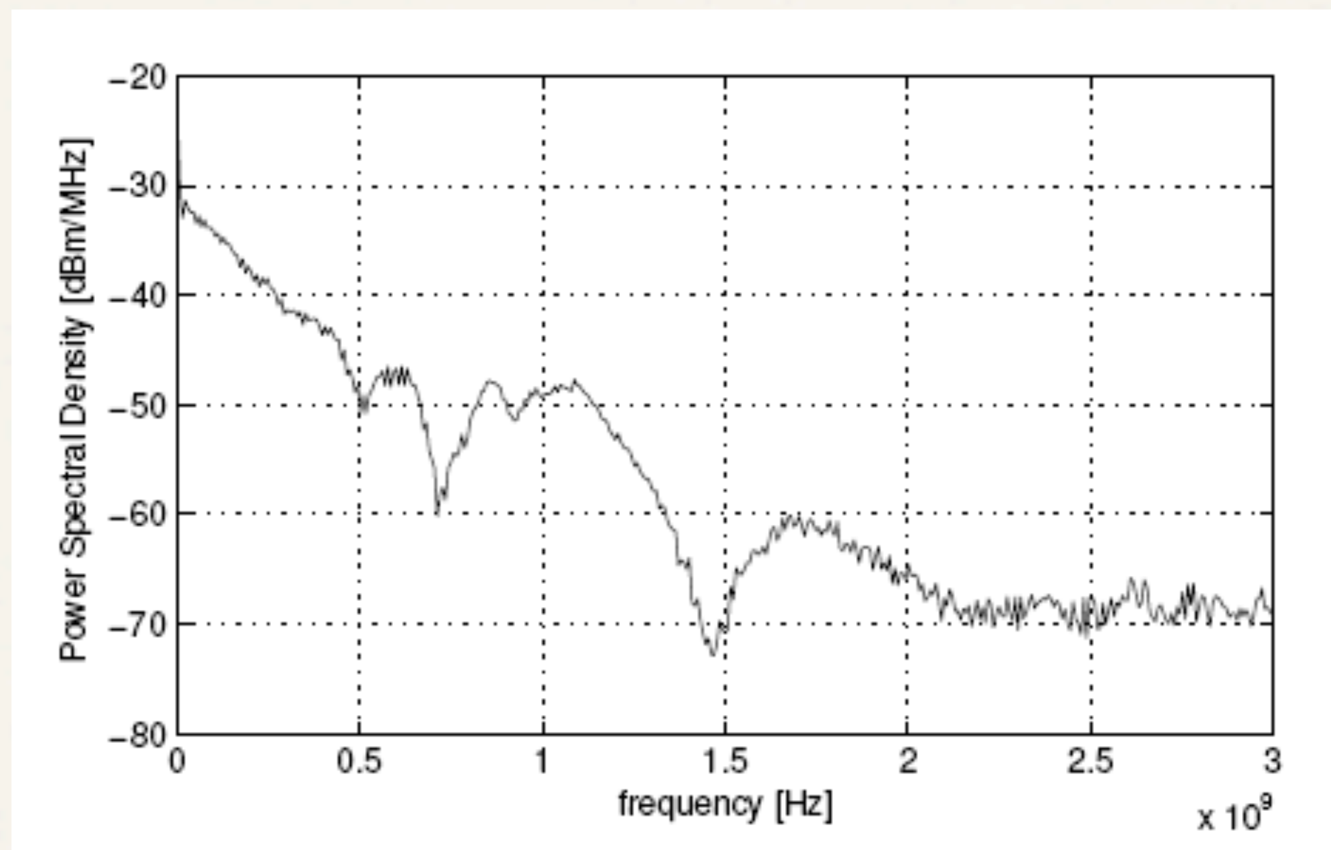
Generator based on a step-recovery diode







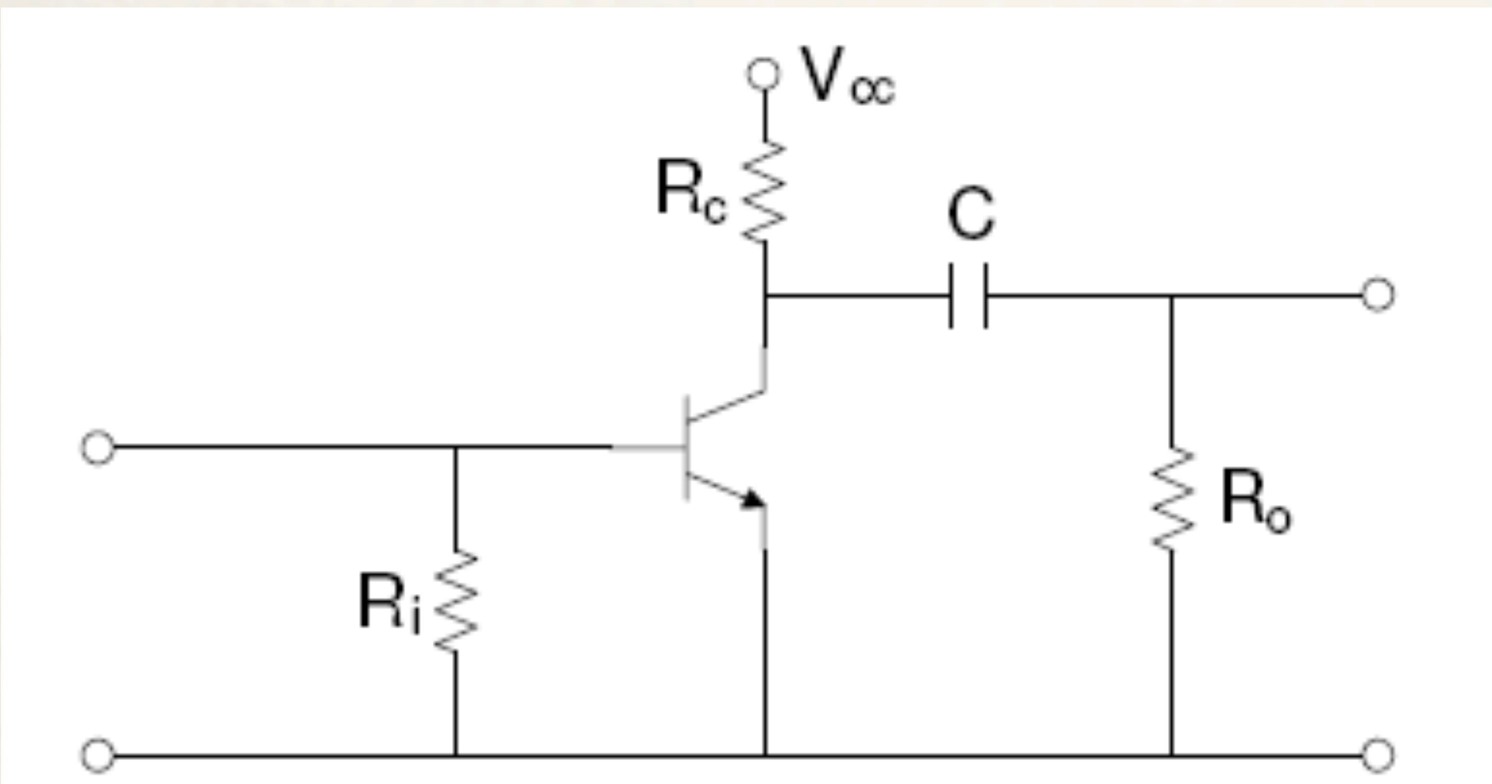


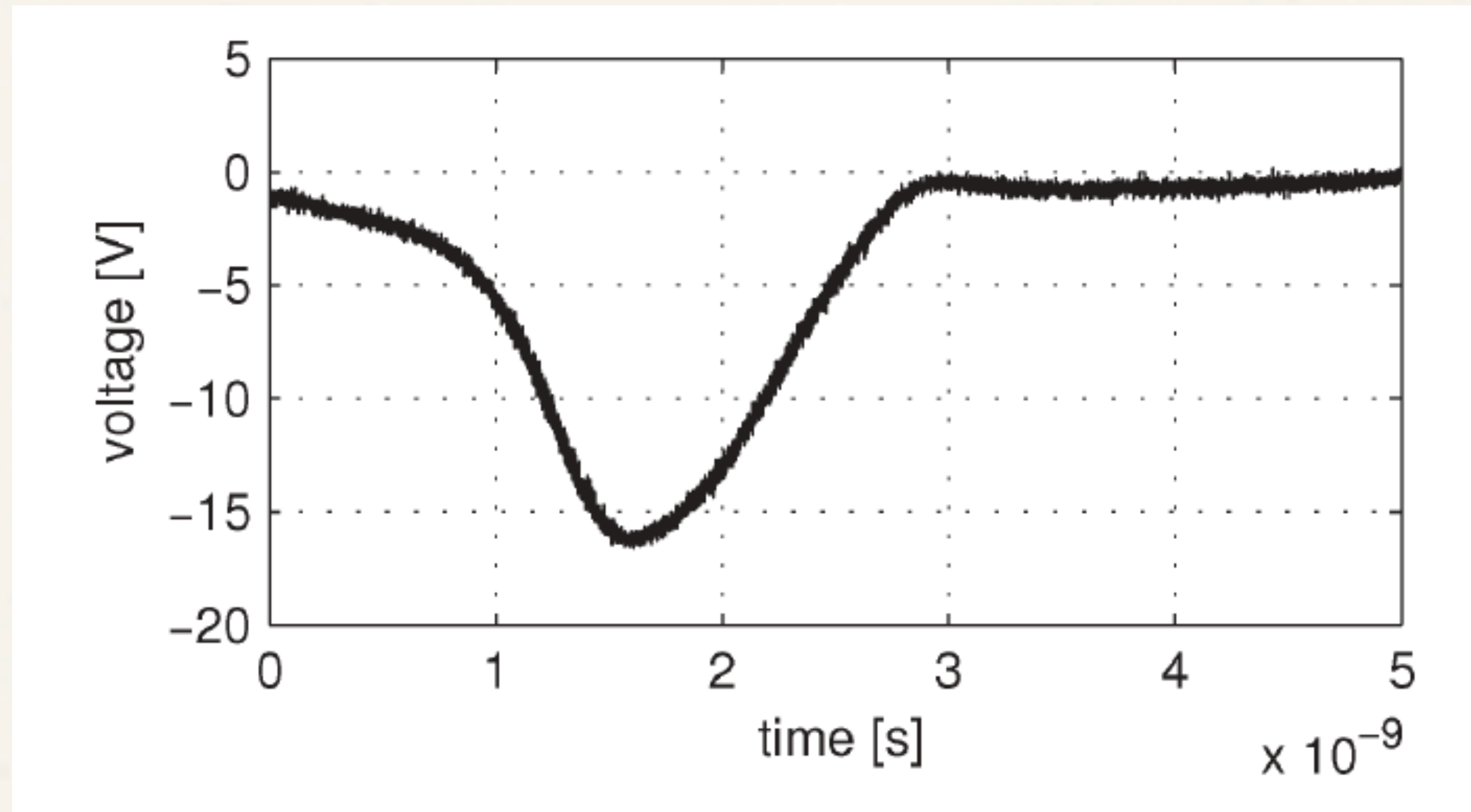


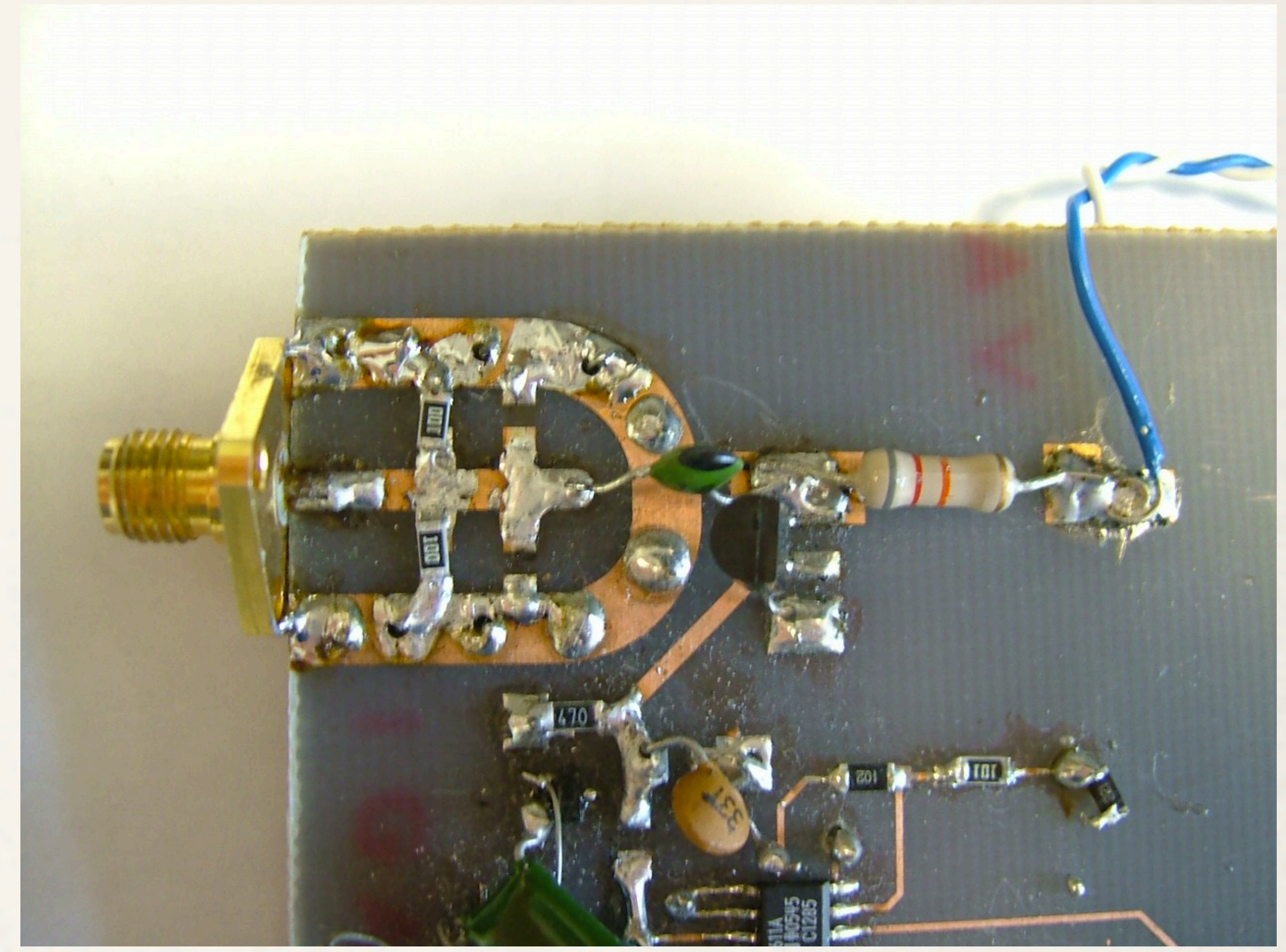
- resolution bandwidth 1MHz,
- PRF =2 MHz
- bandwidth @ -10 dB: 500 MHz

