IEEE Sensors France Chapter:

Measurement Performance of Sensors Systems towards Autonomous Vehicles

https://www.youtube.com/watch?v=Bg8zw1SWiJA&feature=youtu.be

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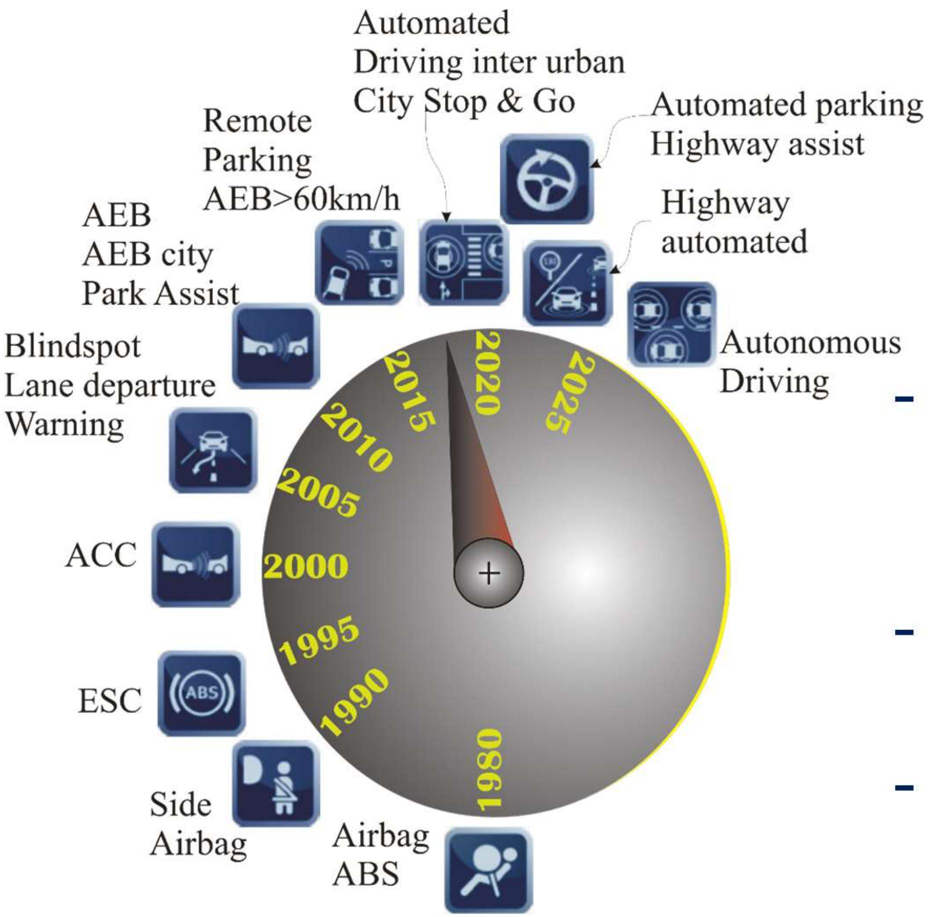
Outline

- Societal, economical, technical challenges of autonomous & connected vehicles and intelligent transport systems (ITS)
- Remote sensing (Radar, Lidar) in smart vehicle & ITS
- Sensing technology for navigation
- eHPC (embedded High Performance Computing) needs of autonomous and connected cars – the H2020 European Processor Initiative (EPI) project
- Arithmetic accuracy for DNN acceleration (Posits in EPI)
- Conclusions

Trends in smart vehicles and ITS



A research theme of high economical and social impact

- **Improving safety** (1.25M killed people/year worldwide, 3.3K/year killed in Italy, 175K/year injuried)
- **Reducing CO2** (diesel-gate cost 18 Billions for carmakers)
- **Improving city life conditions with less pollution/traffic-jam**
- **Improving user experience** (comfort, digital lifestyle, status symbol, info tainment, HMI, inclusive mobility for all)
- **High economic value** (90M of new vehicles/year, 35M of e-bikes/year sold worldwide)

Trends in smart vehicles and ITS

Vehicles are becoming electrified, connected, autonomous

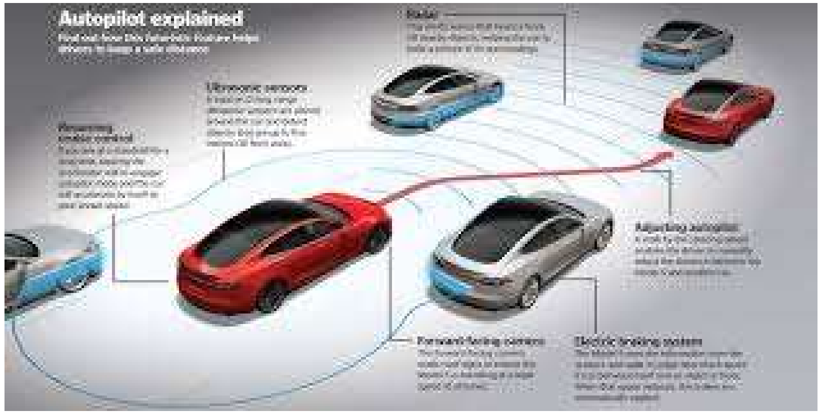
Spin-off of the research results towards Robotics and Industry4.0

Huge investments from Semiconductor and ICT companies and joint alliances with OEM companies *(e.g. INTEL-Mobileye-BMW, NVIDIA-Bosch-Nvidia)*

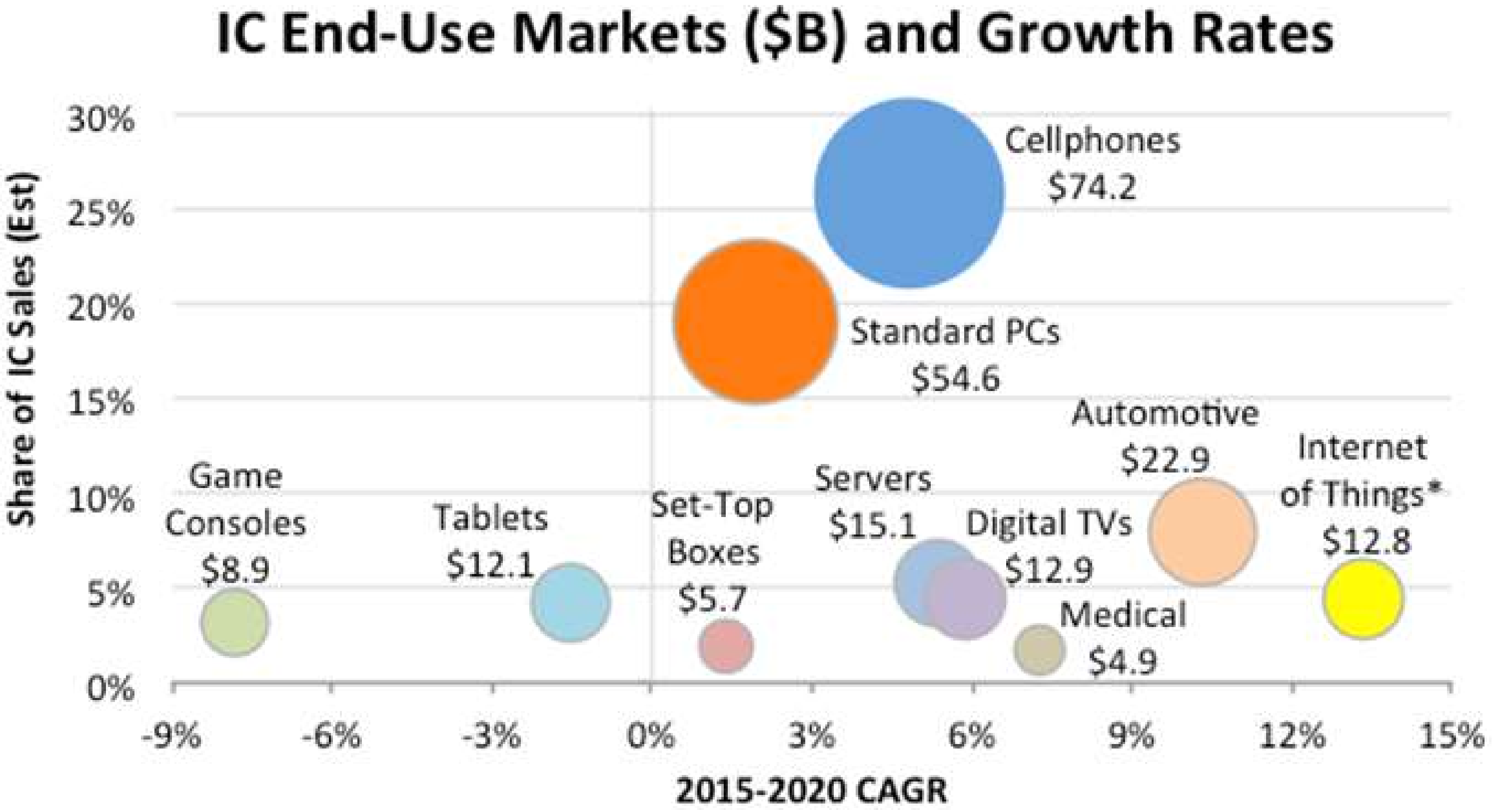
INTEL estimates the vehicle systems, data and services market to be up to $70 billion by 2030