- DSO 20 GSa/s - 6 GHz, tr = 930 ps

Avalanche-based *flasher*



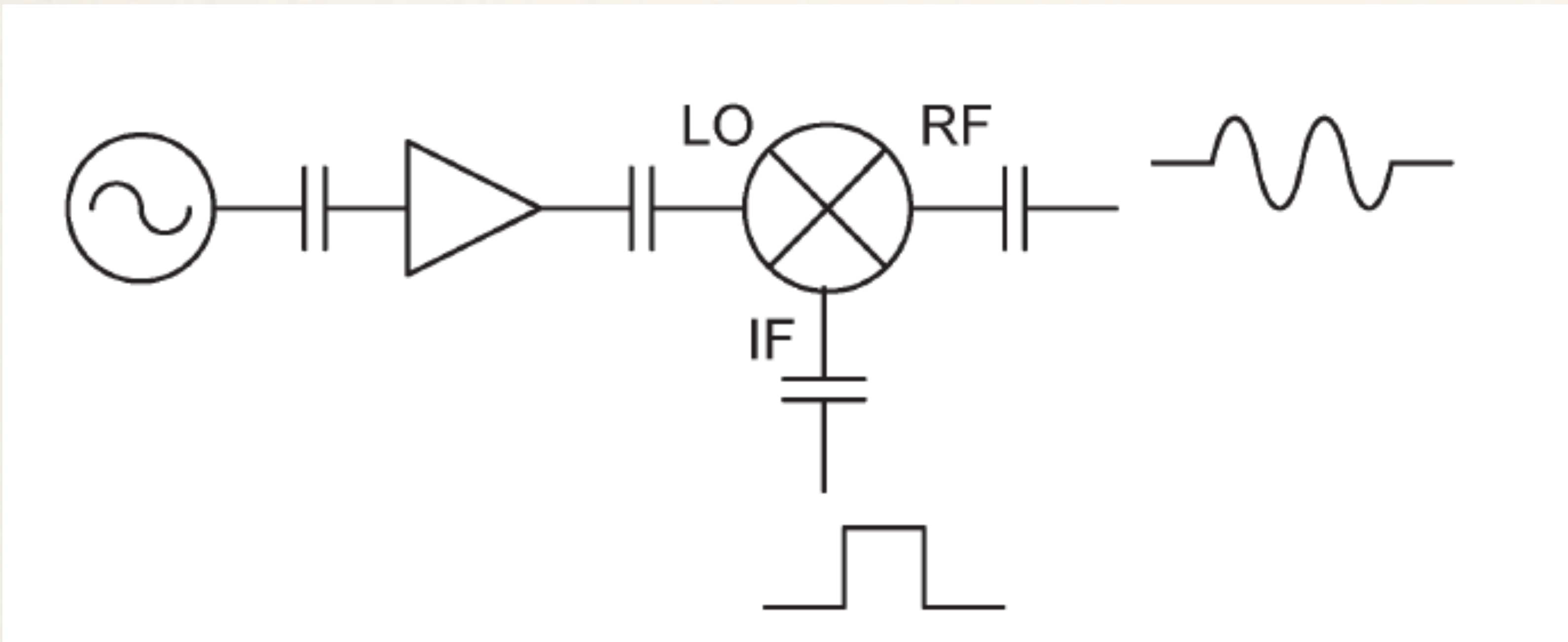


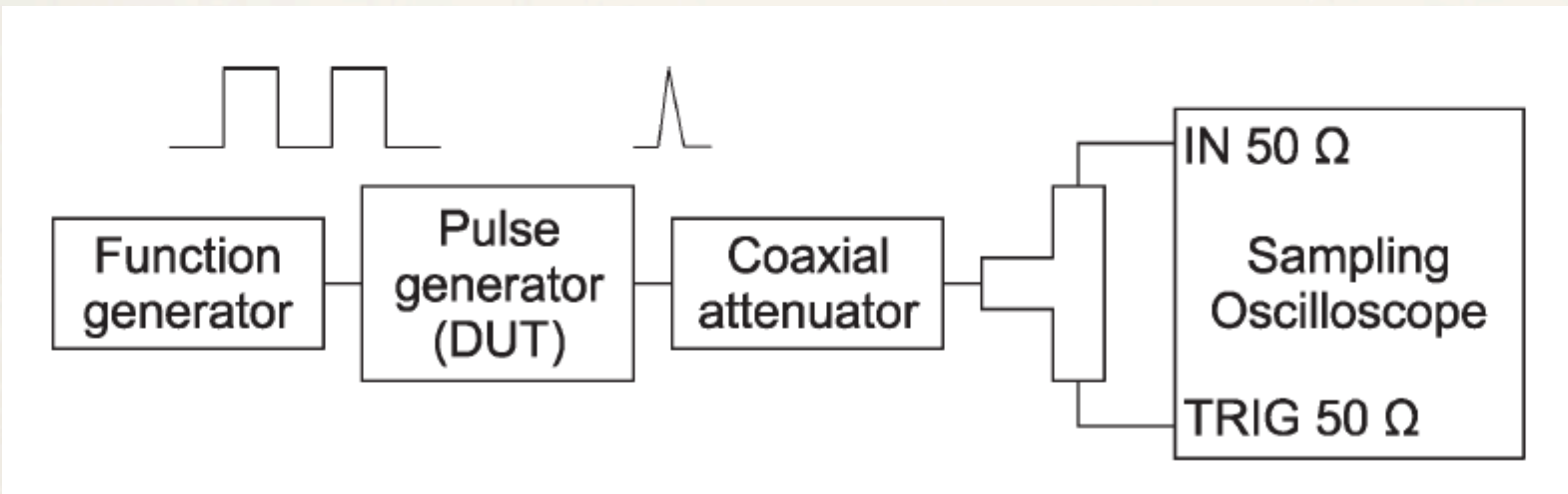


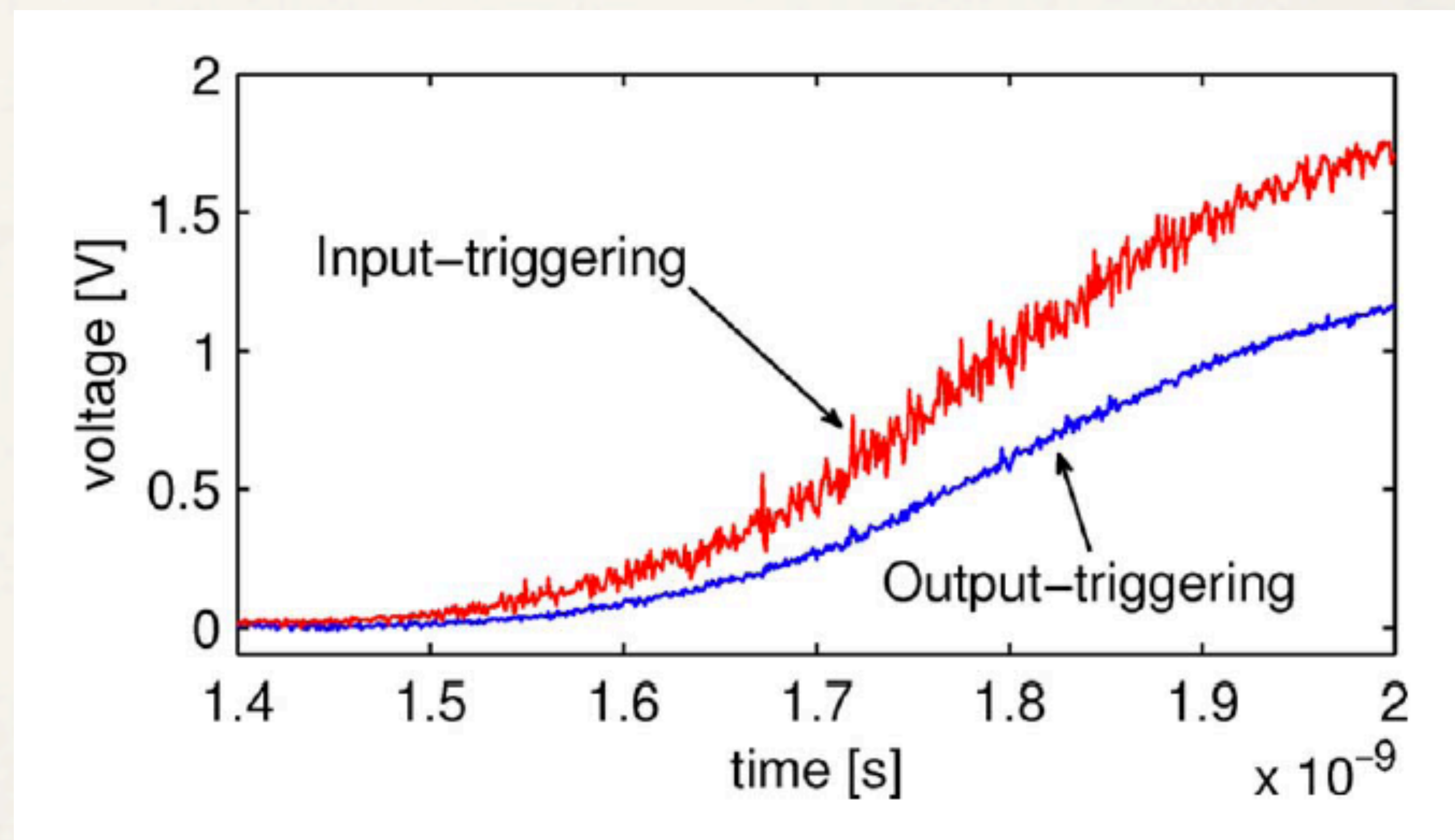
- Large amplitude pulses
- high voltage needed to put BJT in avalanche mode

Modulated pulses

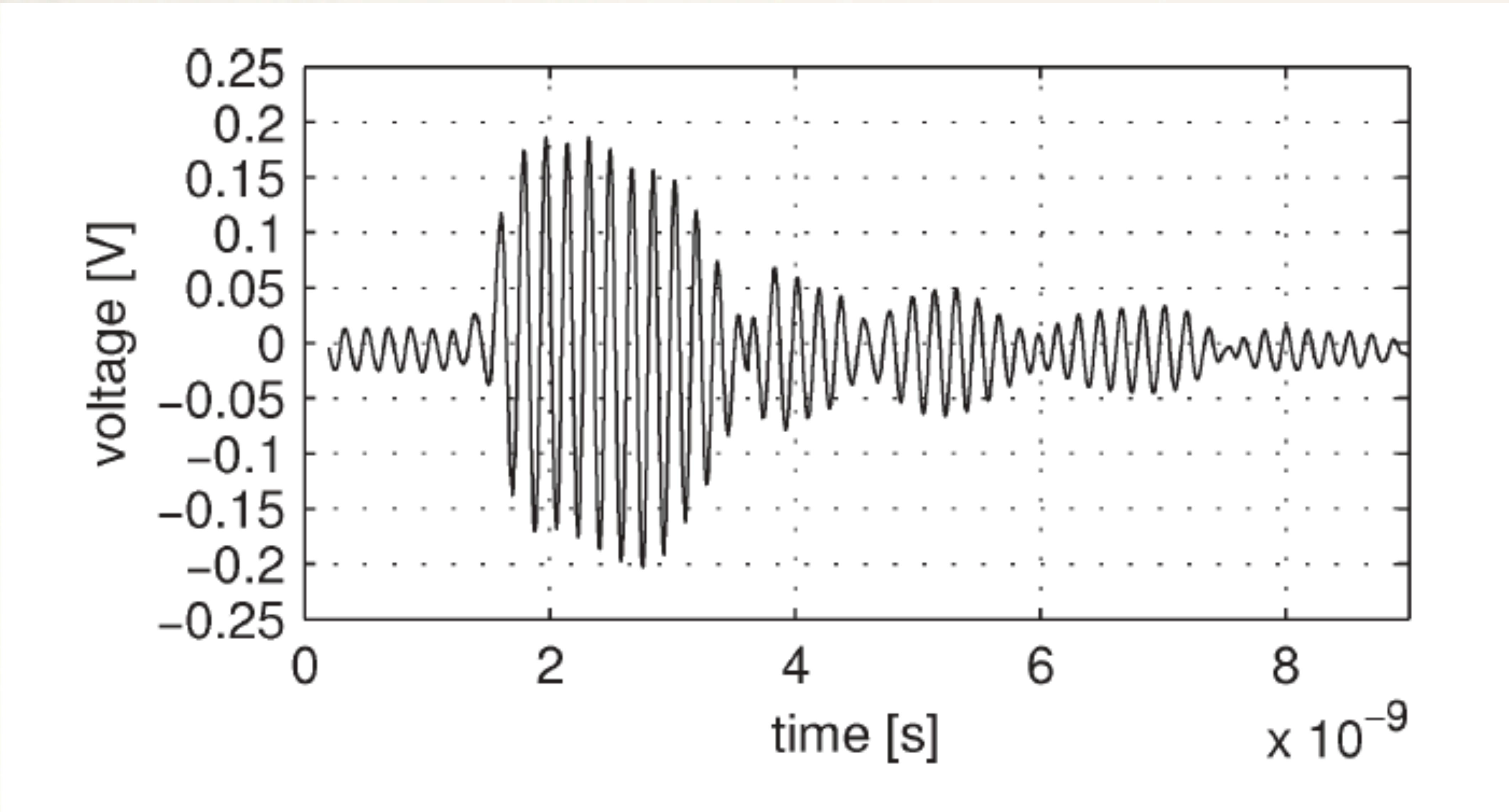
- To reduce antenna size and better comply with masks regarding frequency emissions, we modulated pulses using 5.6 GHz carrier and a mixer
- Sampling oscilloscope: 20 GHz bandwidth, 10 MSa/s, external triggering

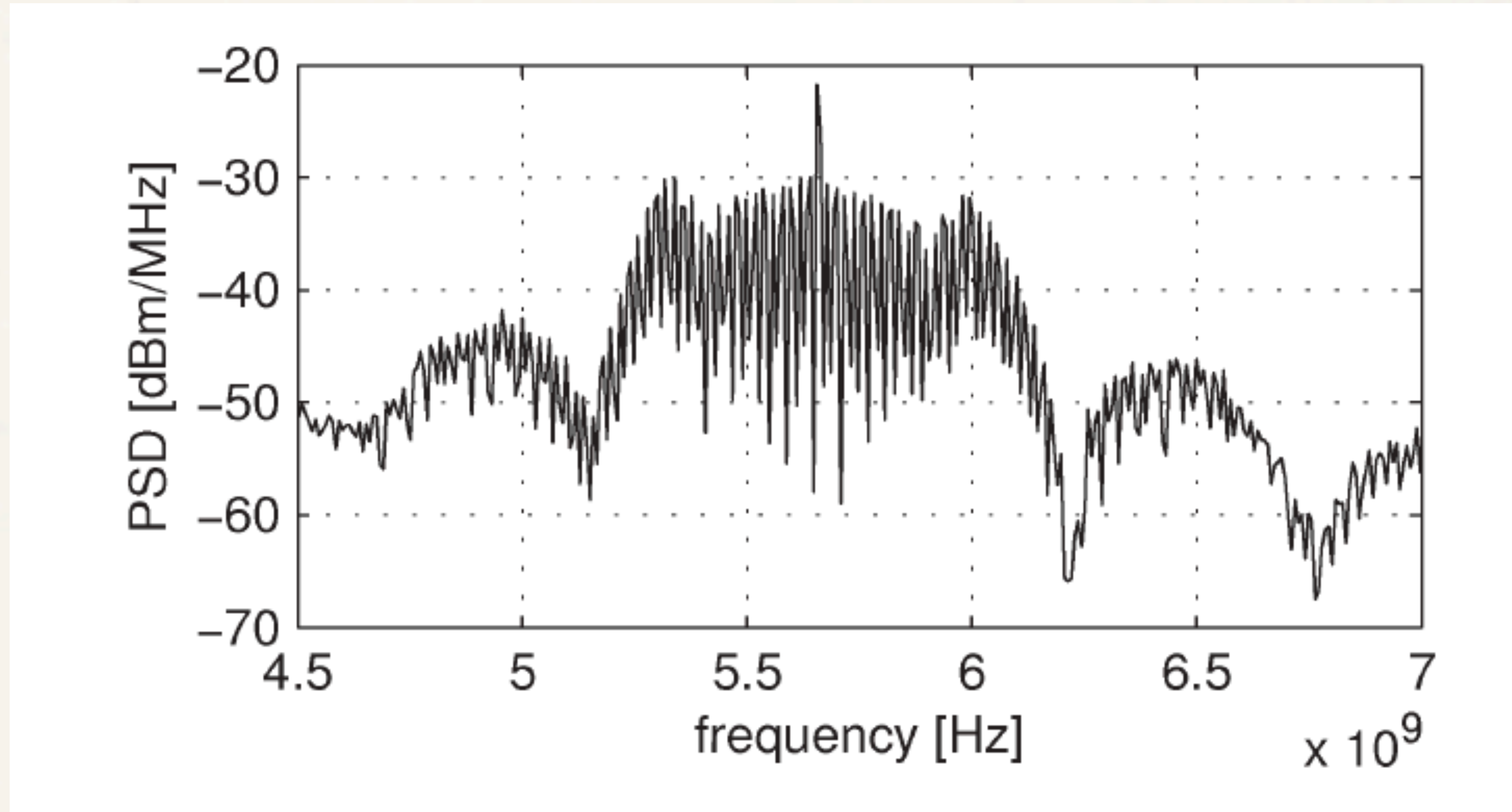




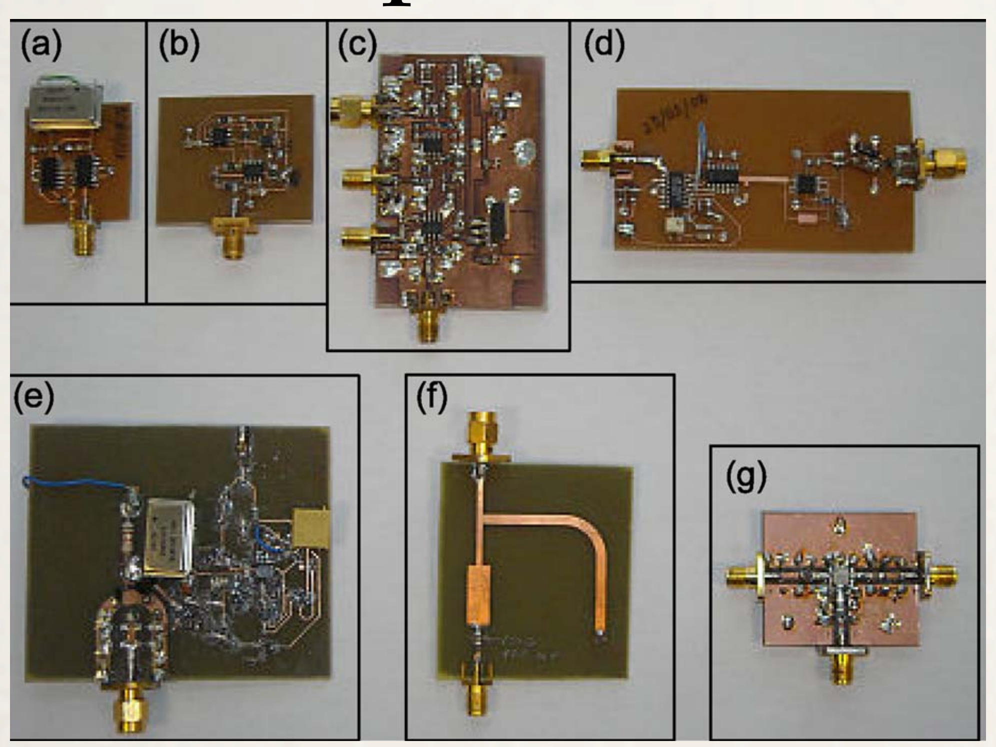


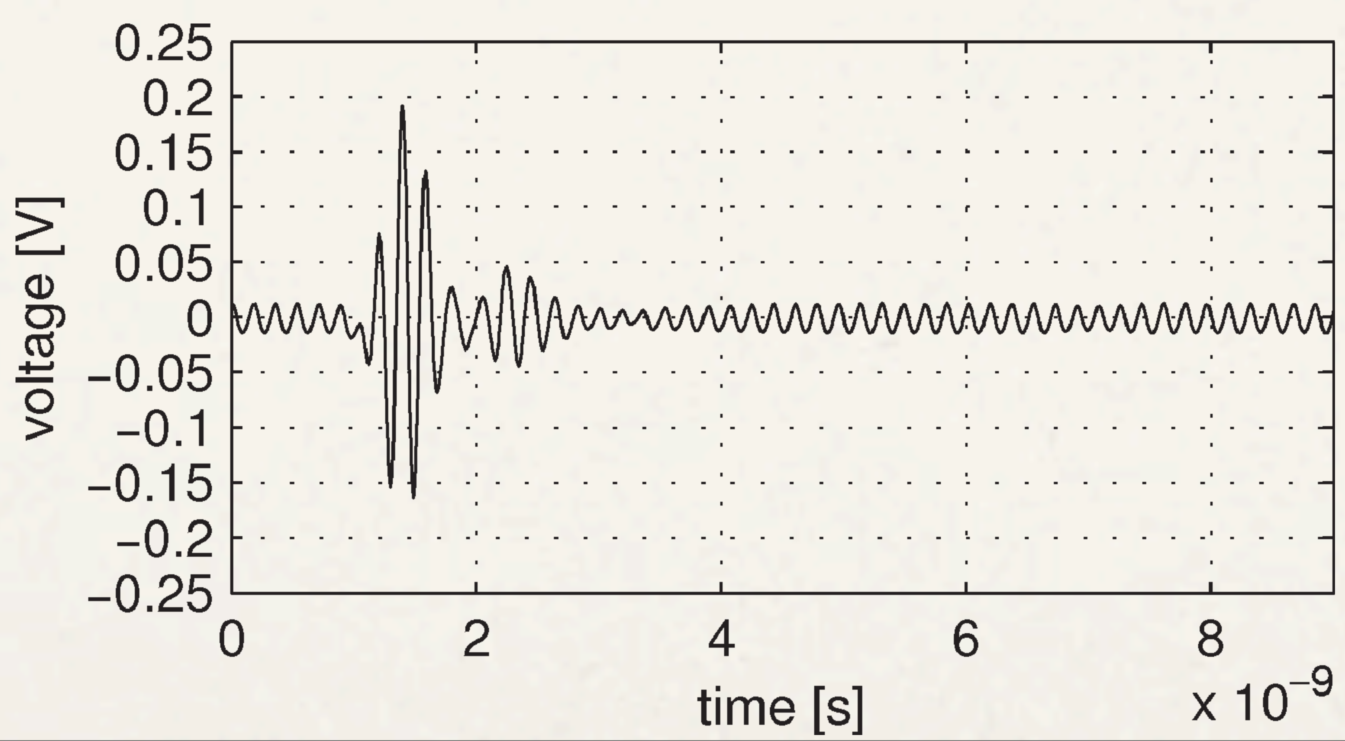
Modulated pulses: measurements





- AHC pulser, 20 MHz PRF, bandwidth about equal to 1 GHz





310 IEEE TRANSACTIONS ON INSTRUMENTATION AND MEASUREMENT, VOL. 60, NO. 1, JANUARY 2011

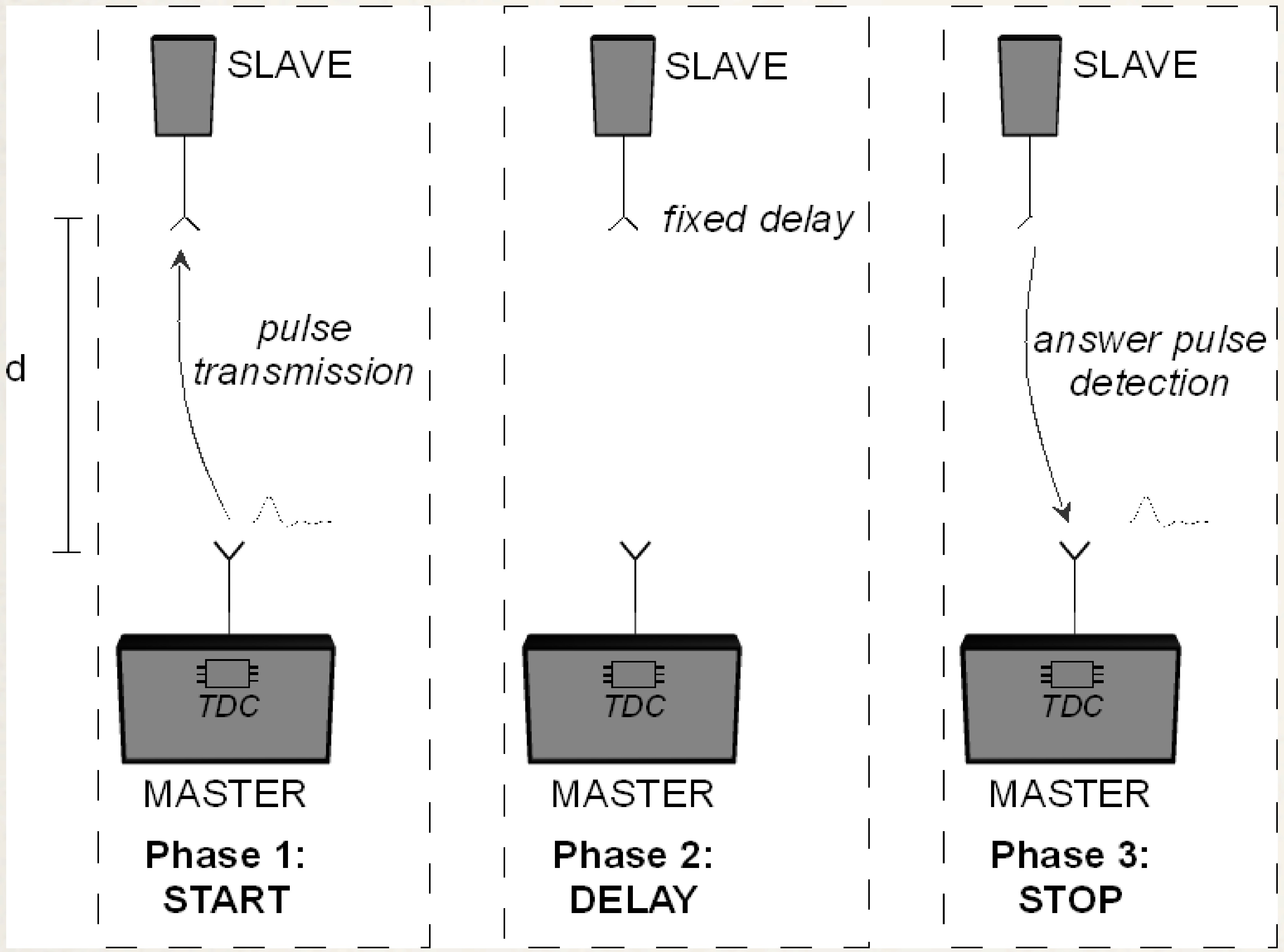
Experimental Comparison of Low-Cost Sub-Nanosecond Pulse Generators