In 2018 VW group committed to $48 billion of investments in electrified and autonomous vehicles for 2019-2025 (MEB -Modularer E-Antriebs-Baukasten- platform; i.e., Modular Electric Propulsion Platform)

ICT-Automotive industry alliances



5GAA
Automotive Association



Automotive ICs market trends

The big dilemma:
Assisted driving or fully autonomous driving?

100% safety not possible

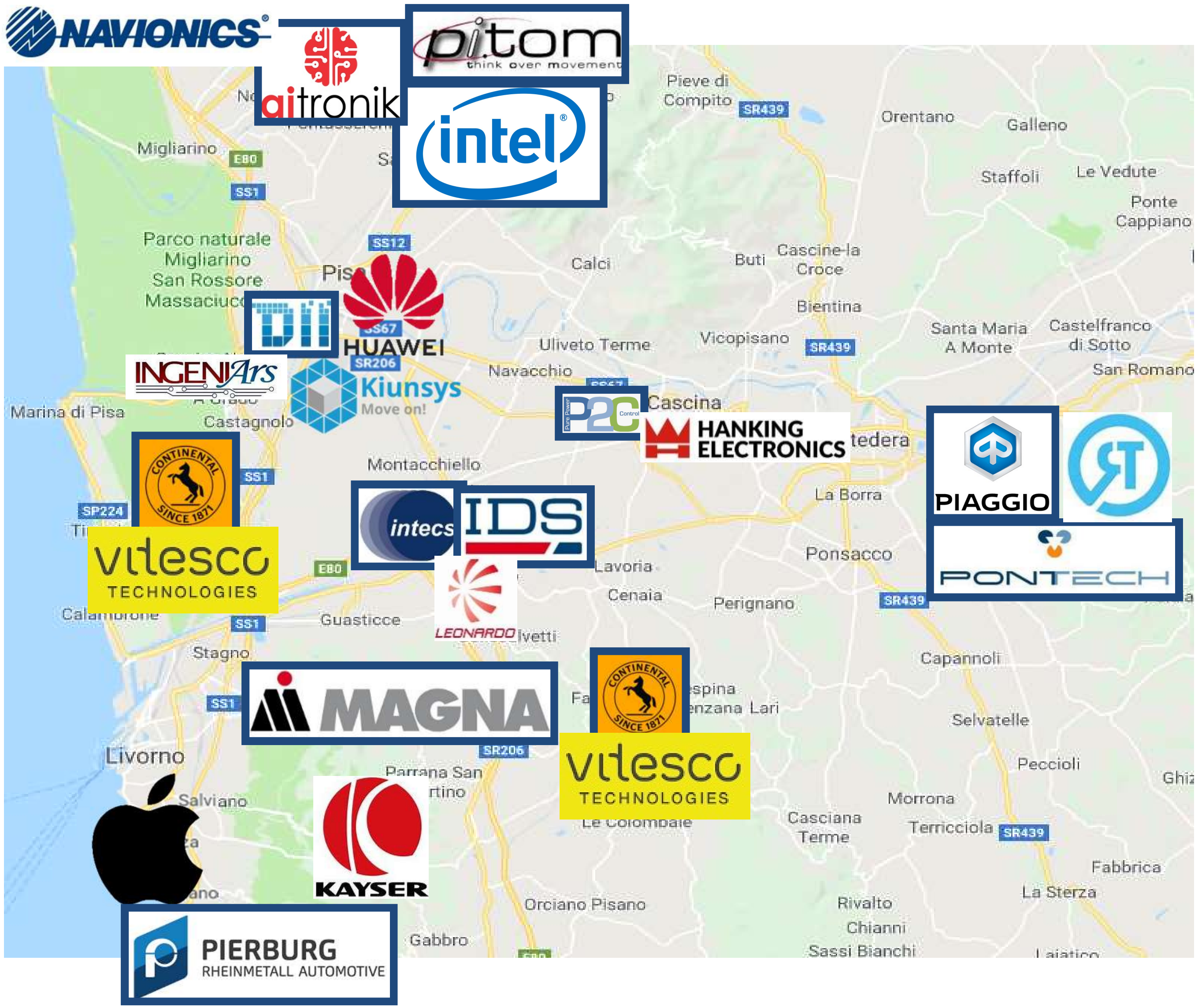
What is possible? a statistics of incidents, injured/died people in favour of ADAS

Beware of legal issue!!!!!

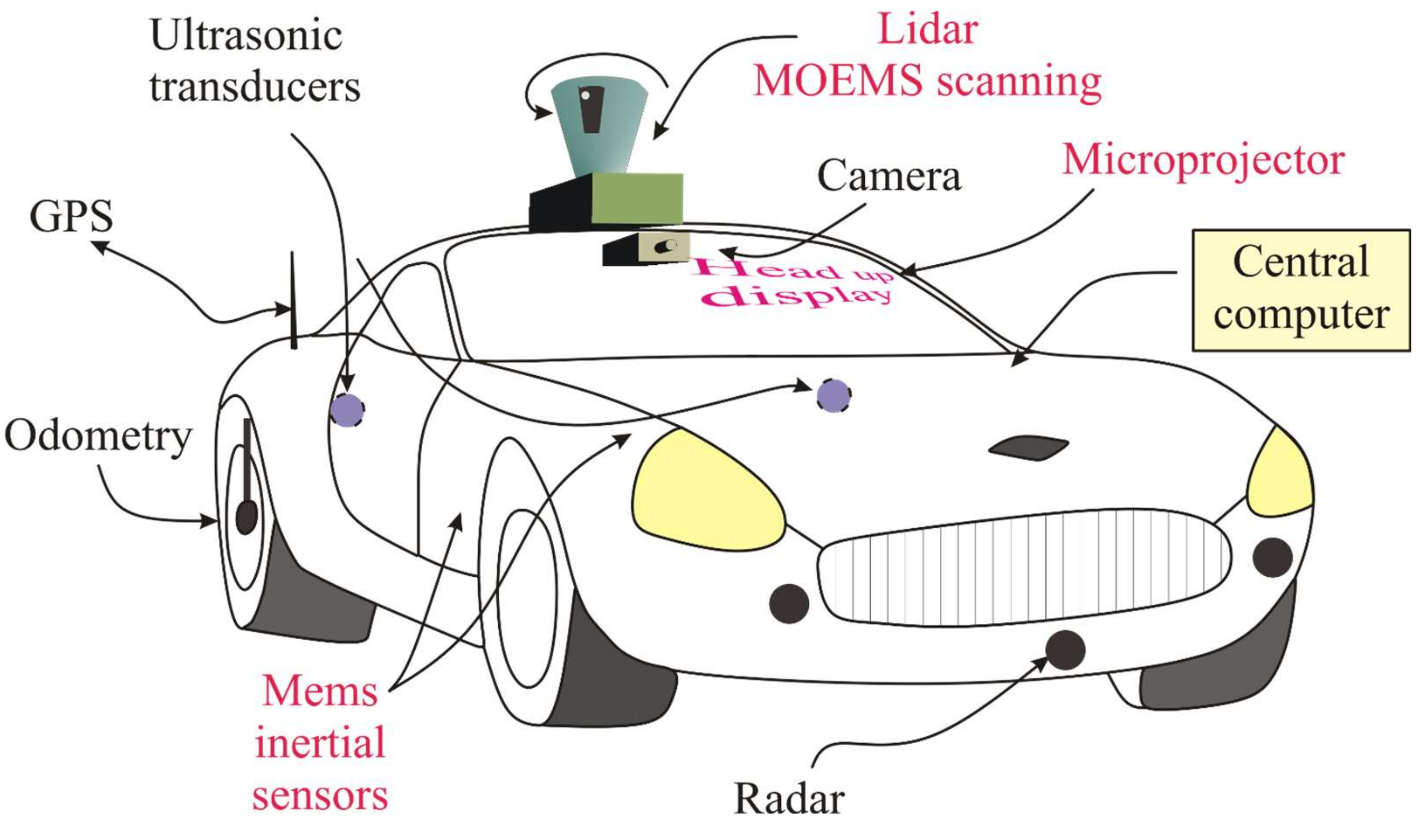
Beware of psychological issues!!!!!

Key issue: <u>robust & accurate measurement</u> of obstacles, environment, driver, car's dynamic/position

What about in the Pisa Area?



Sensing & Measurement Perspective



What?

obstacle detection

Where?

position and direction of cars and obstacles

When?

car to obstacle relative speed

Measurement Performance

range, **resolution** and **accuracy** of distance, angles & speed?

reliable (**uncertainty, repeatability**) measures in harsh environment ?

secure (**trusted, identified, private**) measures?

Vehicle as a platform for pervasive use of I&M

RF & mmWaves
(mmW Radar, 802.11p/bd V2X & 5G C-V2X, GNSS)

Sensors signal processing
(Image, Radar, Lidar, IMU,..& fusion in real-time)

Power Systems
(DC/DC converters, inverters, BMS
12V→48V→ 300V)

Low-power Analog & Mixed-signal ICs

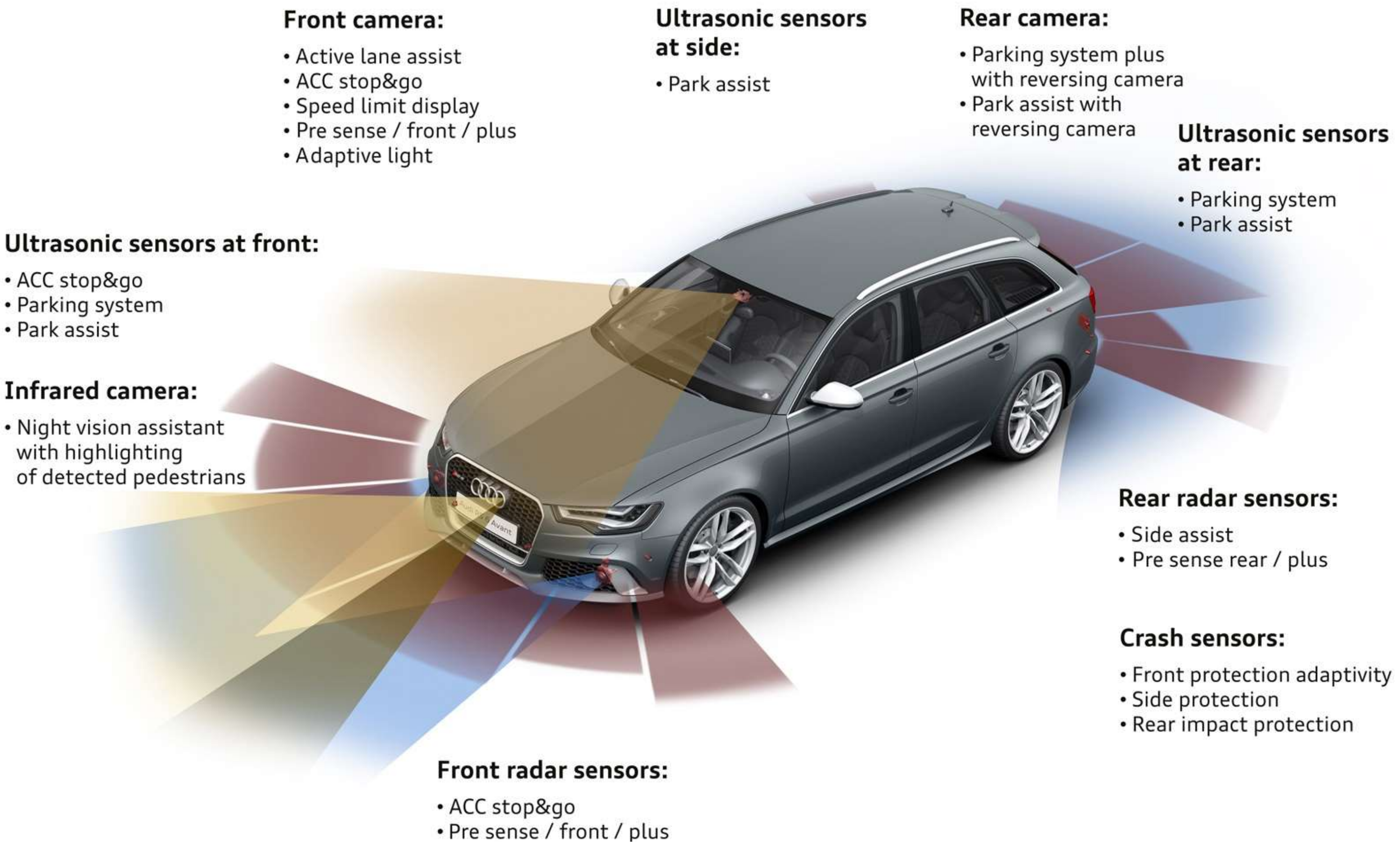
Sensors (device & technologies-MEMS/MOEMS)

Measurements for Predictive-diagnostic
(thermal, EMI/EMC, electrical, ageing, vibrations,..) for functional safety

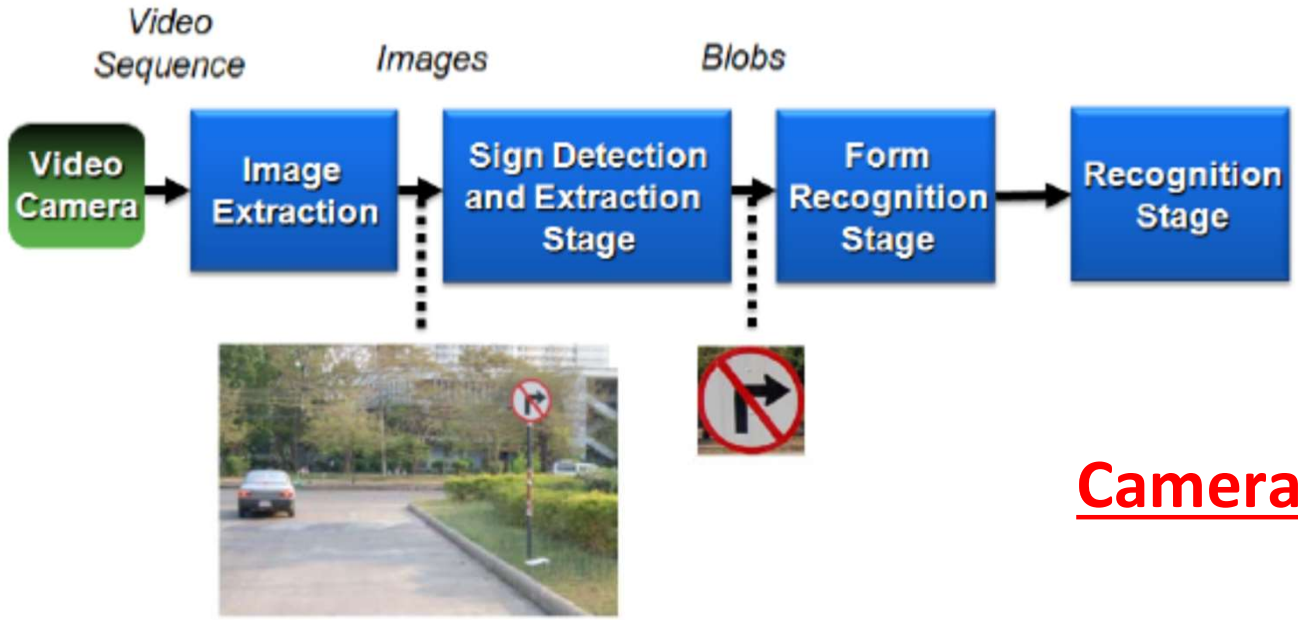
eHPC & memories (multi-core, deep-learning, high SIL in harsh environments)