Alessio De Angelis, *Member, IEEE*, Marco Dionigi, Riccardo Giglietti, and Paolo Carbone, *Senior Member, IEEE*

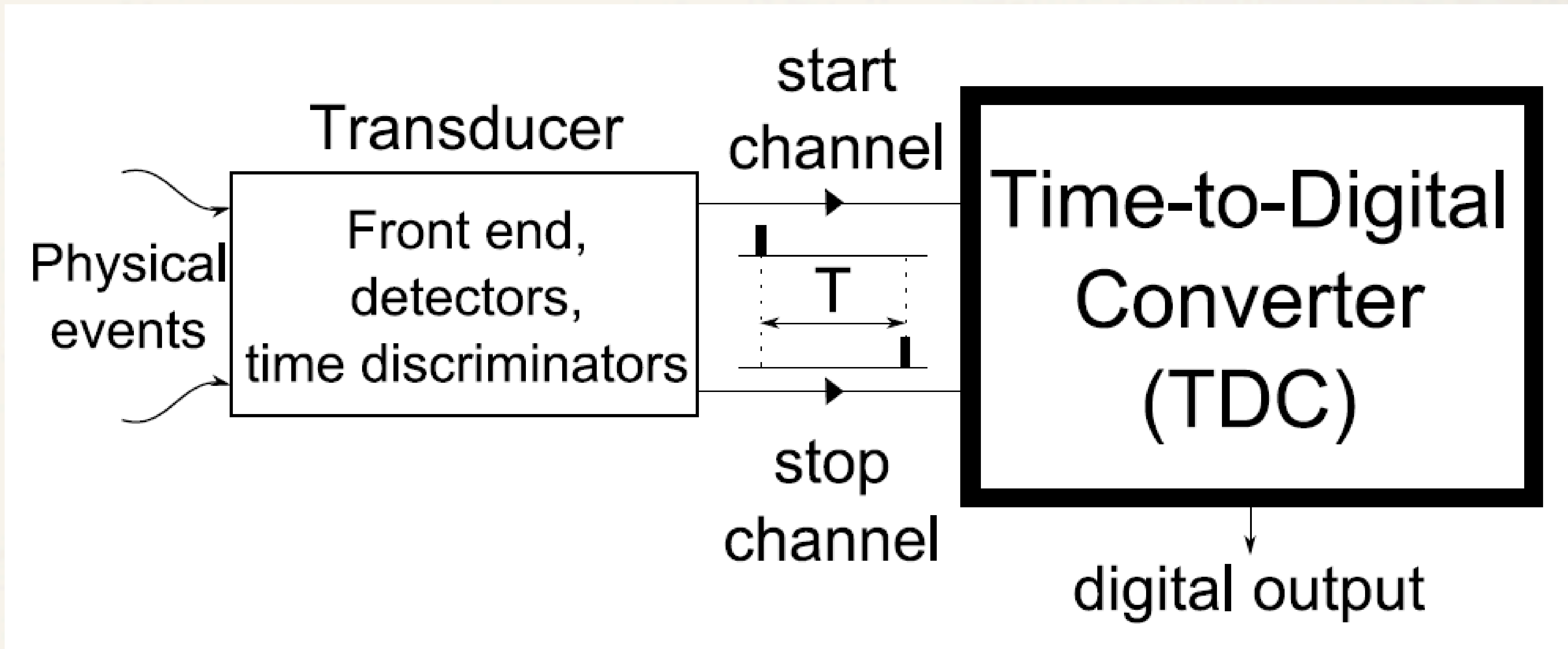
Time-to-digital conversion

From *curiosity* driven research to *problem*-led research

Very first ranging experiments without TDC, as in the wired case



then ... TDC



Short time interval measurements

Time interval measurement spreads into several fields of applications (object/person monitoring, laser/radio ranging, medical applications, high energy physics, time domain reflectometry, frequency synthesis, on-chip jitter measurements,…)

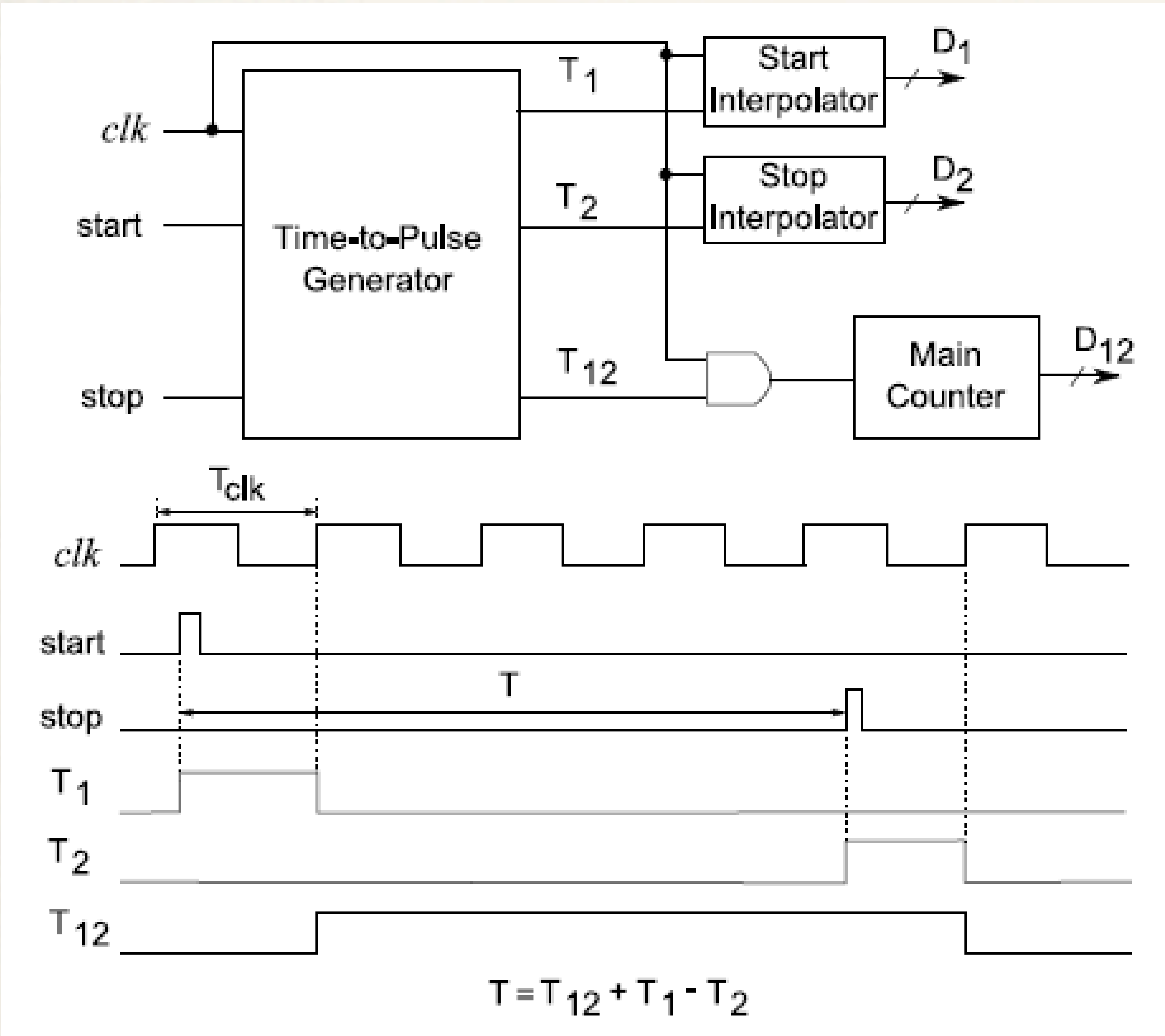
- Lack of agreed terminology;
- No standard clearly defines testing methods

⇒

- Confusion in features definitions;
- Ambiguity when comparing TDCs performances

Similar issues to ordinary data conversion: ADCs and DACs
INL, DNL, effective bits, jitter induced errors, ...

Measurement methods



- Interpolation methods
- Tapped delay lines
- Time-stretching
- all-digital techniques (using FPGAs)
- stochastic TDCs

Ongoing research on TDCs

$$\mathrm{FoM} = \frac{2^{\mathrm{ENOB}} \times m_r}{P_d \times A}$$

mr: Measurement rate

Pd: Power consumption

A: Size

Ref.	Year	Tech.	MR [ns]	LSB [ps]	m_r [kHz]	P_d [mW]	Size [mm^2]	σ [ps]	FoM	FoM_P
[40]	1994	1.2 μm	16	107	250	8.28	4.4	–	0.79	3.49
[36]	2000	0.8 μm	2500	32	156	350	11.9	30	0.90	10.72
[4]	2004	0.5 μm	80	312.5÷500	10e+3	175	2.88	97.5	4.70	13.53
[13]	2006	0.35 μm	204e+3	12.2	500	40	7.5	8.1	12117.2	90879.2
[3]	2007	0.13 μm	2	31	0.5e+6	1	0.525	–	41586.4	21832.9
[18]	2008	90 nm	0.640	1.25	10e+3	3	0.6[a]	< 1.25	821.12	492.672
[15]	2009	0.35 μm	327e+3	1.2	5e+3	33	4.45	3.2	1.00e+6	4.47e+6

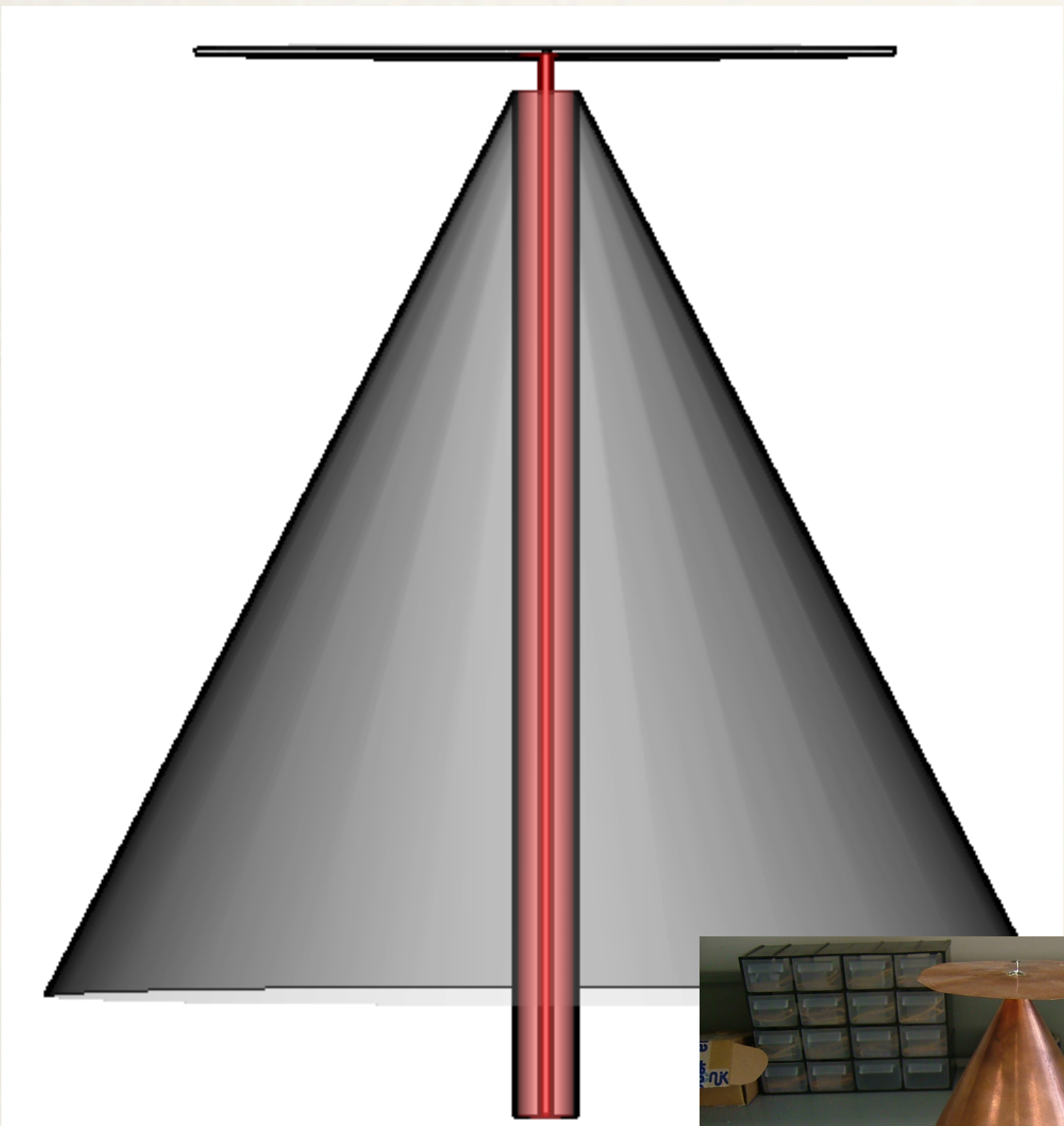
(a) Excluding pads.

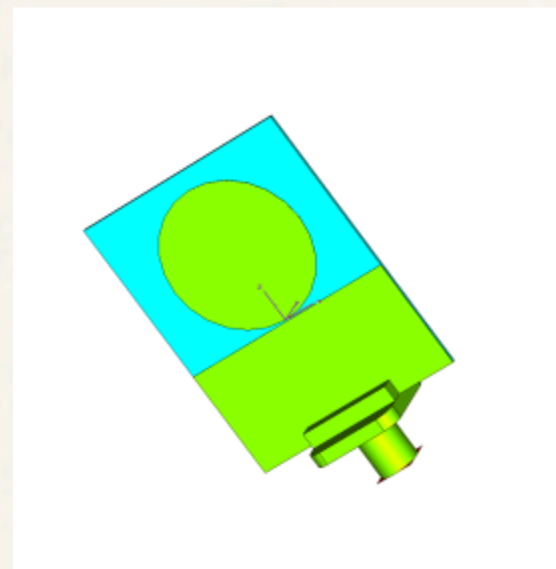
Research opportunities in the TDC area

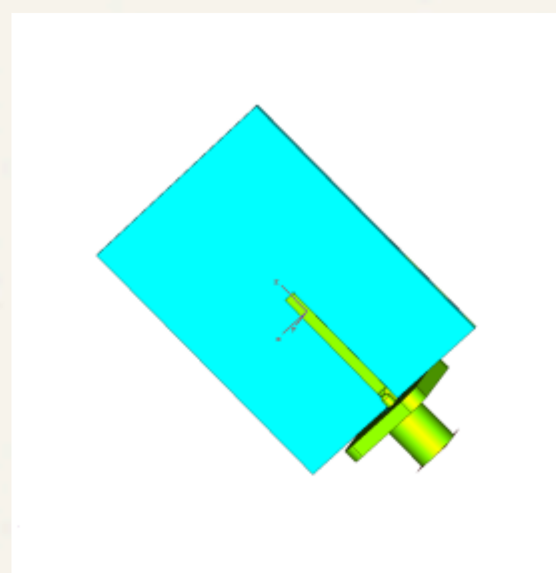
- Characterization and testing methods
- New architectures (power consumption, sensitivity to environmental factors, ...)
- Applications: radar, all time-domain based sensing/measuring systems (more in coming slides)
- Our contributions in the area of modeling, VLSI design of a new architecture using pulse stretching and incremental sigma delta

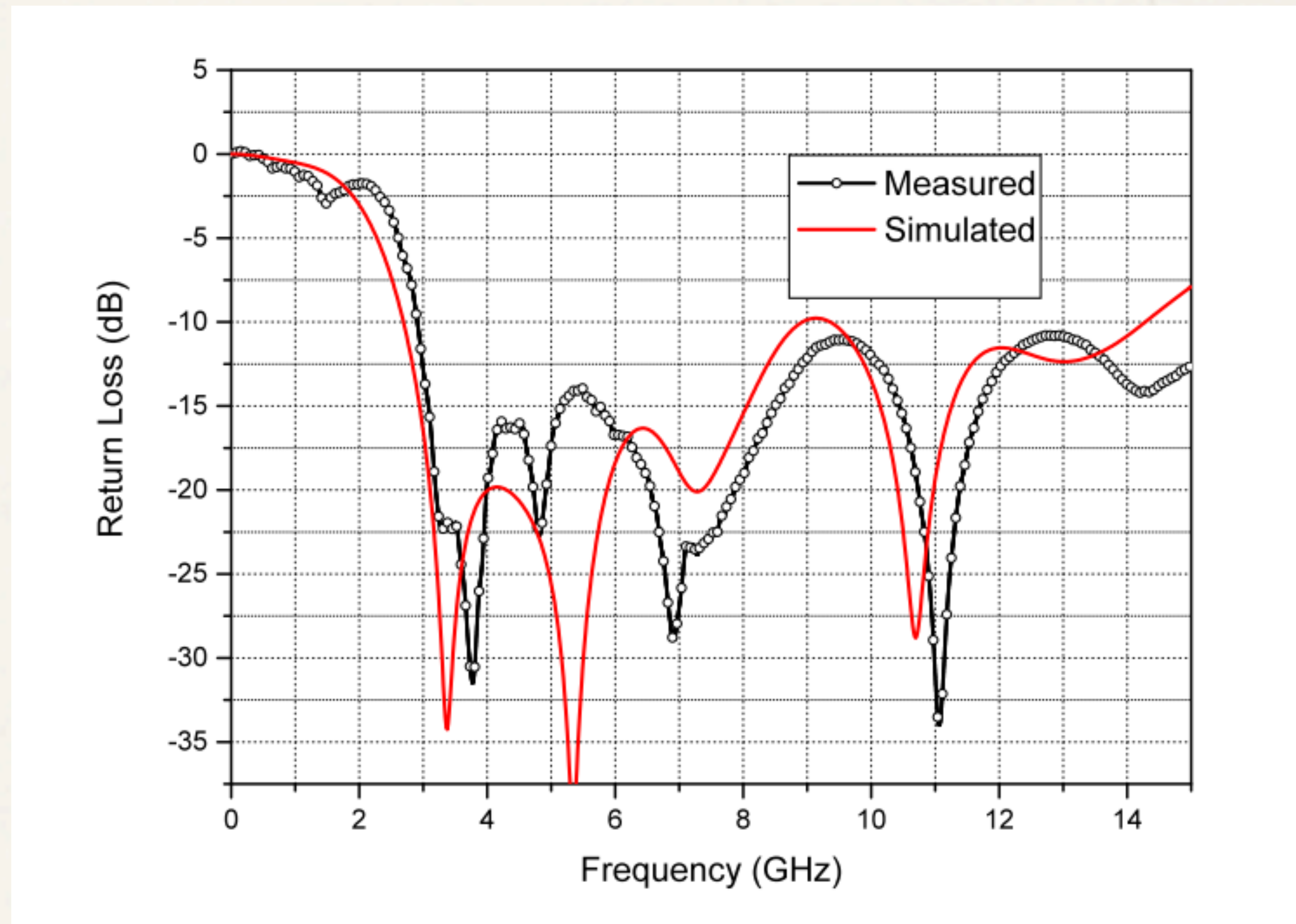
Antennas

- 2 major realization: disc-cone - 1 GHz and planar - 5-6 GHz





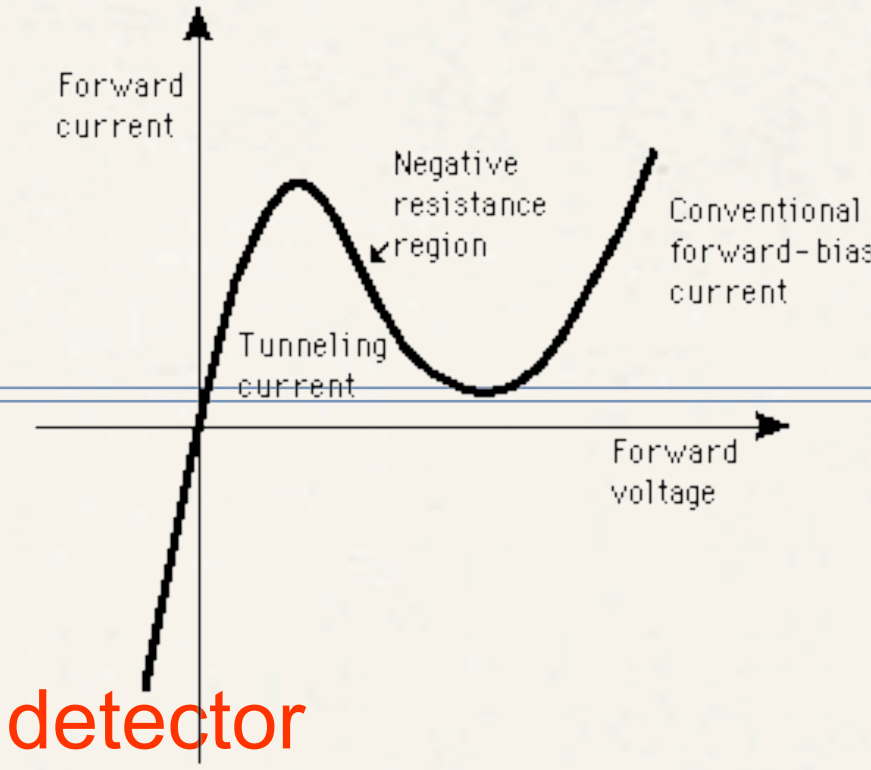


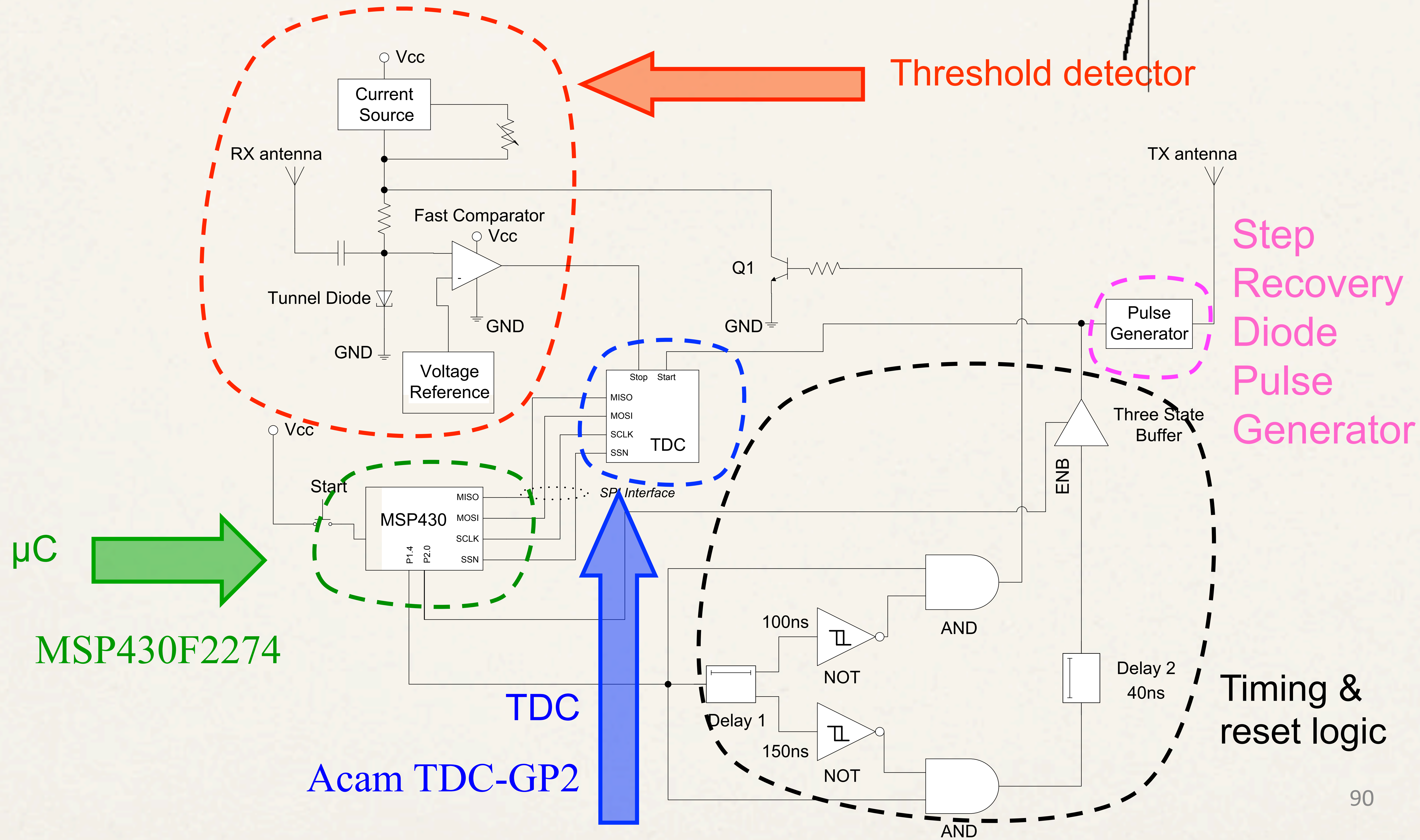


putting everything together

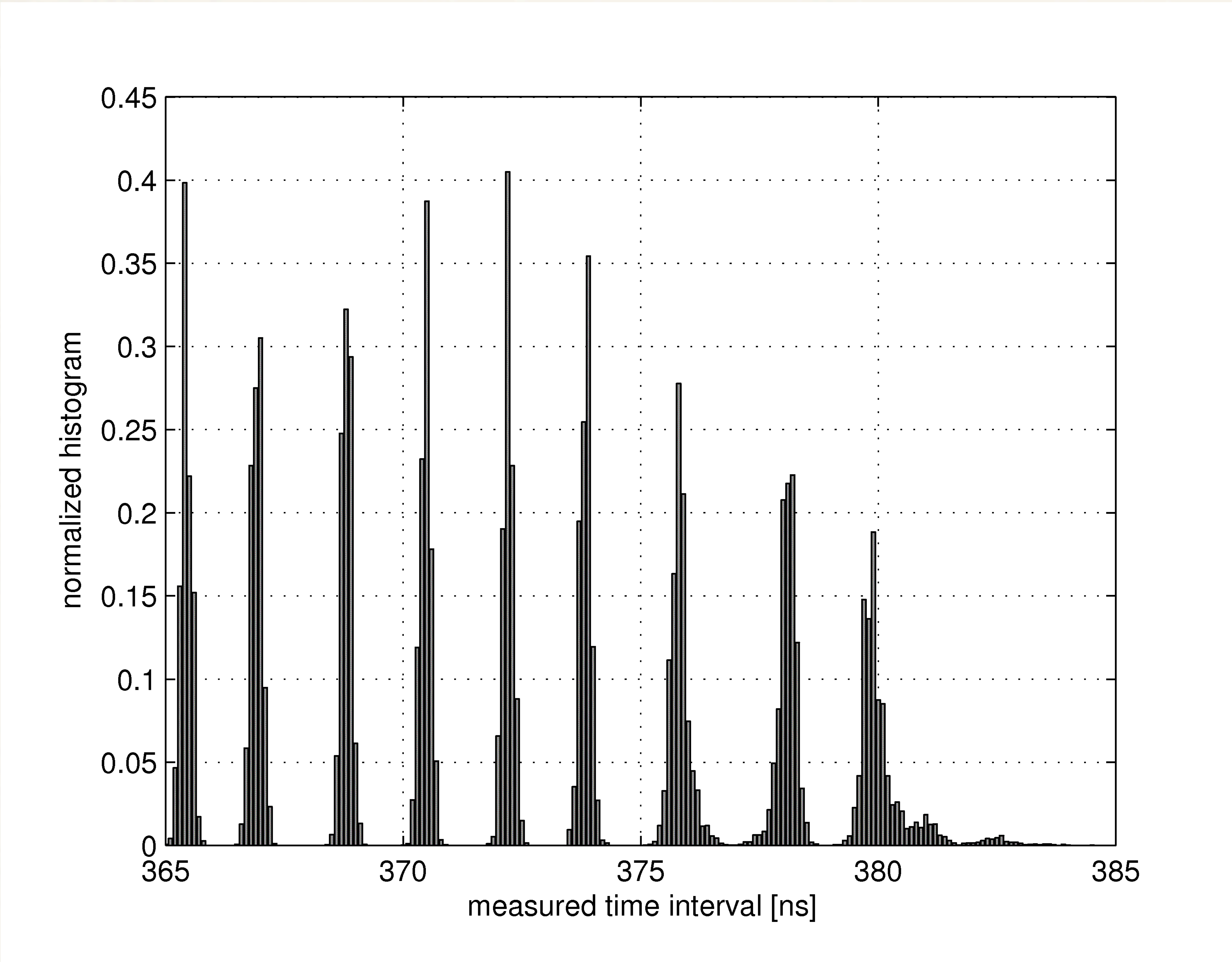
System Architecture:

Master Device





Ranging measurements



Dist:60-220 cm

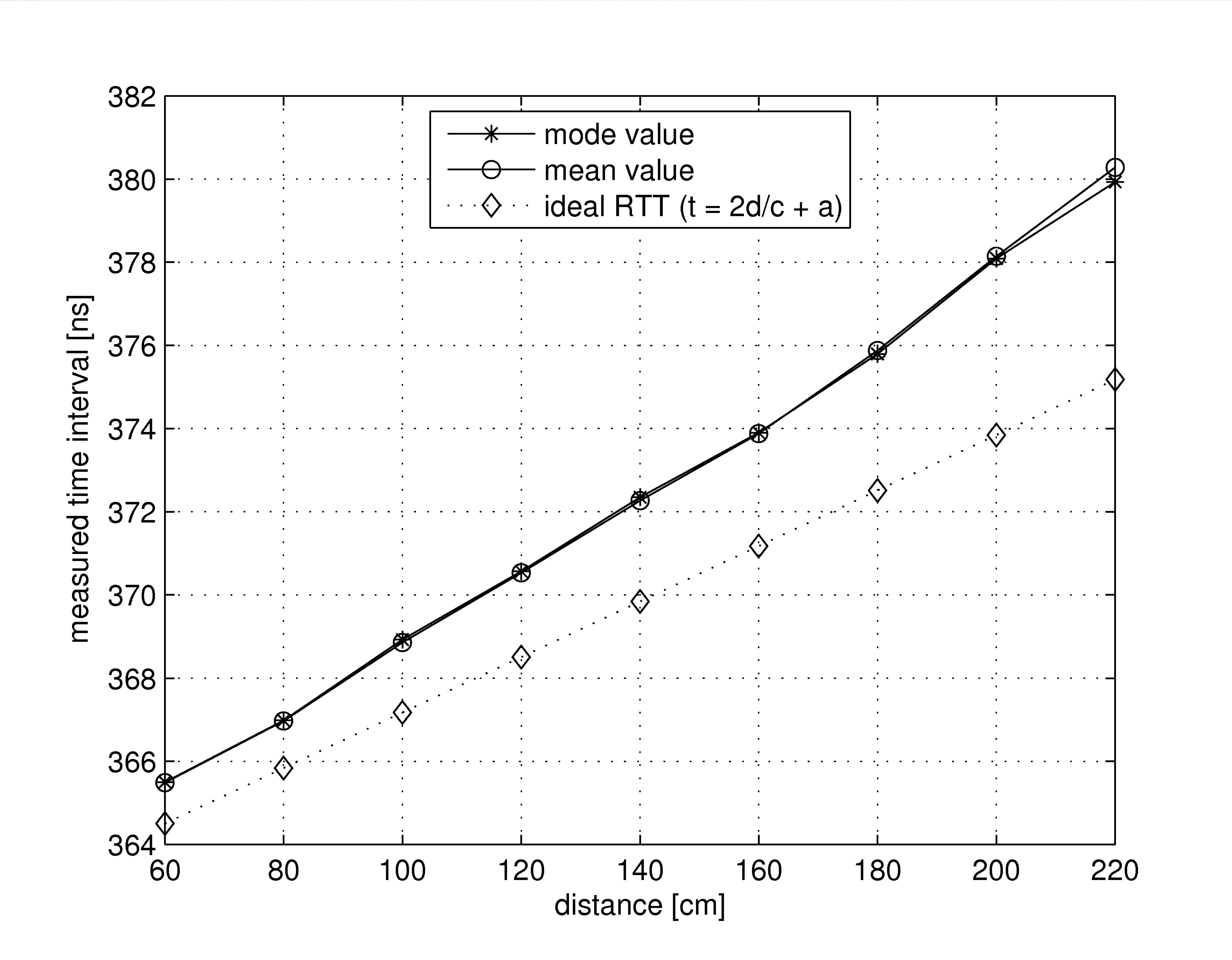
Step: 20 cm

7500 RTT measurement results for each distance.

$std \cong 0.3ns$

Heteroscedastic system

Validation

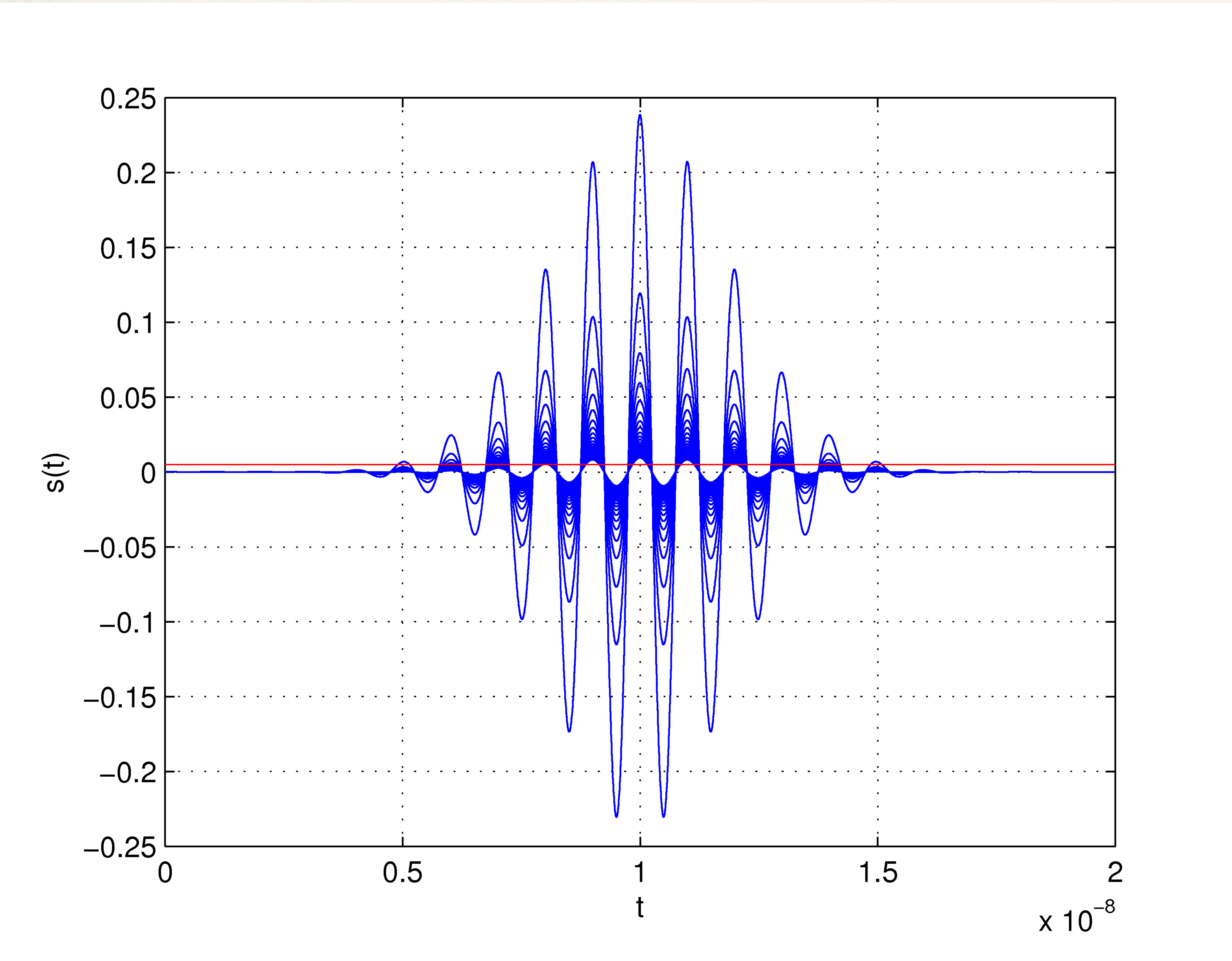


Measured RTT

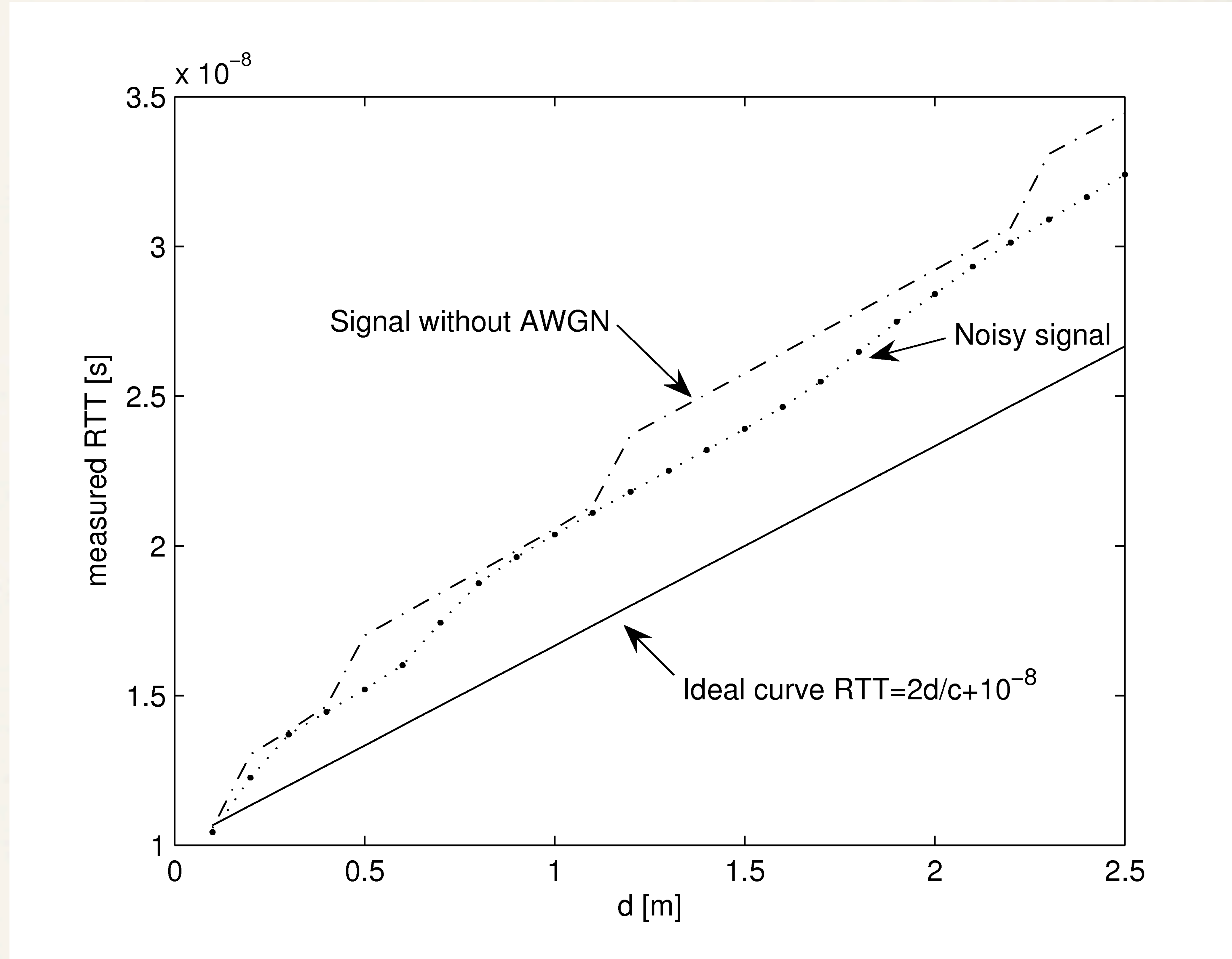
Mean and Mode values vs distance

Higher slope than ideal

...why?