ADAS: multi-disciplinary I&M research field

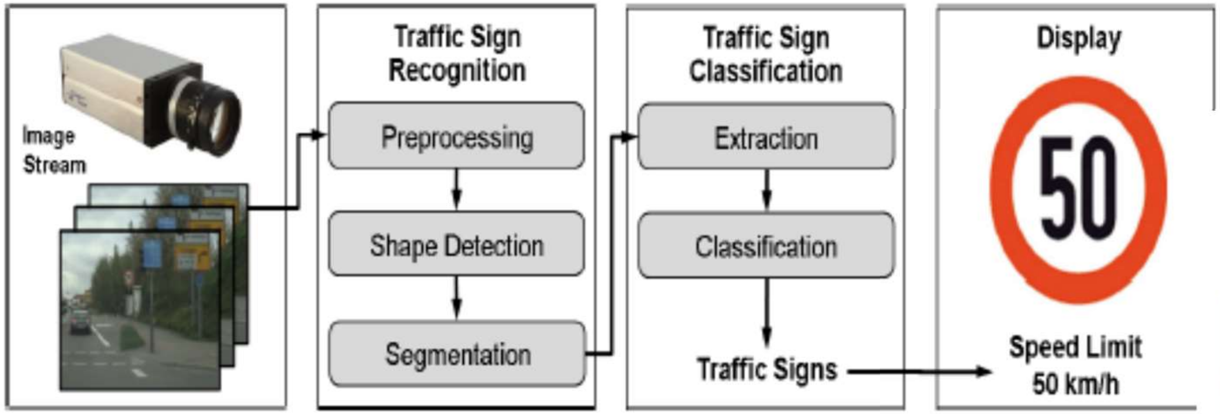
Sensors & acquisition instruments

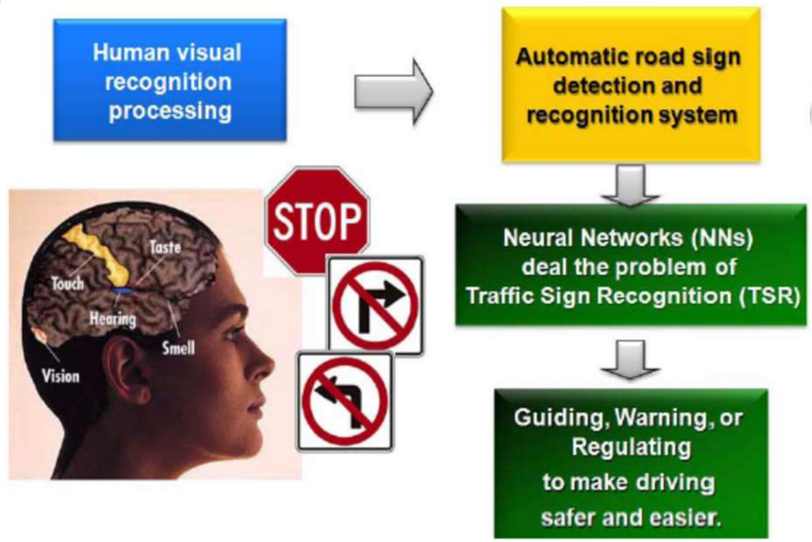


ADAS: multi-disciplinary I&M research field



Camera-based measurements

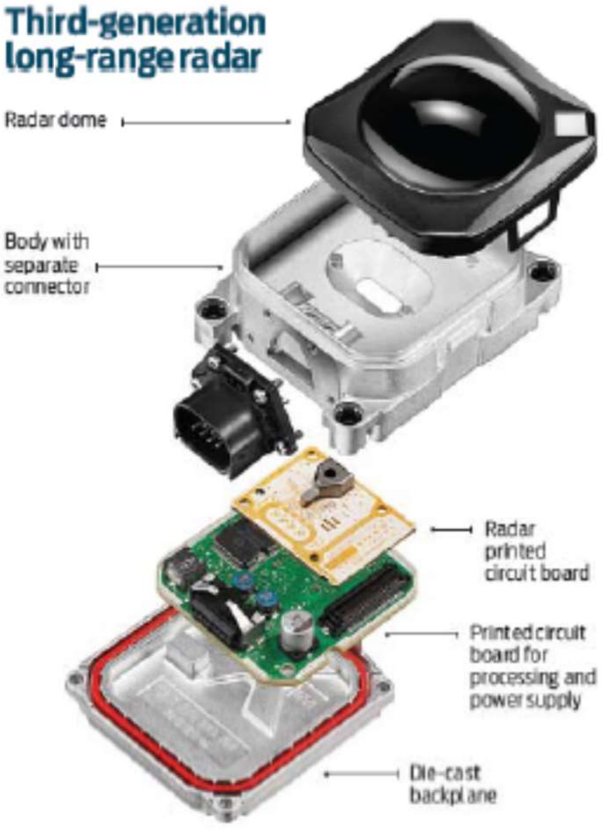




ADAS: multi-disciplinary I&M research field

Radar measurements and RF/mmW electronics/electromagnetics (10, 24, 77 GHz?)

active circuits (LNA, PA, PLL), passives (antenna, balun, filters) and technologies (GaN, GaAs, SiGe, CMOS SOI, metamaterials, nanotechnologies..)



Mixed-signal and digital electronics (ADC, DAC), real-time low-power baseband signal processing