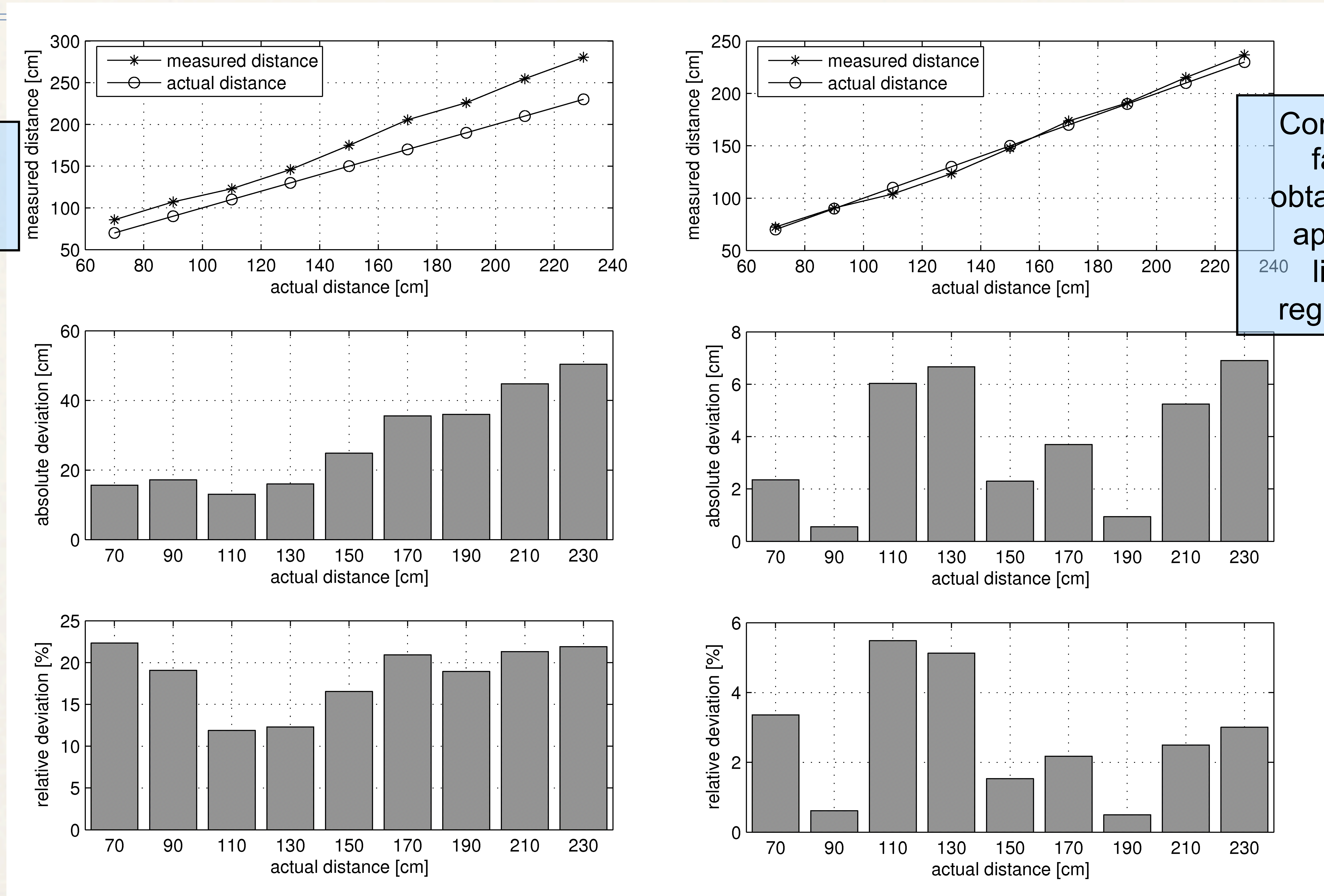
s(t)
t
x 10−8



x 10−8
measured RTT [s]
d [m]
Signal without AWGN
Noisy signal
Ideal curve RTT=2d/c+10−8

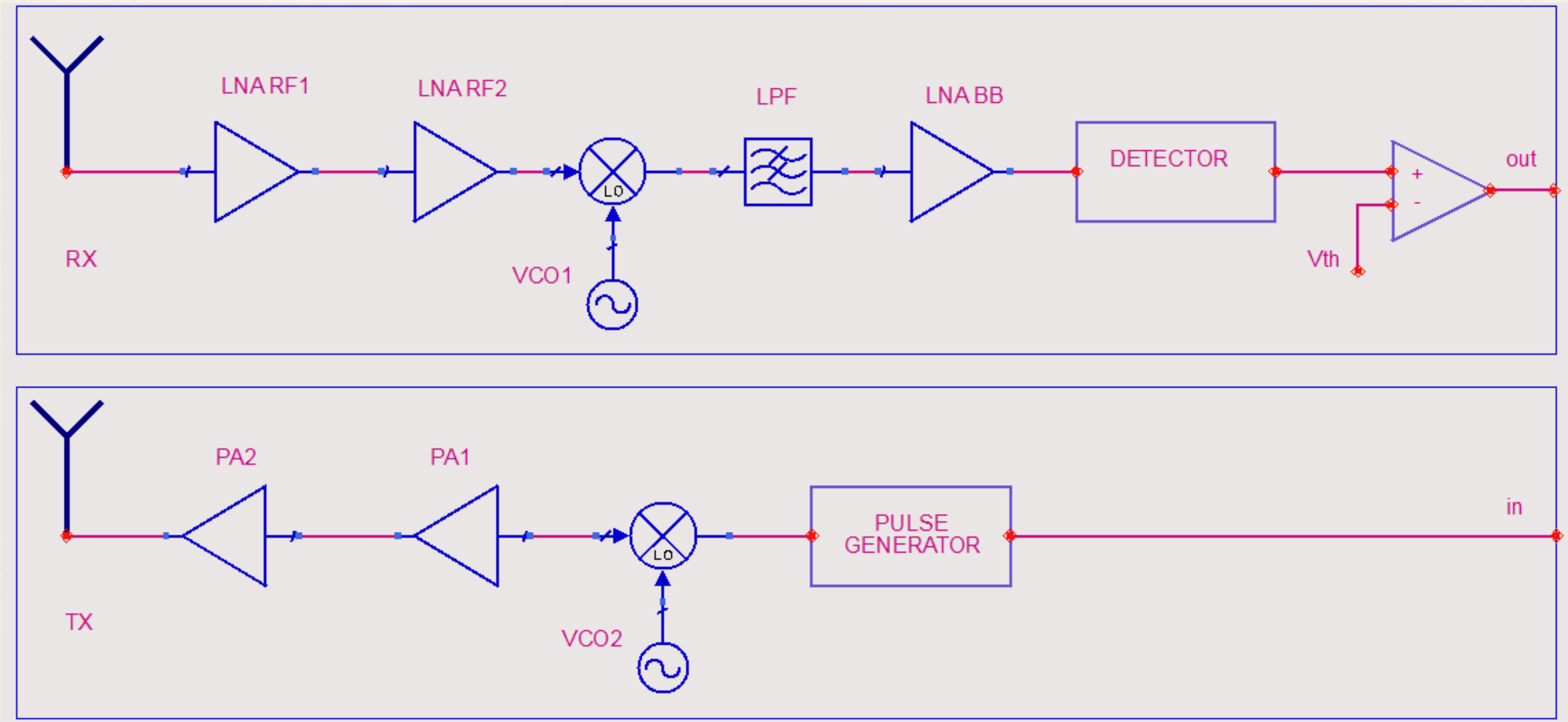
Ranging: experimental data

Experi-
mental
data

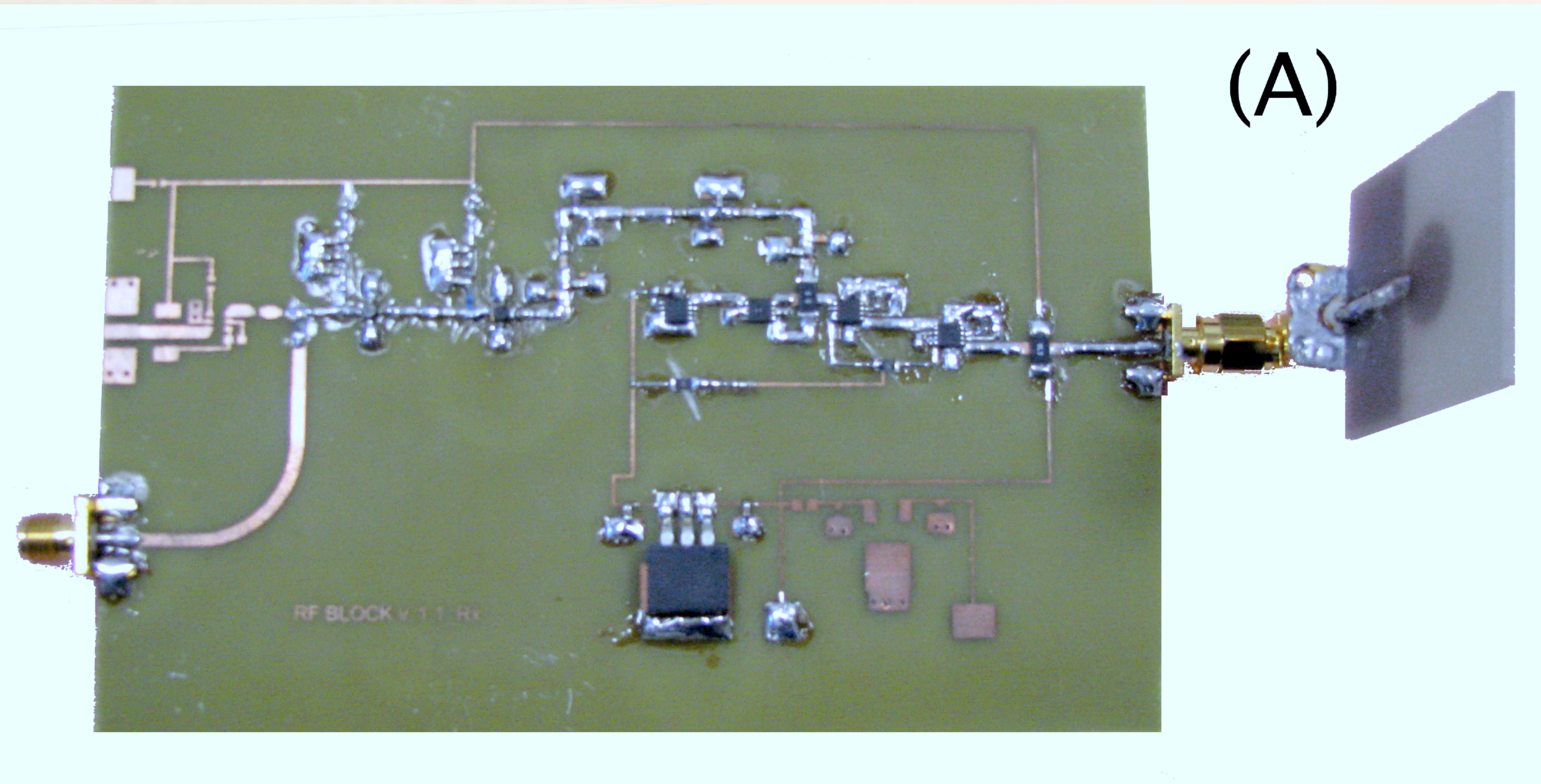


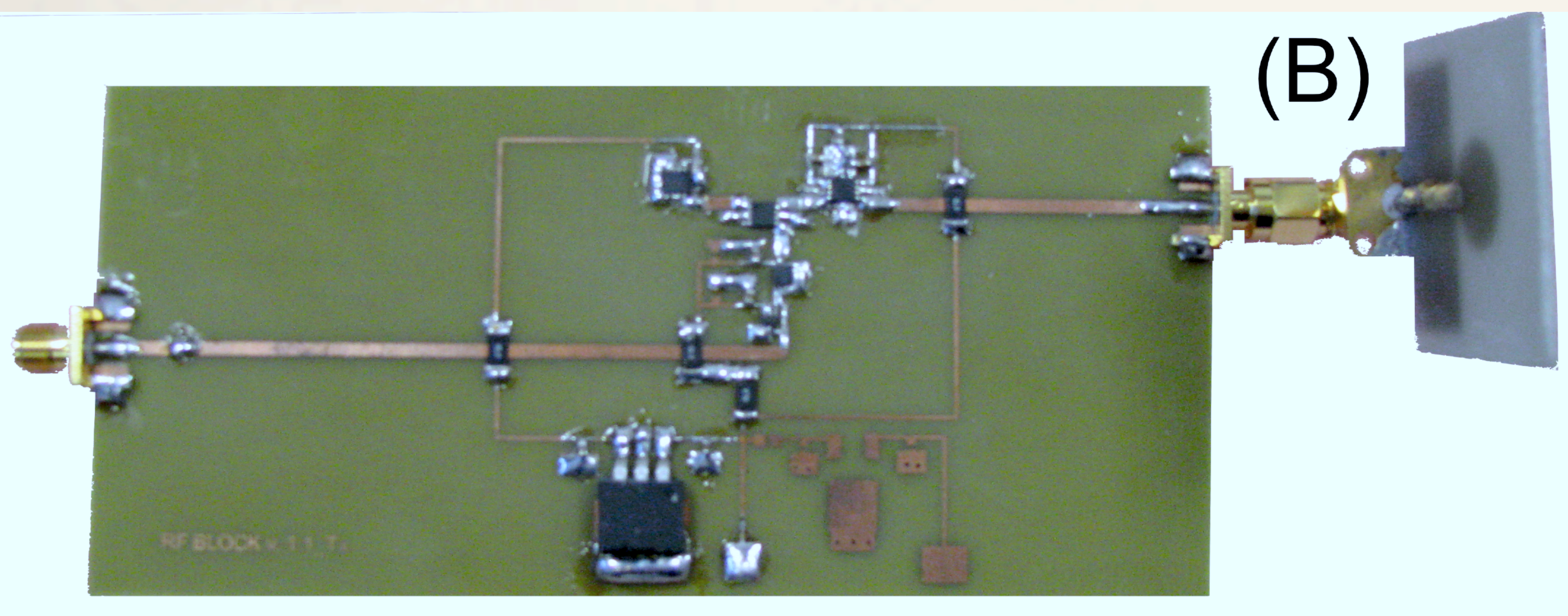
Correction factor obtained by applying linear regression

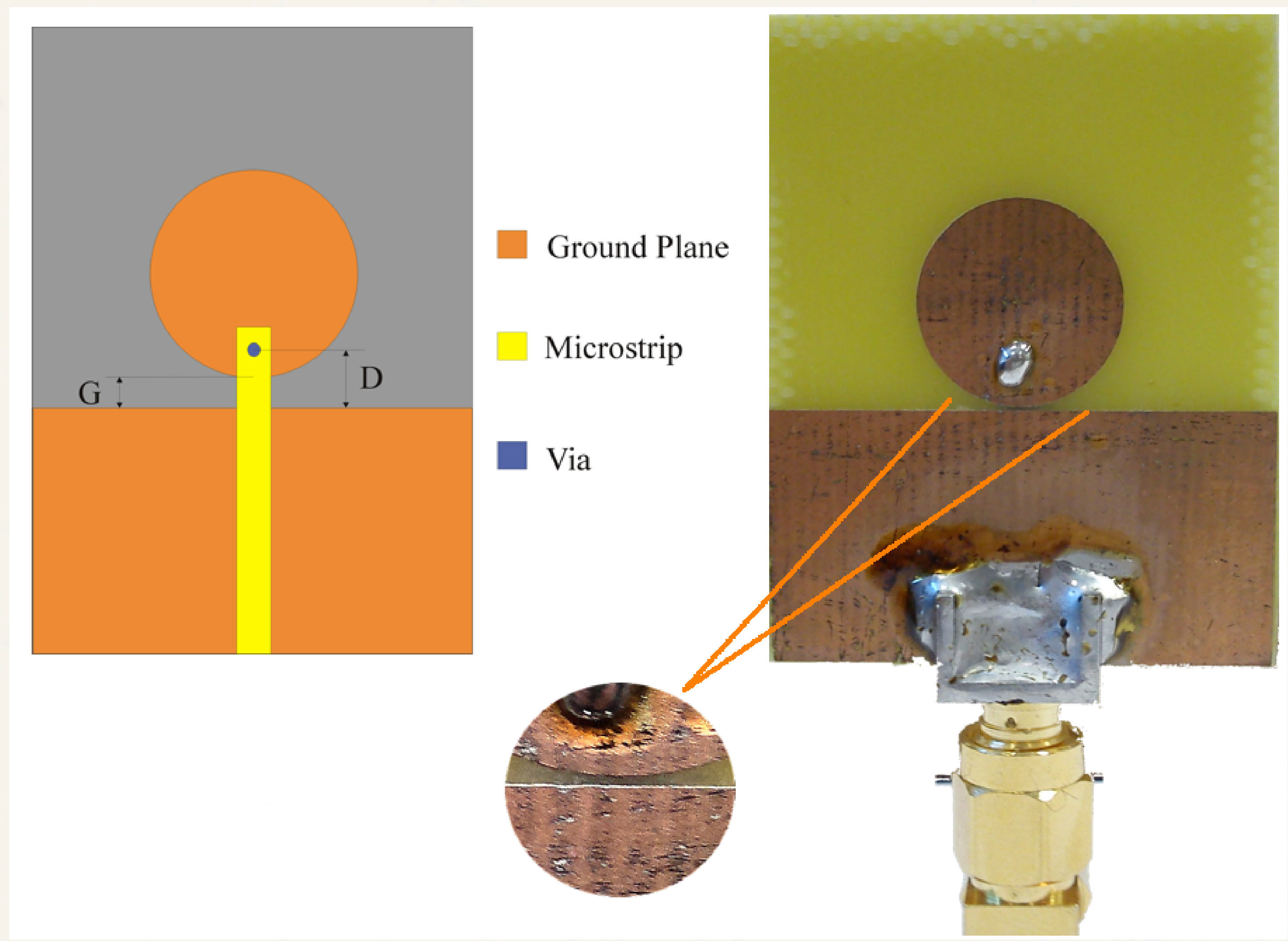
Shifted band

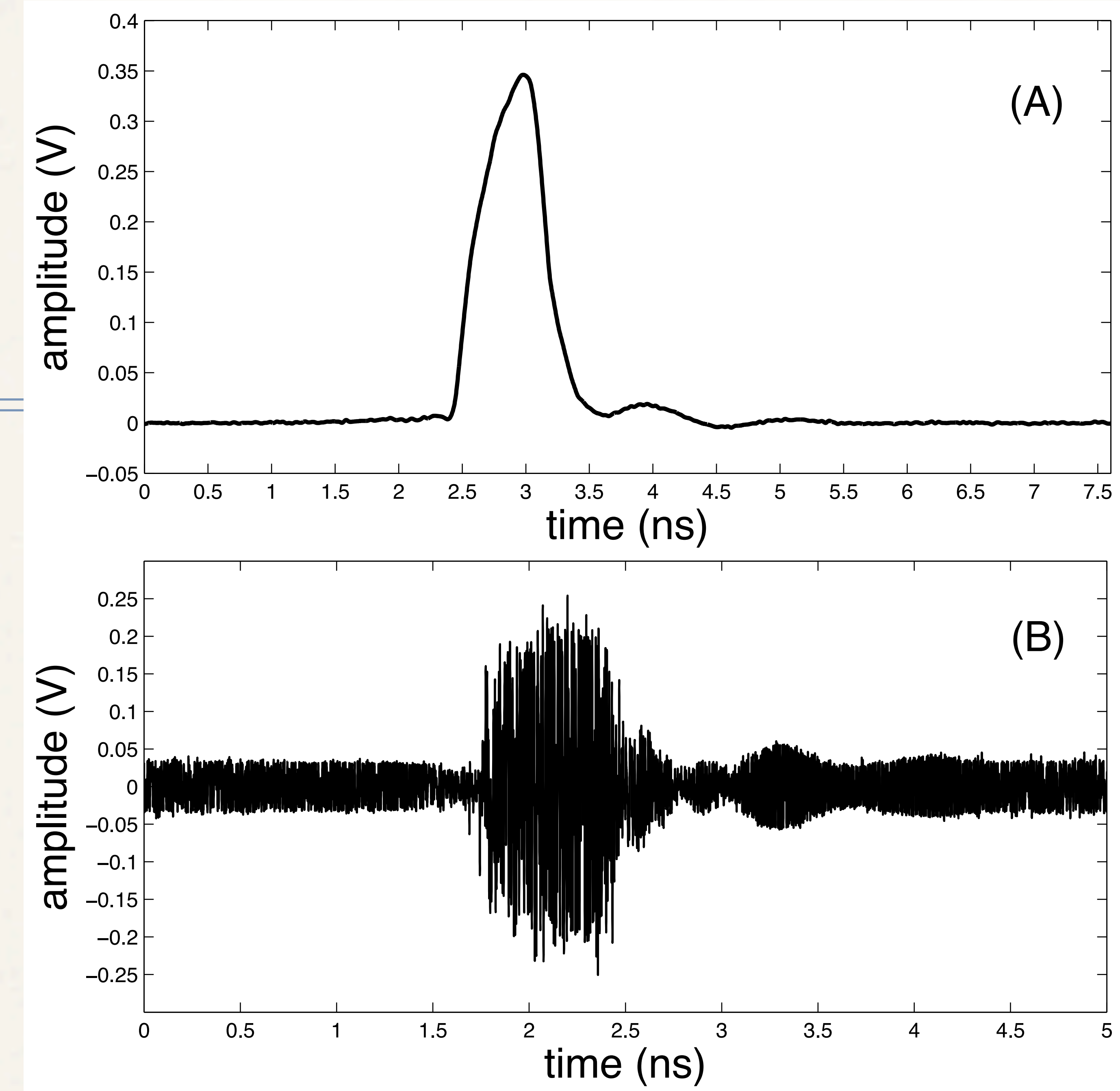


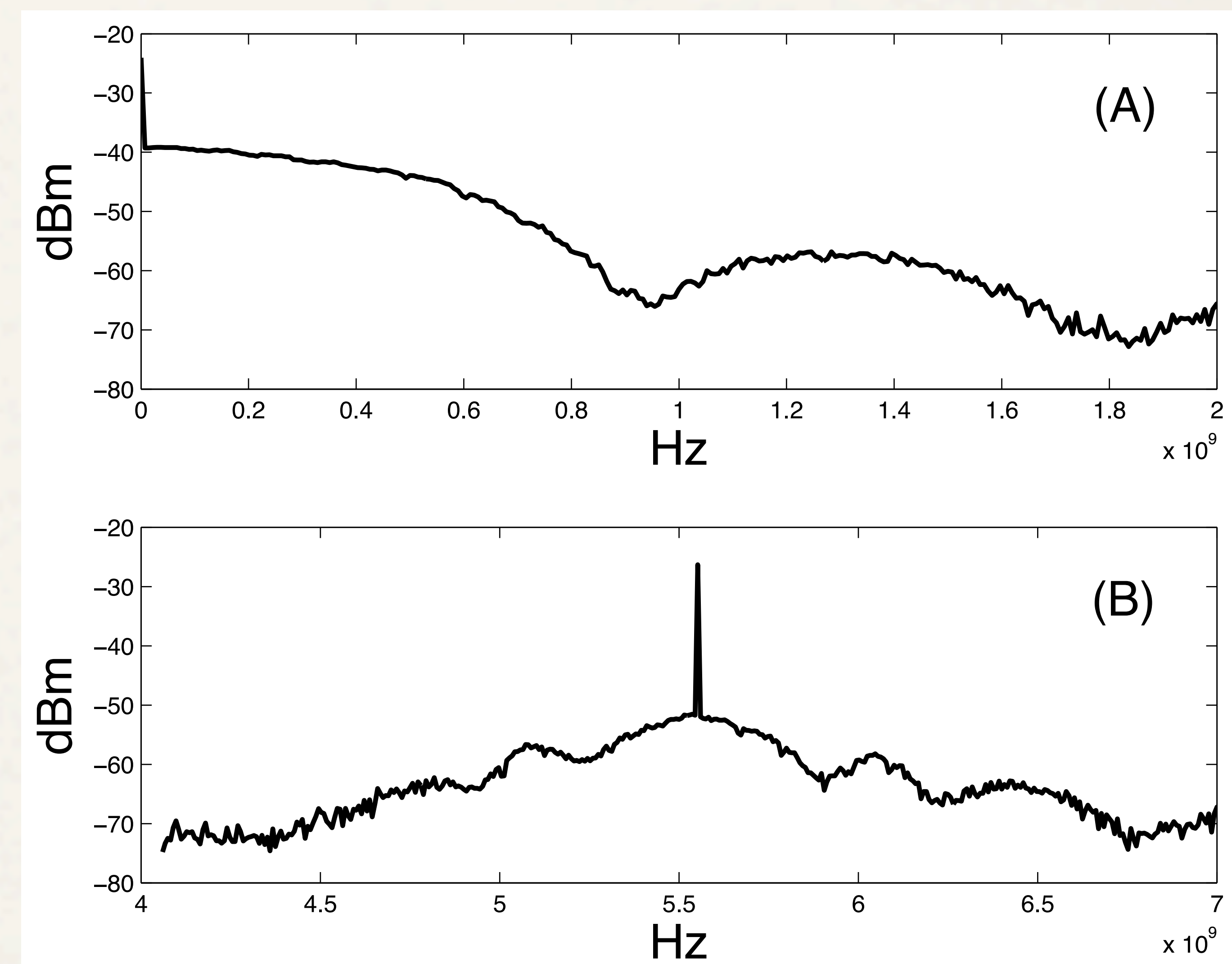
The realized instrument



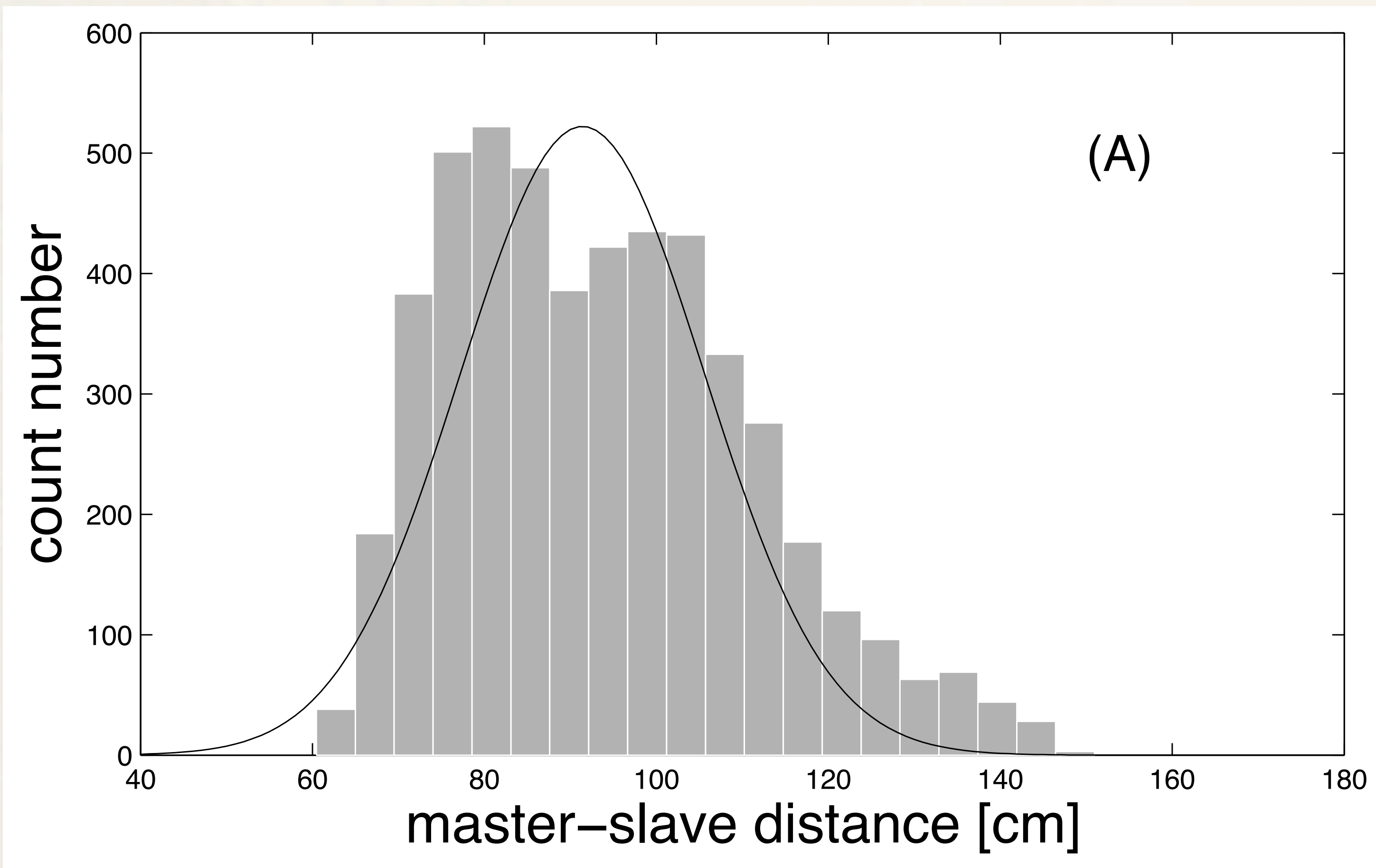








Experimental characterization



- Not strictly Gaussian
- Applied NLS and outlier removal using Mahalanobis distance

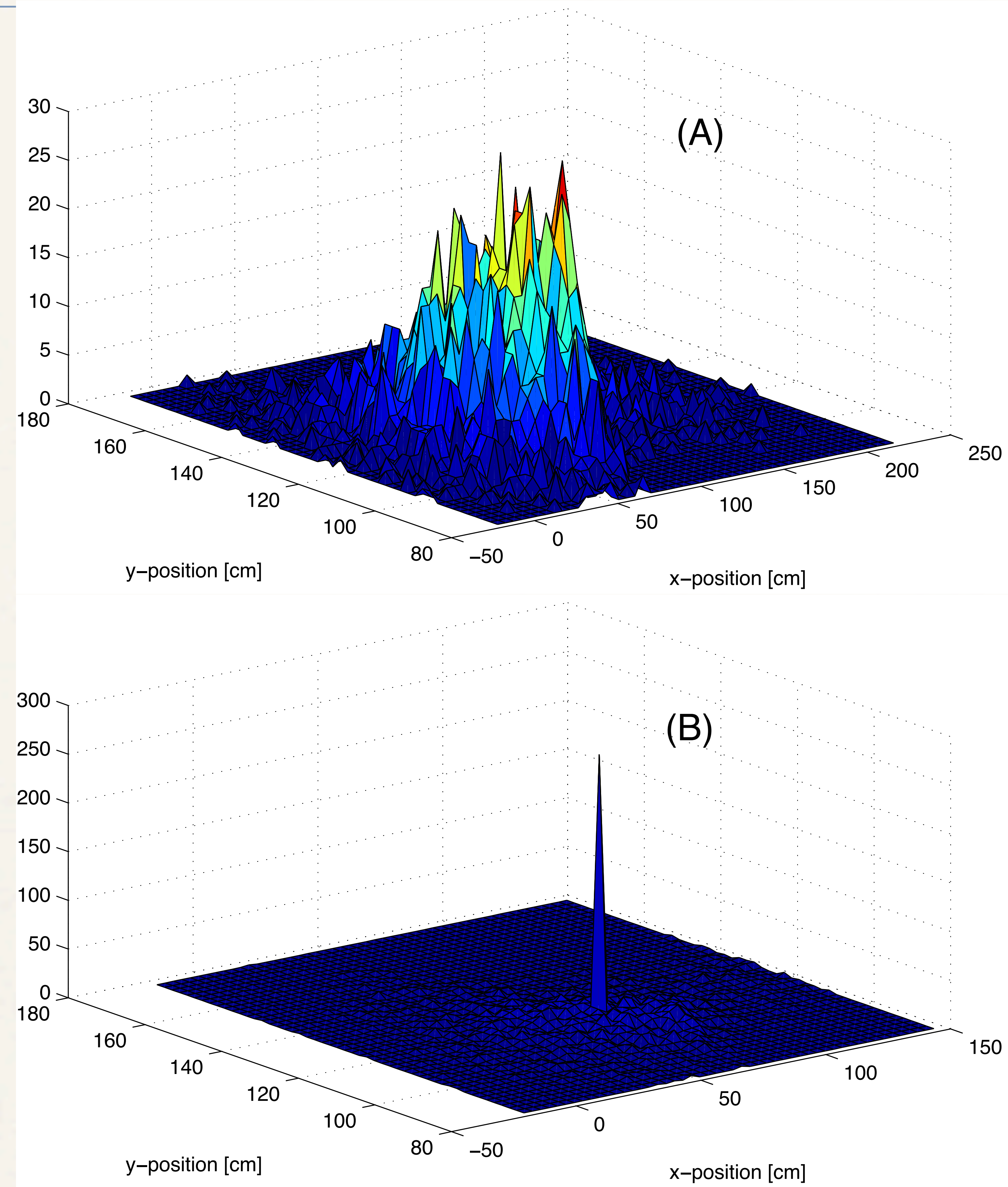
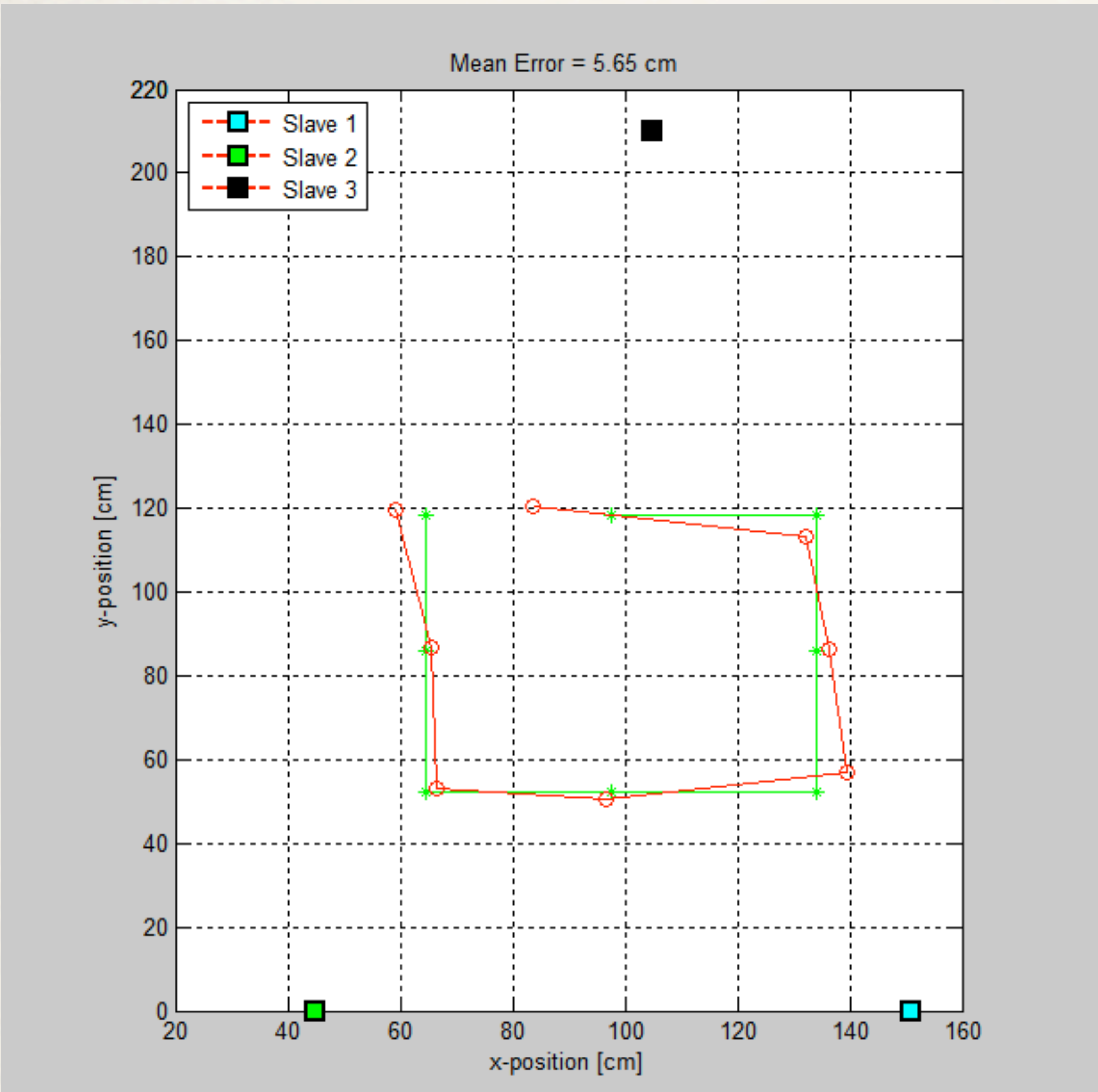


Fig. 10. Two–dimensional histograms of $5 \cdot 10^3$ estimated position coordinates obtained before (A) and after (B) removing outliers.

Positioning results: static



5000 records for each point
NLS - estimate

Micro-displacements: achievable resolution below 1mm,
if several measurement results are averaged

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A 5.6 GHz UWB Position Measurement System

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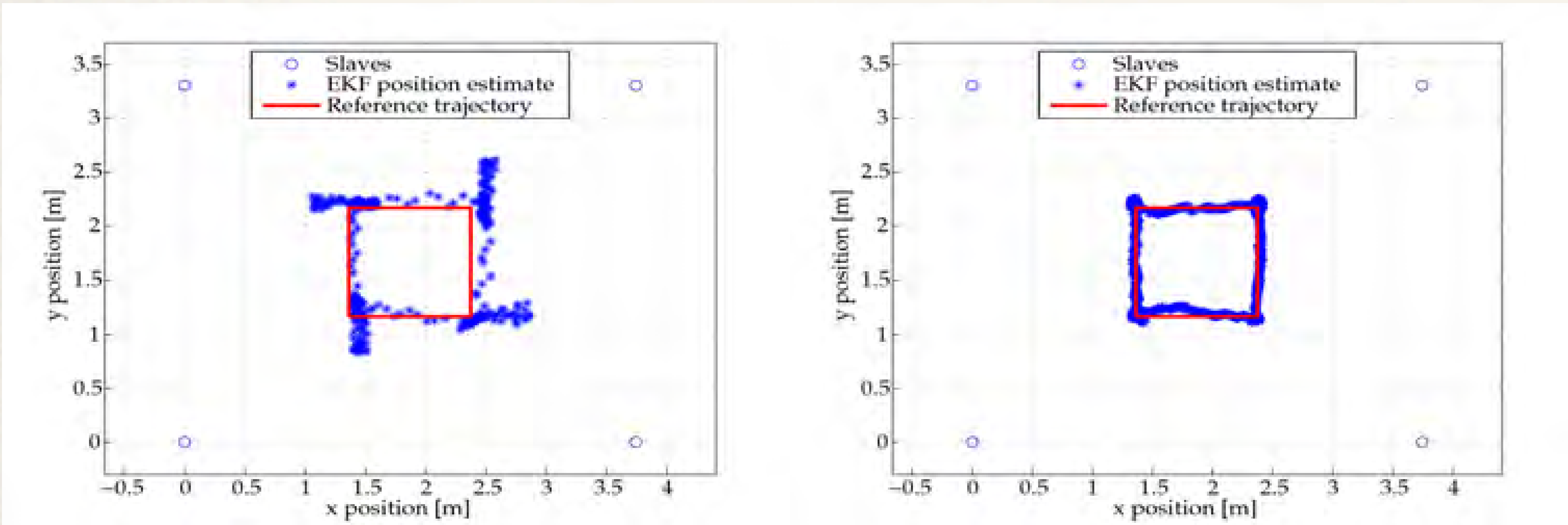
Positioning results: dynamic / tracking



(a) (b)

Fig. 17. High-dynamic tests, (a) UWB-positioning stand-alone: it can be noticed that overshoot is present, and poor tracking performance is observed. (b) information fusion with INS: no overshoot and better tracking performance has been observed (De Angelis et al., 2009b).