Packaging

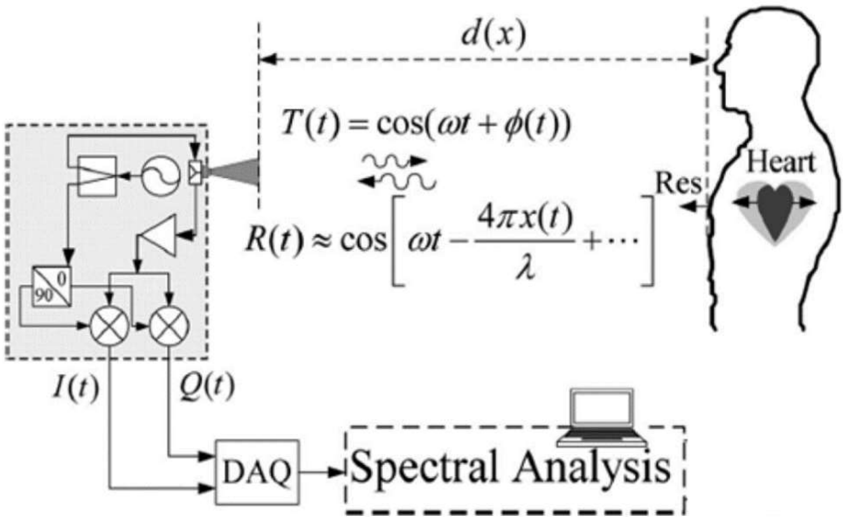
EMI/EMC

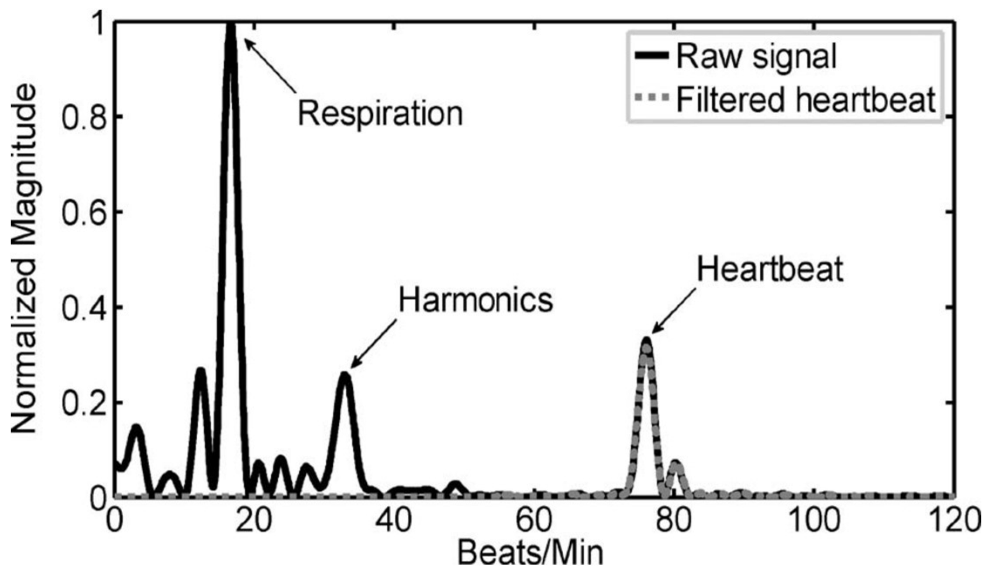
ADAS: multi-disciplinary I&M research field

Biometric measurements for driver's attention or fatigue detection

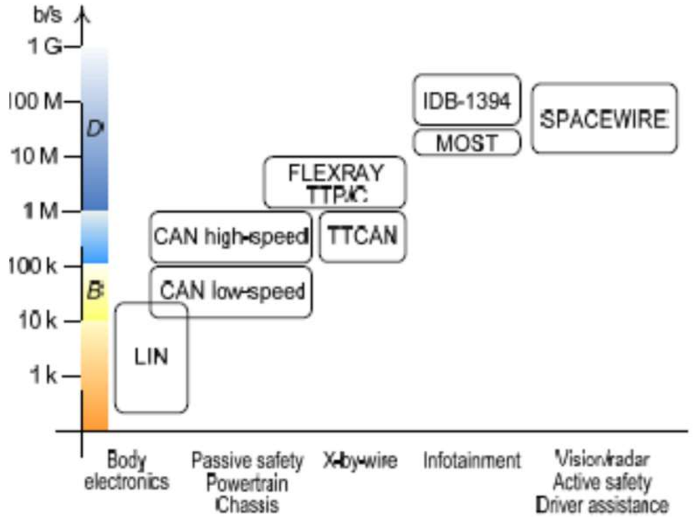
Driver drowsiness check by
HR variability (integrated radar for contactless measure)
Eye Opening Level monitoring (camera)
Galvanic Skin Response (smart wheel)

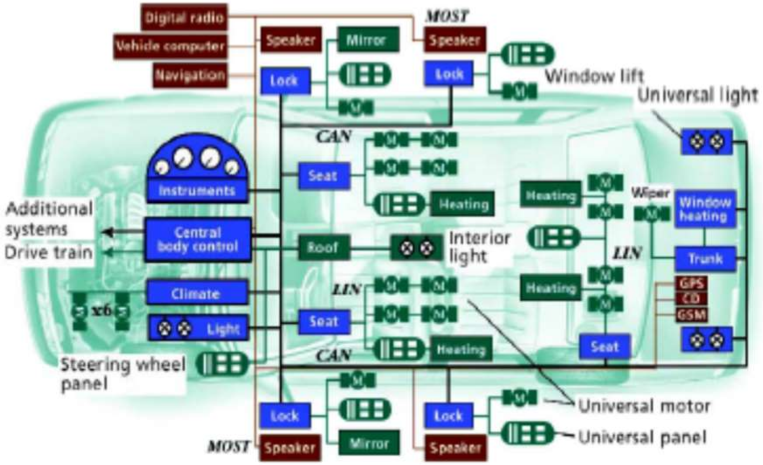
TIM2010, TIM2016



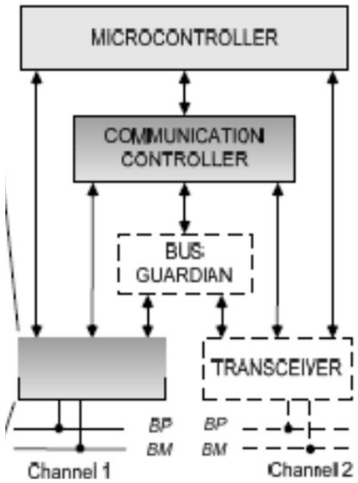


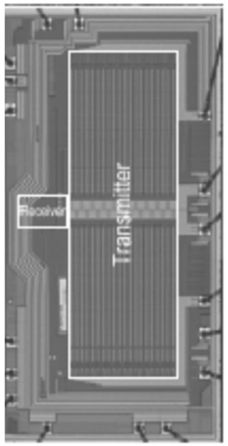
ADAS is a multi-disciplinary I&M research field