- Sensor fusion using Inertial Measurement Unit to compensate when static data are not available

Experimental Radio Indoor Positioning Systems Based on Round-Trip Time Measurement

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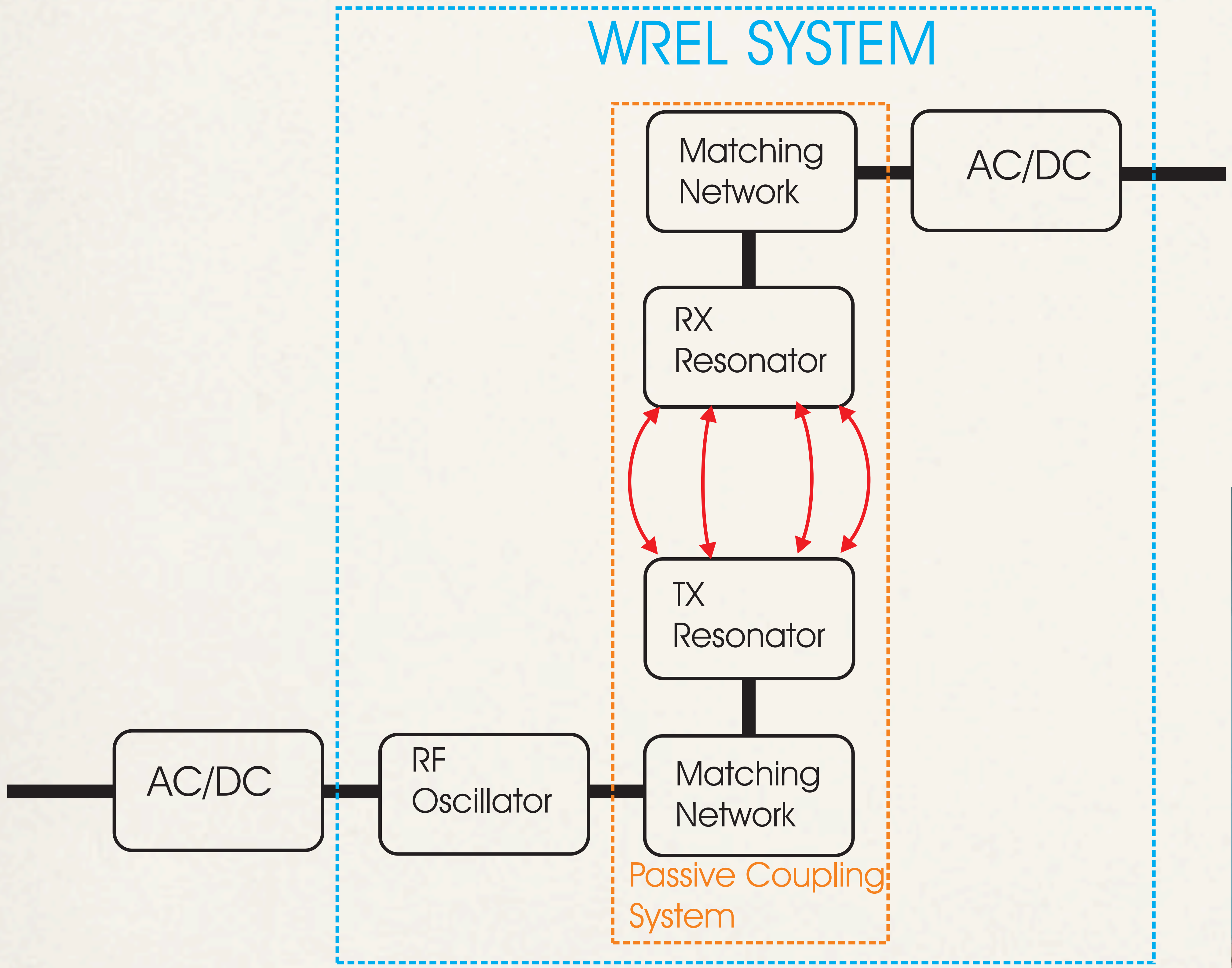
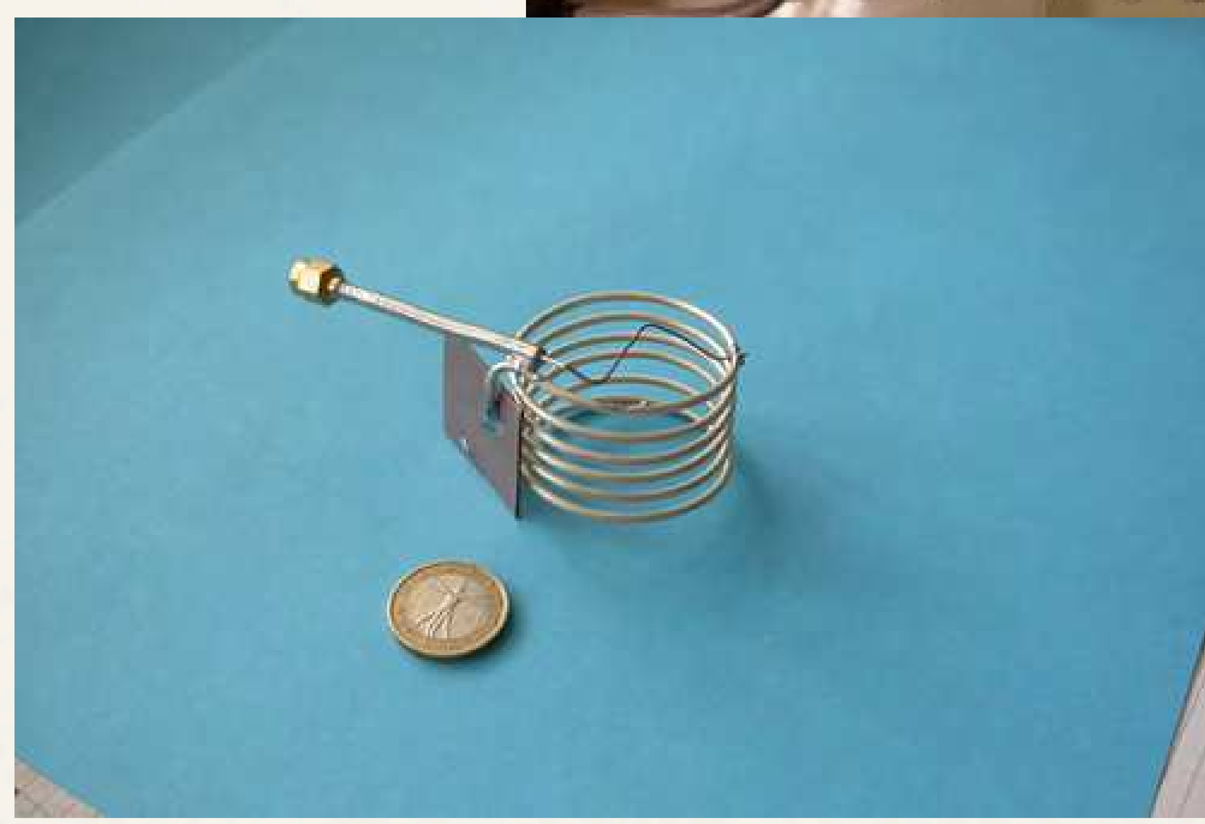
New directions

- Mutually coupled simple resonant coils for ranging: inductive coupling





Experimental results

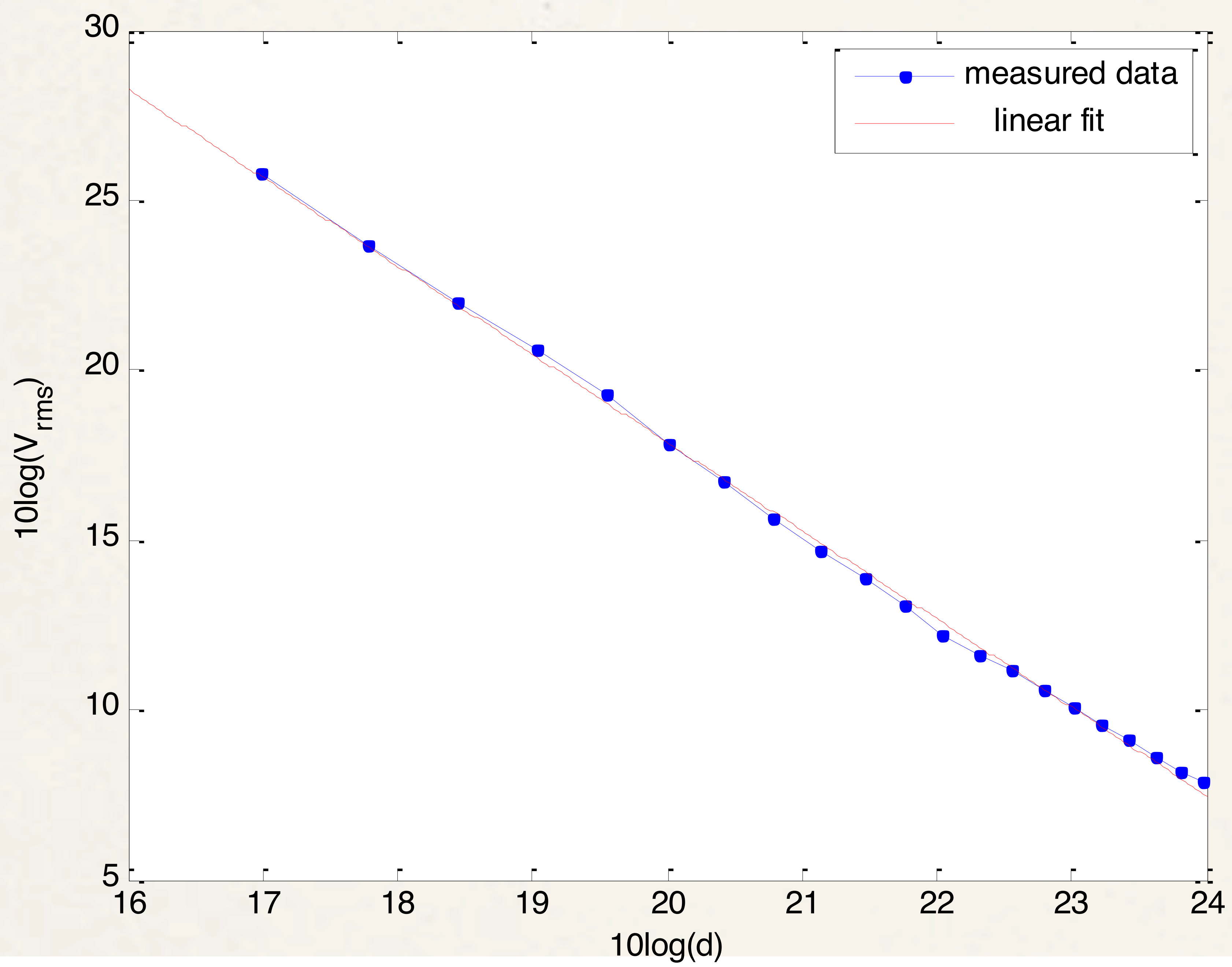


Fig. 5: received rms voltage, expressed in mV, vs distance, expressed in cm, obtained for the developed two resonator system.

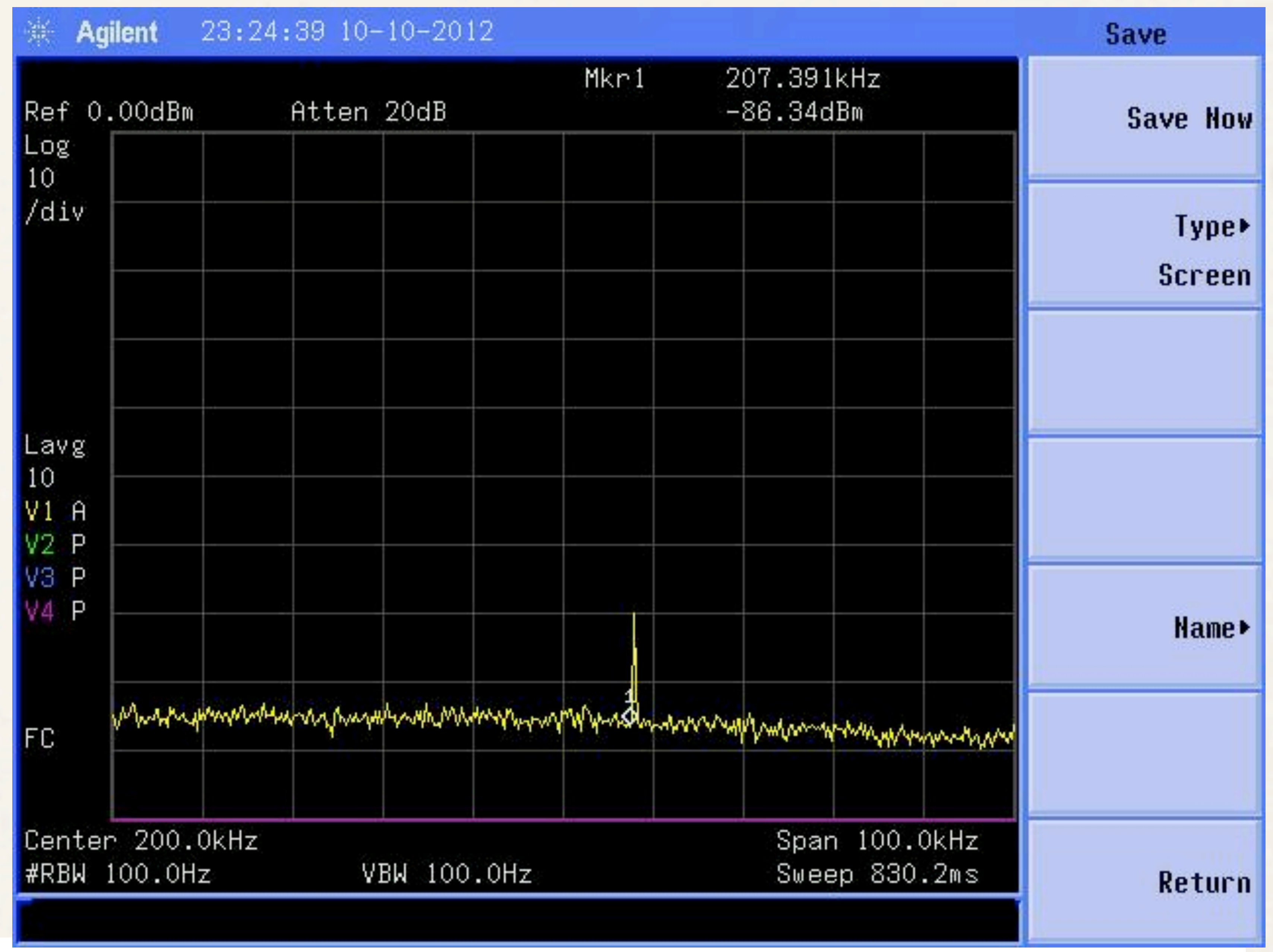


Fig. 6: received signal spectrum, obtained for a distance of about 8m between the transmitter and the receiver.

Timestamping and synchronizing: what time is it?

- Issue: synchronize nodes in a sensor network
- required in many application: would be beneficial for positioning as well
- natural outcome of the developed system
- TDCs on board of master / slaves used to measure delay between clocks and pulse triggers/ receiving instants

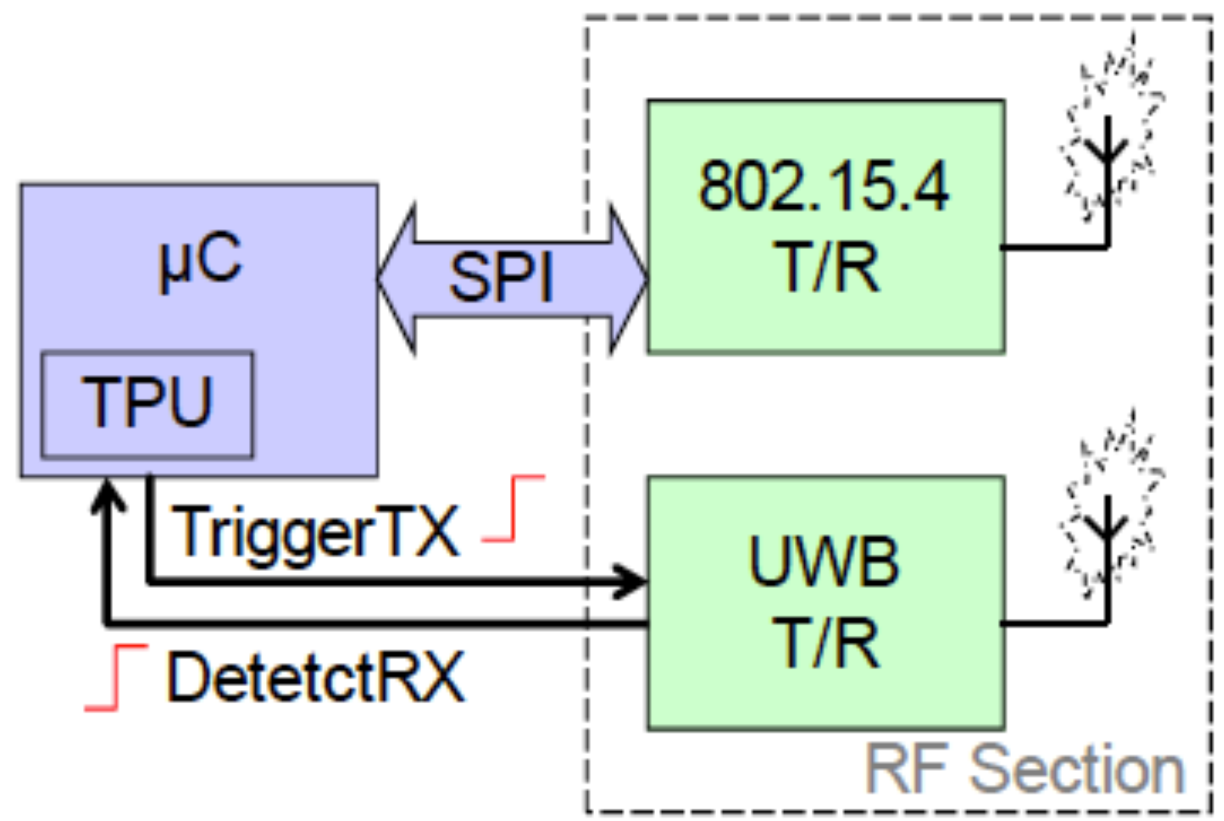


Fig.3. Block diagram of the proposed node.

High-precision UWB-based timestamping

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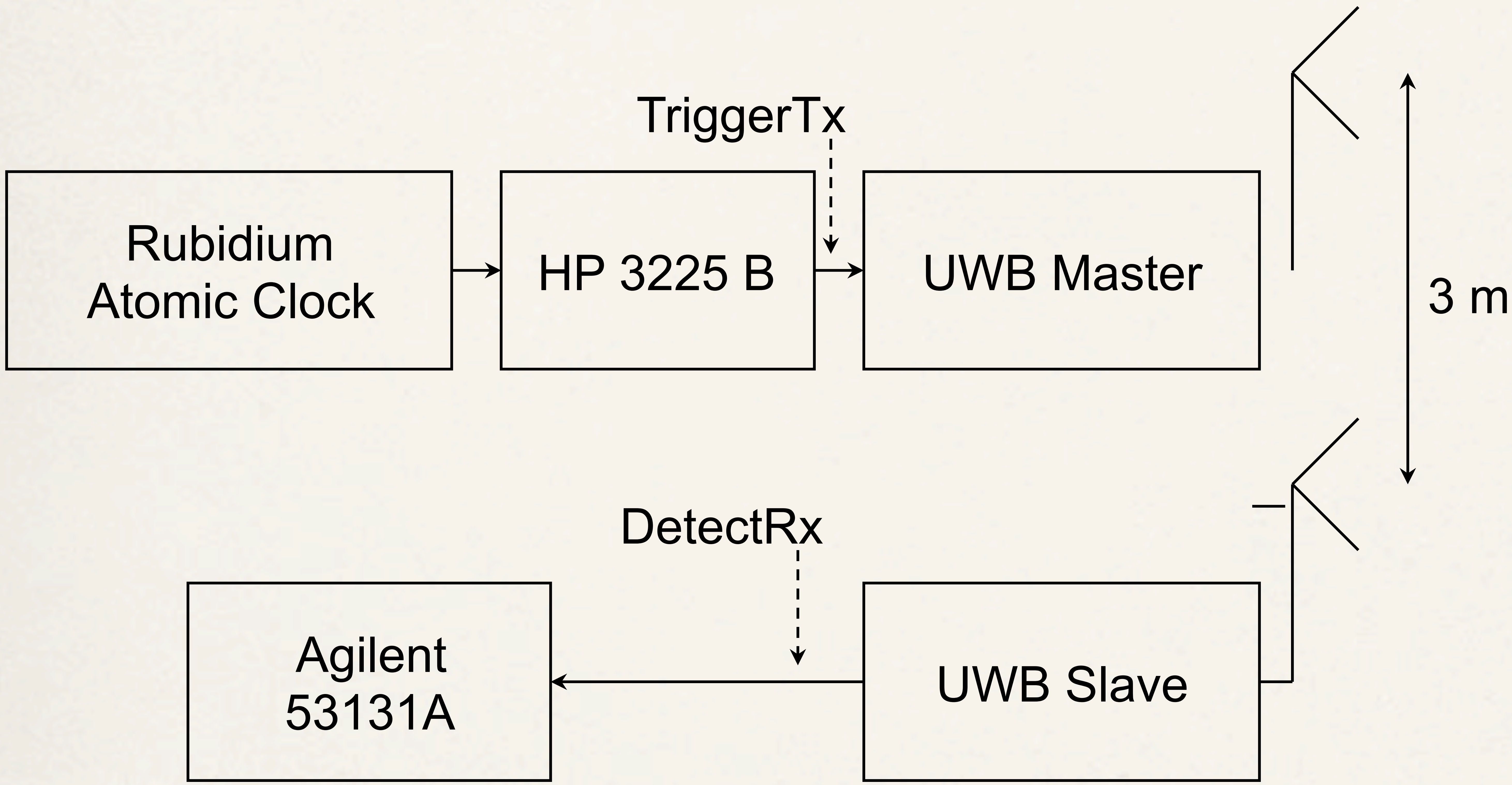
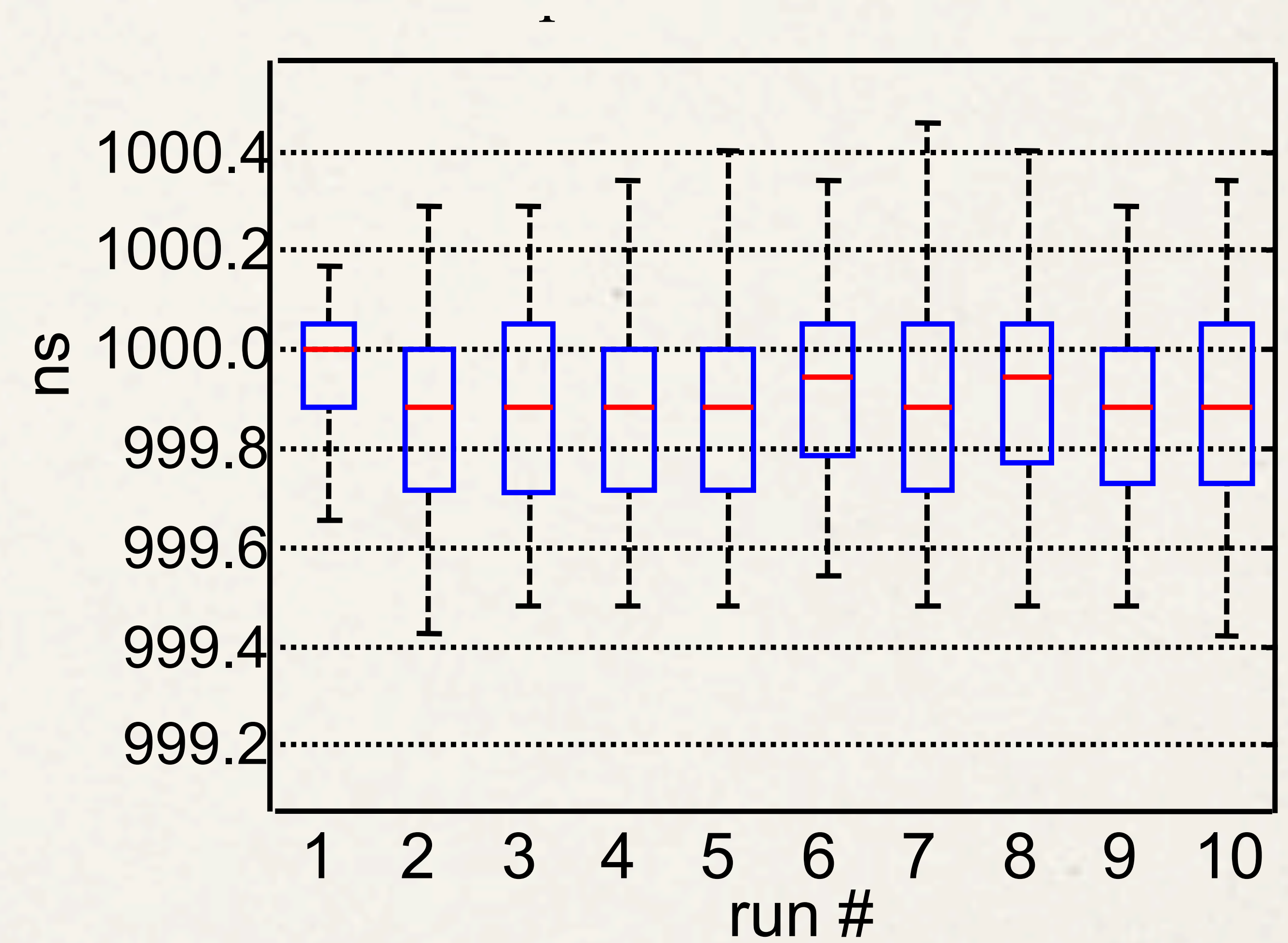
Timestamping & Synchronizing

- Transfer timing information between transceivers for synchronization purposes
- Standard deviation:
- - using counter: < 1 ps
- - using TDC: < 19 ps





Serendipity or the law of unintended consequences

A low-cost (<50 euro) fast humidity sensor

- Measurement of humidity in woodchips of great interest in a growing market of wood stoves
- Cable radar: pulse sent in closed-loop or open-ended wire, measured RTT
- Time of flight as a function of medium effective dielectric constants
- In turn, effective dielectric constant dependent on humidity surrounding cable: humidity sensor
- all developed electronics ‘recyclable’ to realize sensor for humidity in wood-chips (or other material)

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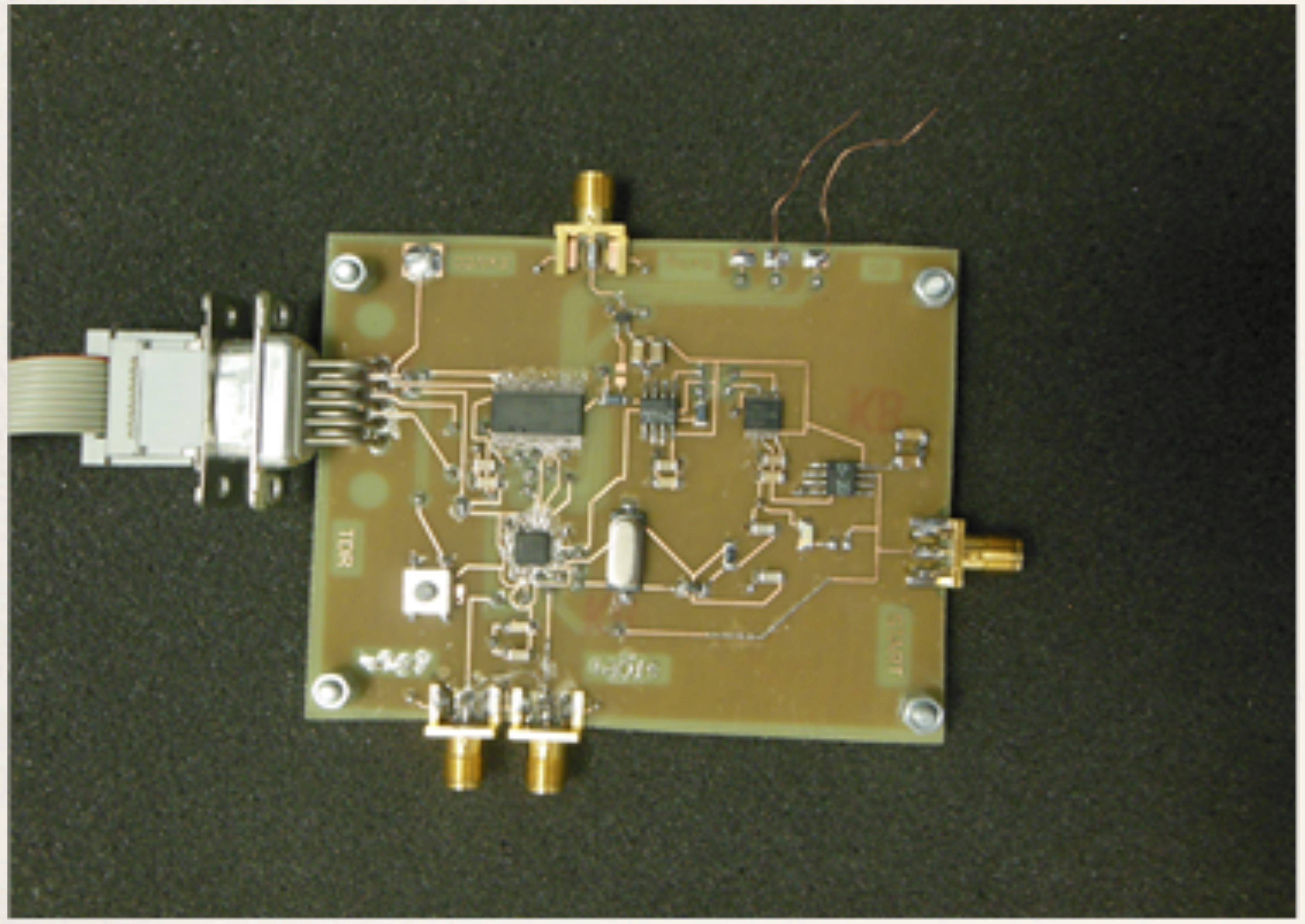
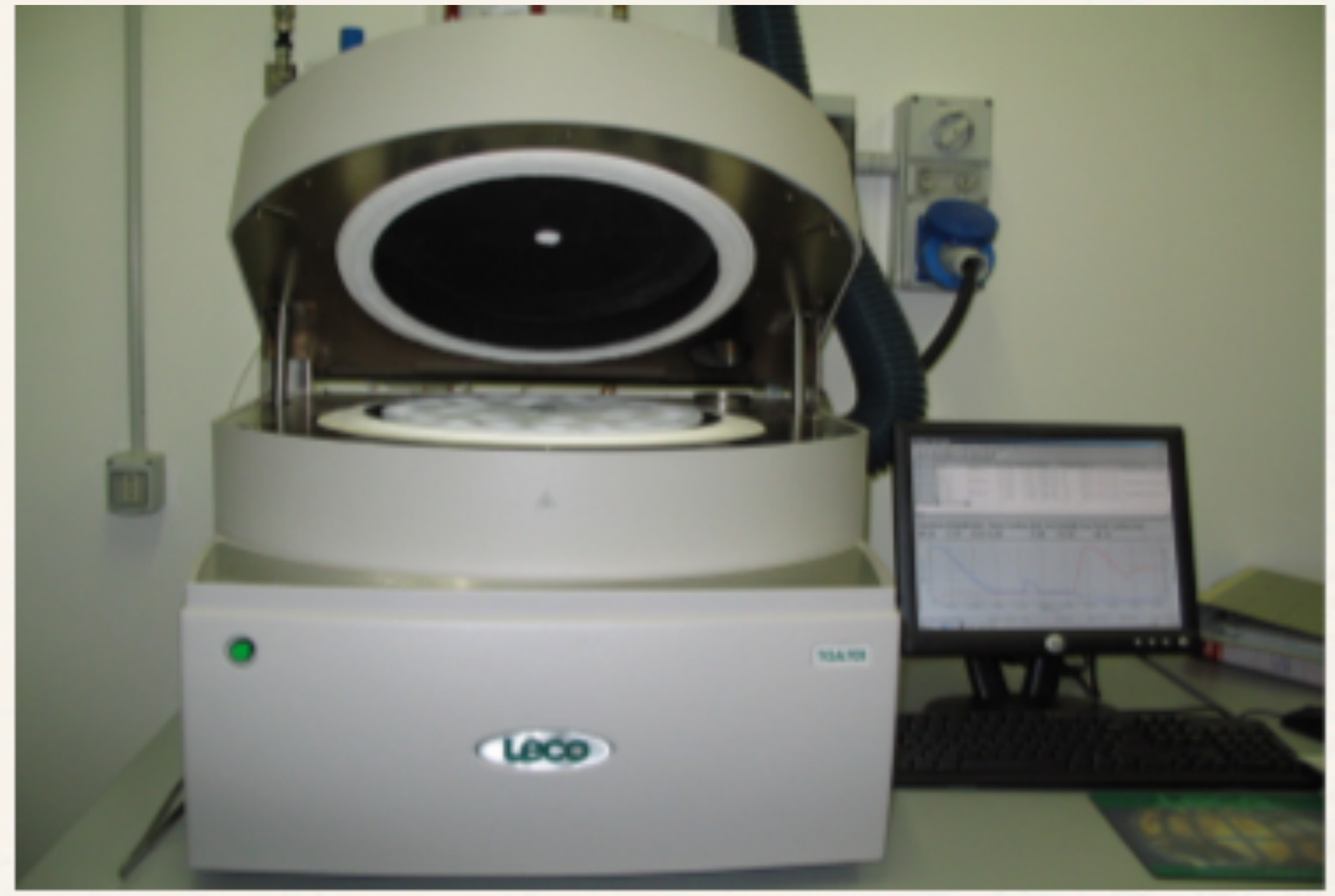
Systems



The developed μc-TDC Demo-Board.

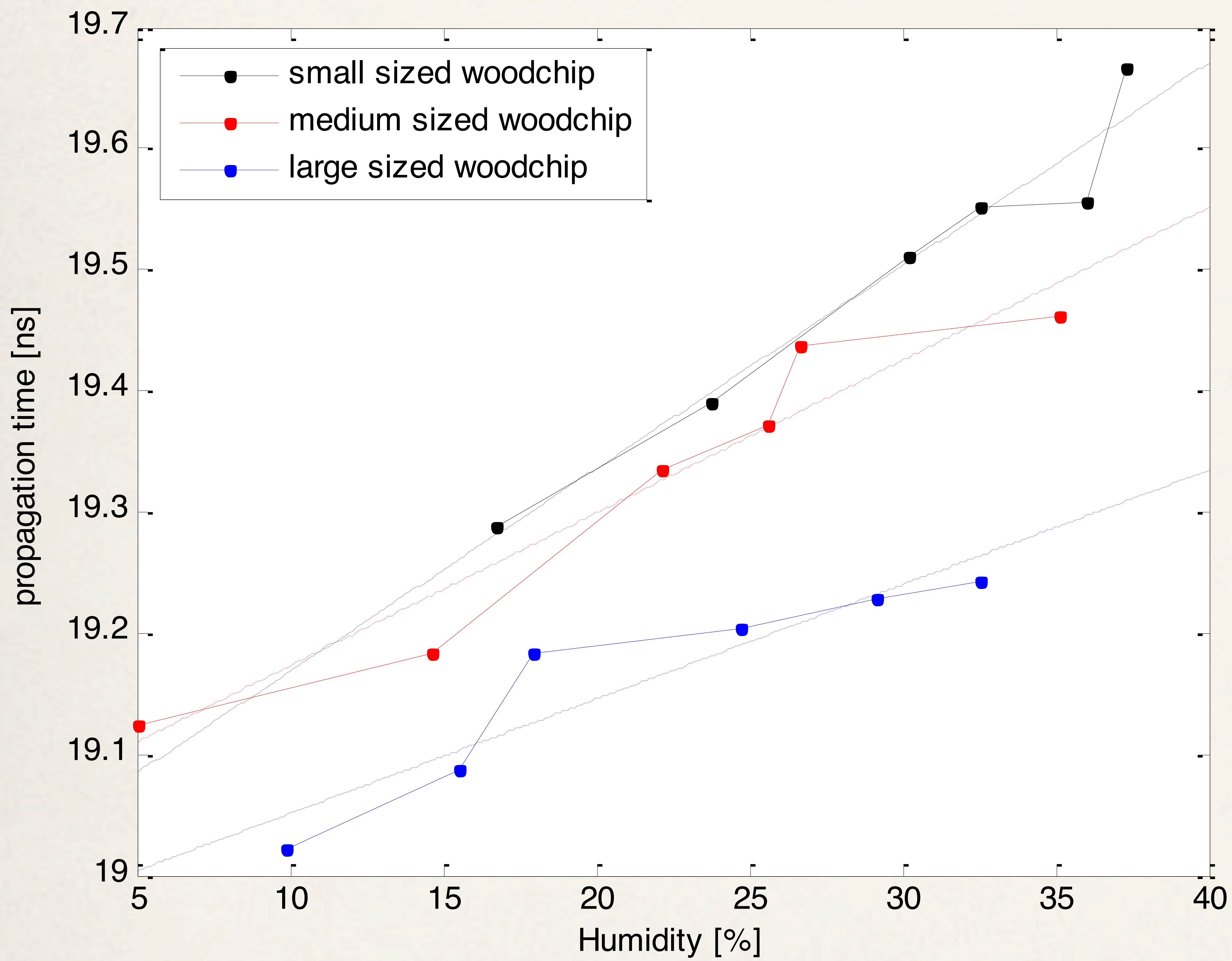
vs

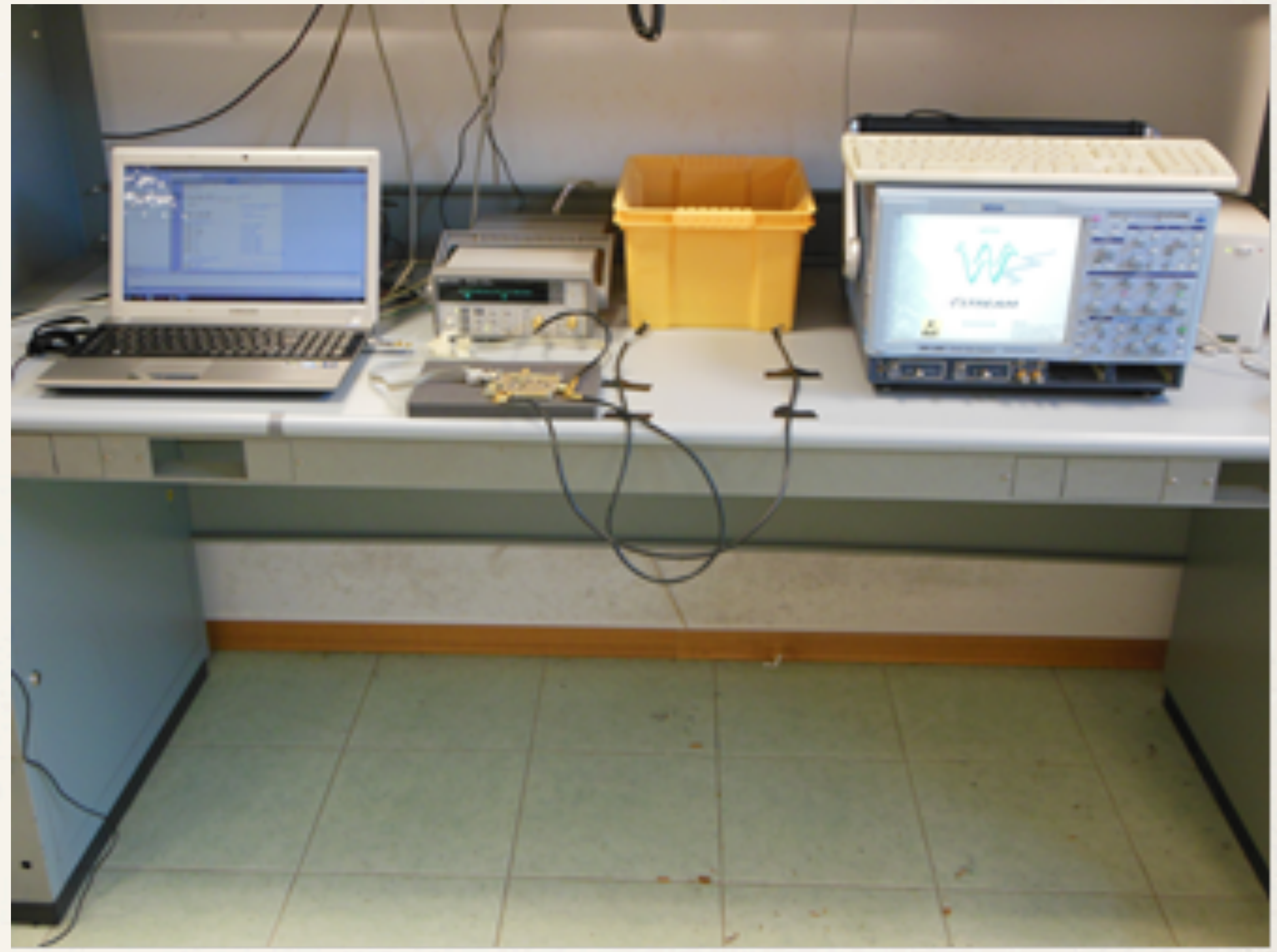


The LECO TGA-701 for humidity content measurement

- Thermogravimetric Analysis (TGA) used as a reference (procedure described EN 14774-2 standard)

Experimental results





some unanticipated consequences ...

- Done most of my research career in signal processing (with some VLSI at an early stage)
- Is easy to understand and to *touch* research easier to be funded and more attractive?
- Provocativeness: interesting /curious application oriented problems attract more easily attention: more students to contribute, more colleagues willing to collaborate, easier to be communicated to the general public, easier to be financed: choice of research subject has consequences -> the value of research: *method-led* research vs *problem-led* research
- national/continental policies about research, drive choices for financing research projects: better apply some anticipative/adaptive (?) behavior

Conclusions

- A fascinating old problem: not a single solution, many competing technologies
- A system engineering type of problem: realizing an indoor positioning system from scratch using off-the-shelf components
- Although technical solutions are known, several technical issues must be solved, especially at the interface between sub-systems
- Signal processing must know properties of hardware solutions to optimize accuracy of estimates
- In the end, the outcome is a measurement instruments, whose performance in terms of position accuracy strongly depends on the adopted system integration approach