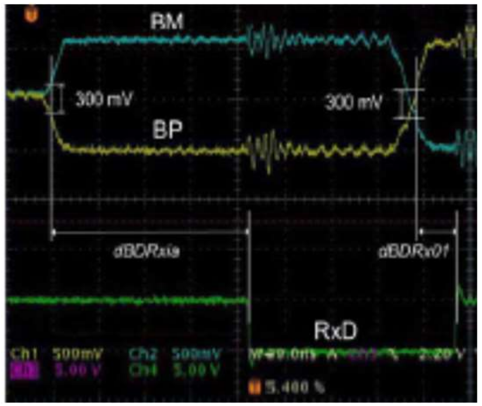


On-board diagnostic/control measurements & networking



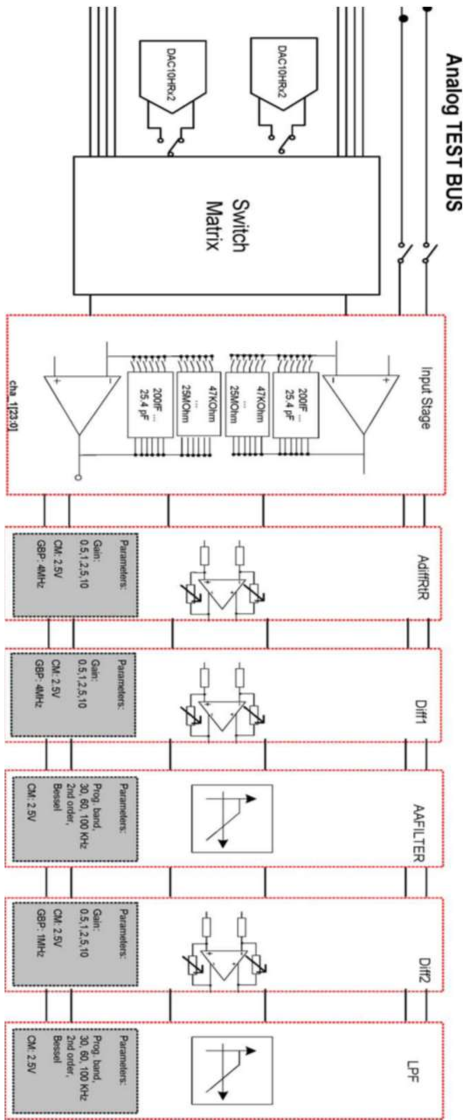


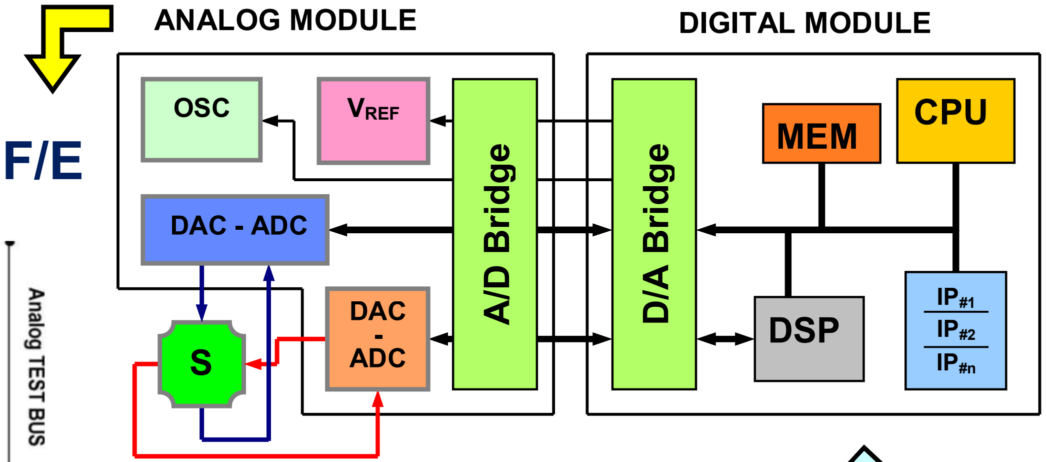
	min	max
Battery	-0.3 V	+58 V
Bus DC Voltage	-58 V	+58 V
Junction Temp. (TJ)	-40°C	+150°C
ESD (HBM)	-4 kV	+4 kV
Latchup immunity	-100 mA	100 mA



ADAS: multi-disciplinary I&M research field

Multi-channel config. analog F/E





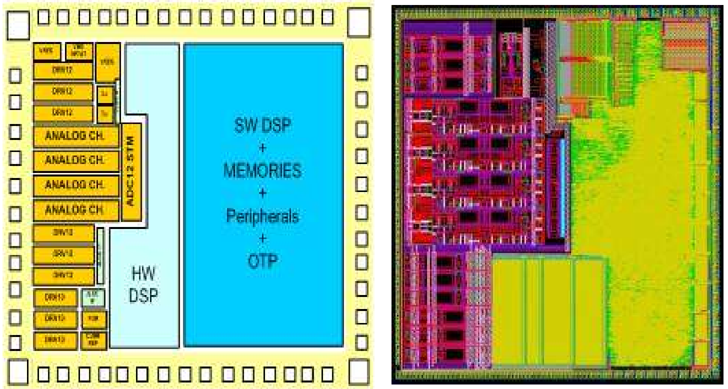
Intelligent Generic Sensor Interface

Generic Sensor

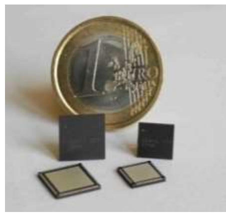
- **temperature**
- **speed**
- **pressure**
- **acceleration**
- **angular speed**
- **gas ……**

Automotive, Space, Industrial

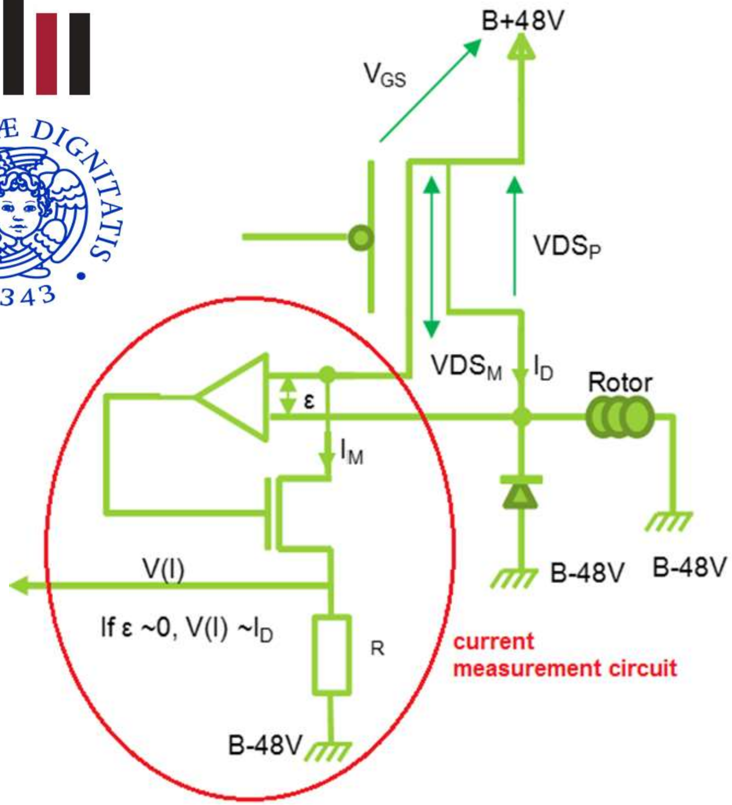
2 IEEE TIM in 2011, IEEE TIM16

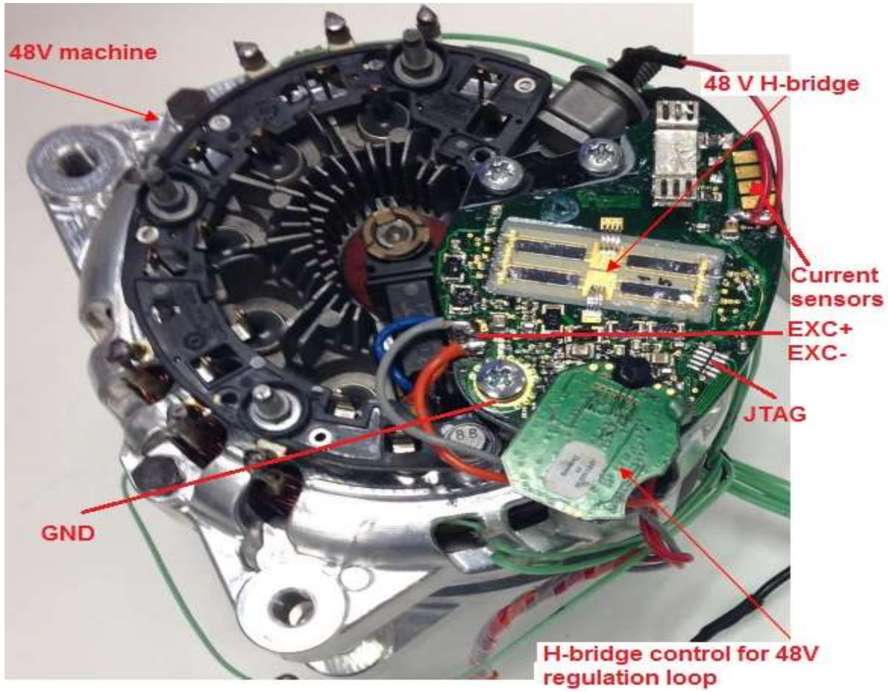


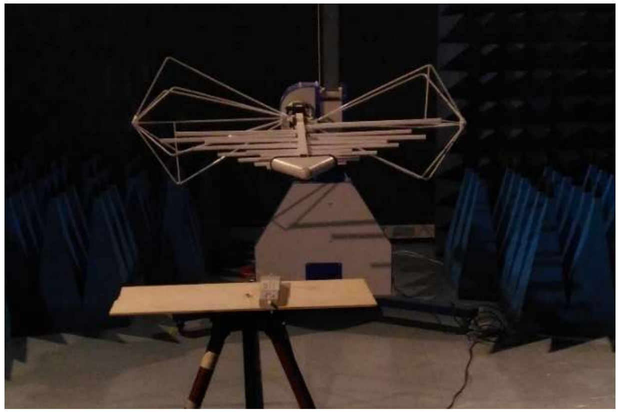
Proven in real-products (SD41x)

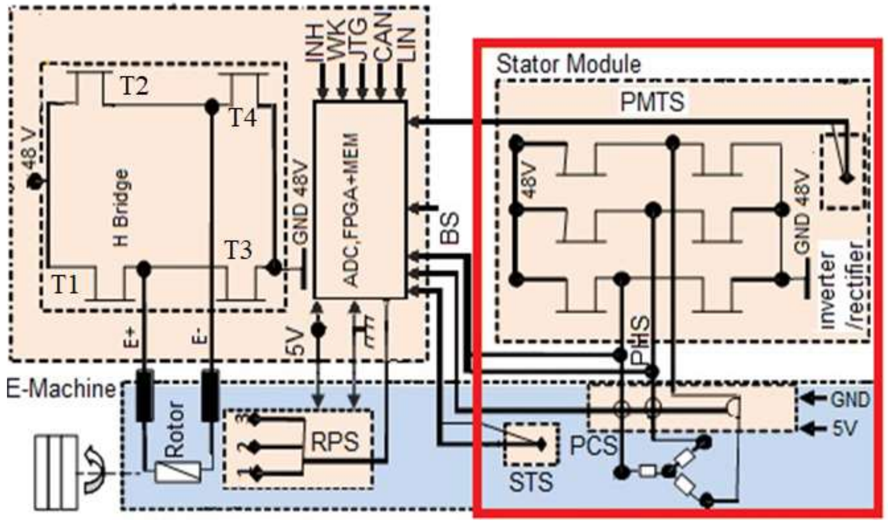


Integrated measurements of power systems

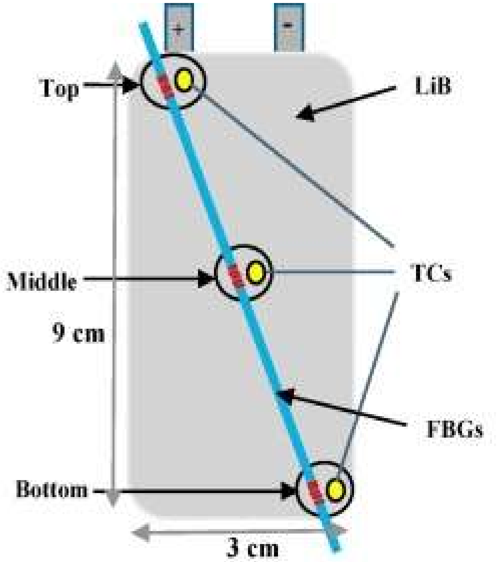


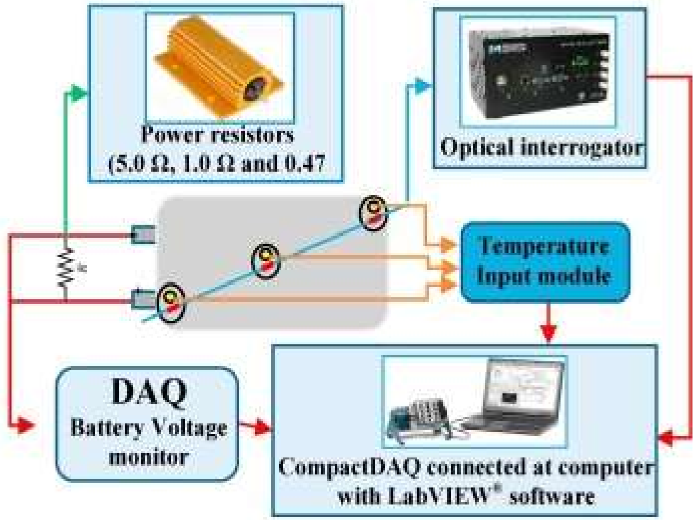


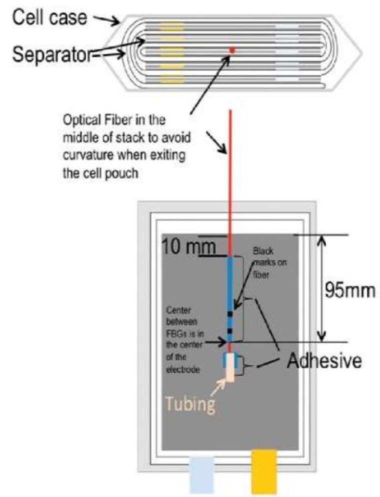




Optical sensing exploited for safe batteries



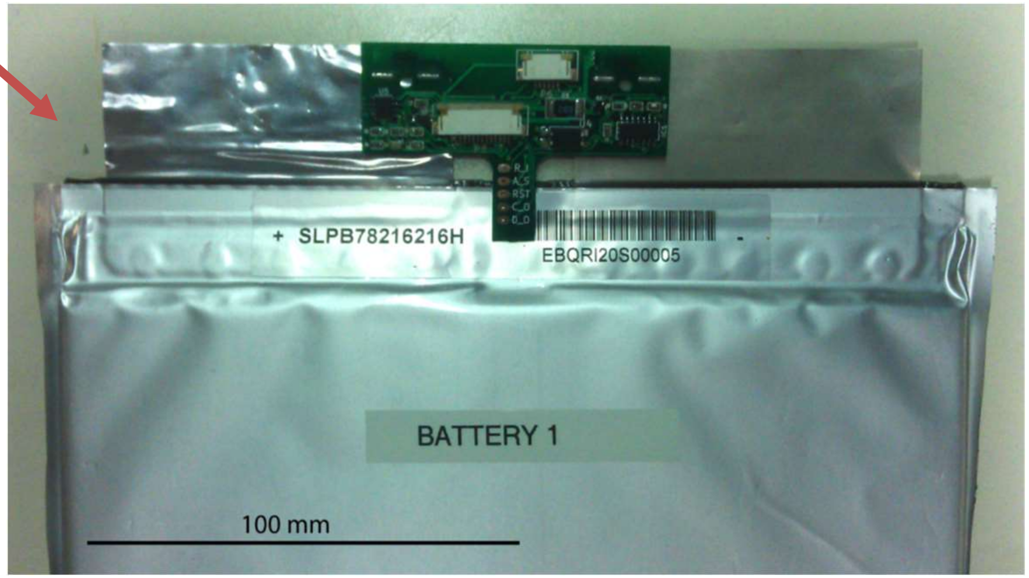




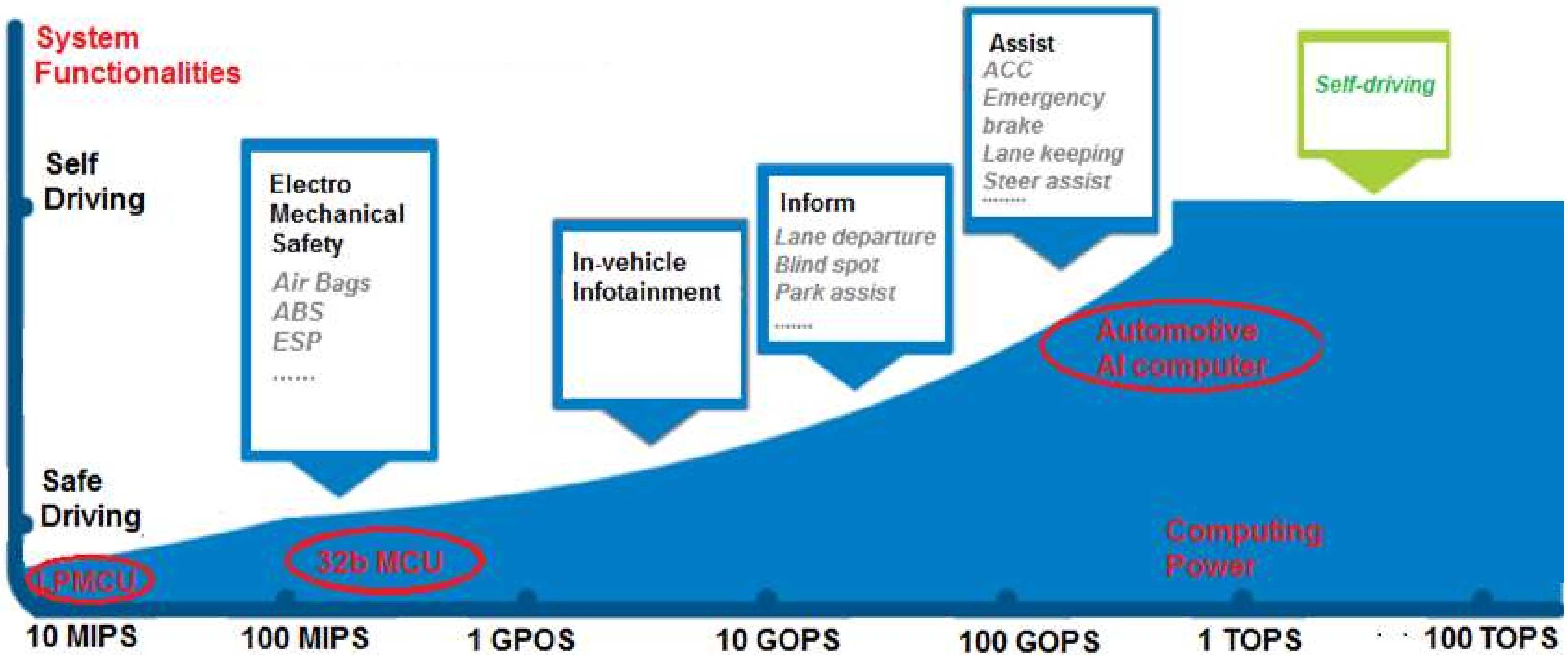
Optical fibers (exploiting Fiber Bragg grating) used for distributed strain, temperature and pressure measurements Challenge→ SiliconPhotonics integration of the optical interrogator

Beyond the **State of Art** of strain gauge, thermistors & hall sensors

IN SUPREMÆ DIGNITATIS 1343

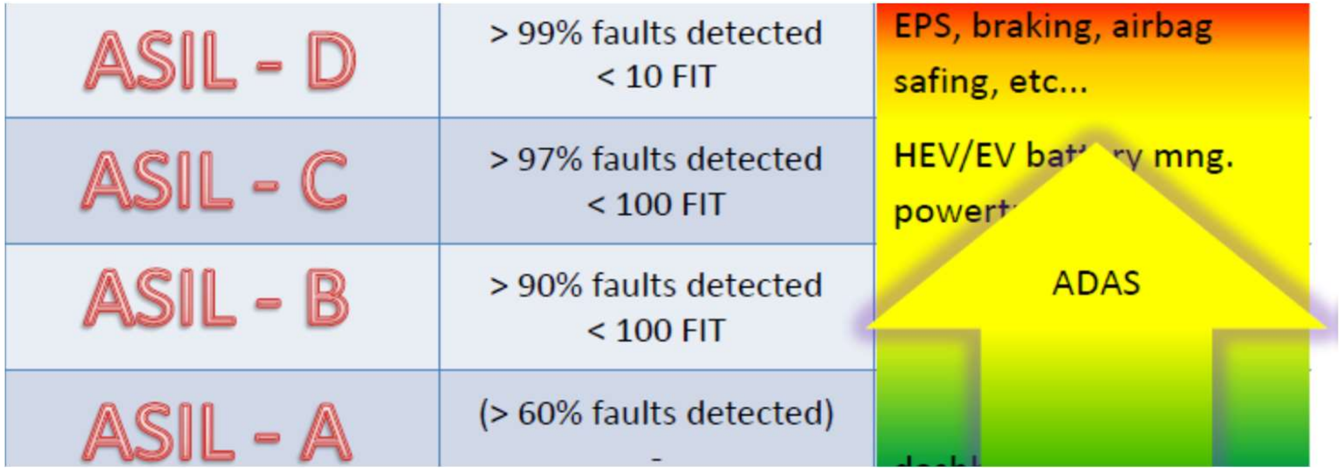


ADAS: multi-disciplinary I&M research field

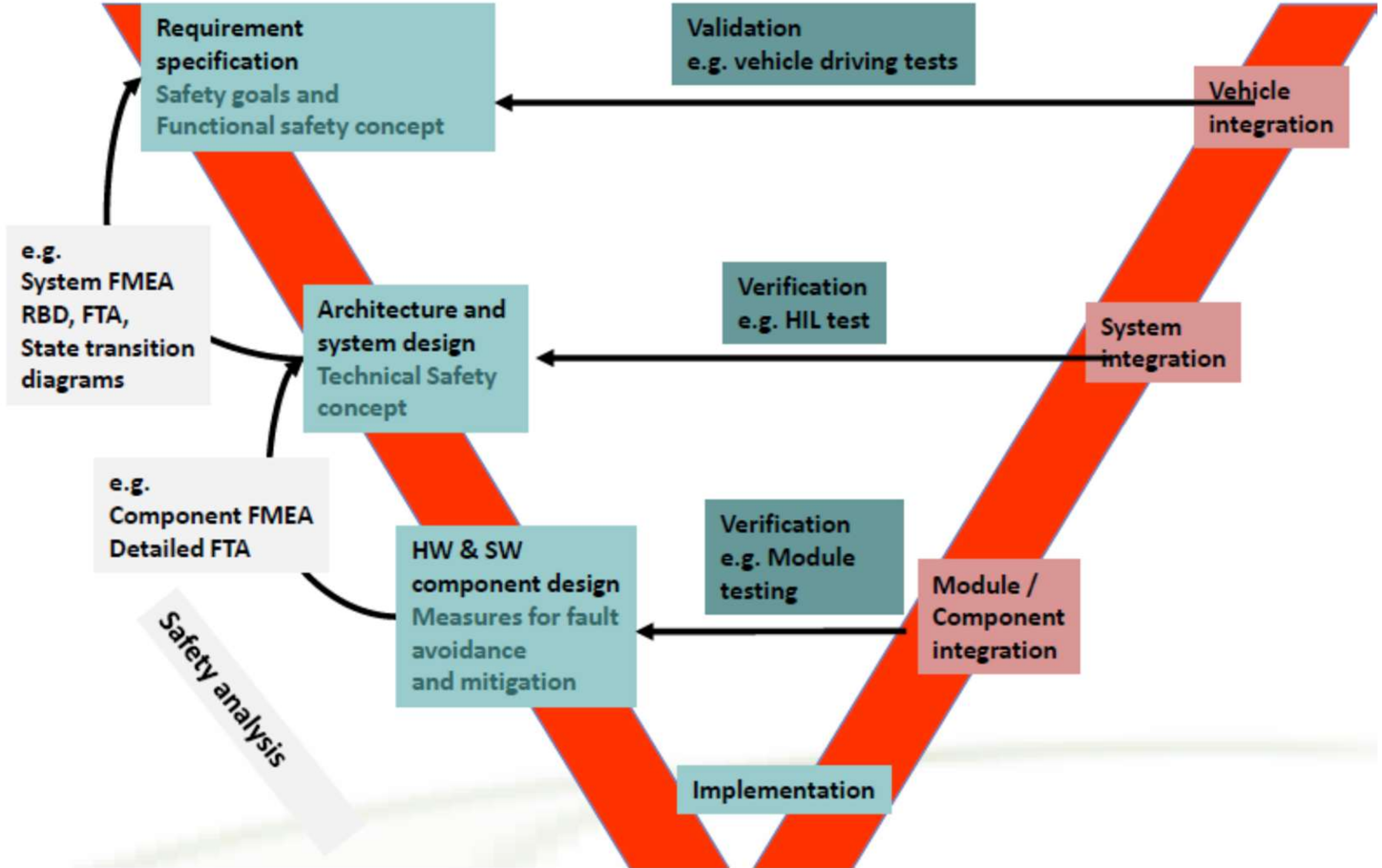


State-of-art is 32b MCU with high-SIL Increase in system but functionalities towards autonomous driving
will require multi-core platforms with capability in TOPS domain
(NVIDIA Xavier claims 30 TOPS, Drive AGX Pegasus claims 160 TOPS, Tesla FSD claims 144 TOPS)

ADAS: multi-disciplinary I&M research field



ASIL - D	> 99% faults detected < 10 FIT	EPS, braking, airbag safing, etc...
ASIL - C	> 97% faults detected < 100 FIT	HEV/EV bat ry mng. powert
ASIL - B	> 90% faults detected < 100 FIT	ADAS
ASIL - A	(> 60% faults detected)	



Functional safety
ISO26262
& Verification

Outline

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- Remote sensing (Radar, Lidar) in smart vehicle & ITS
- Sensing technology for navigation
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- Arithmetic accuracy for DNN acceleration (Posits in EPI)
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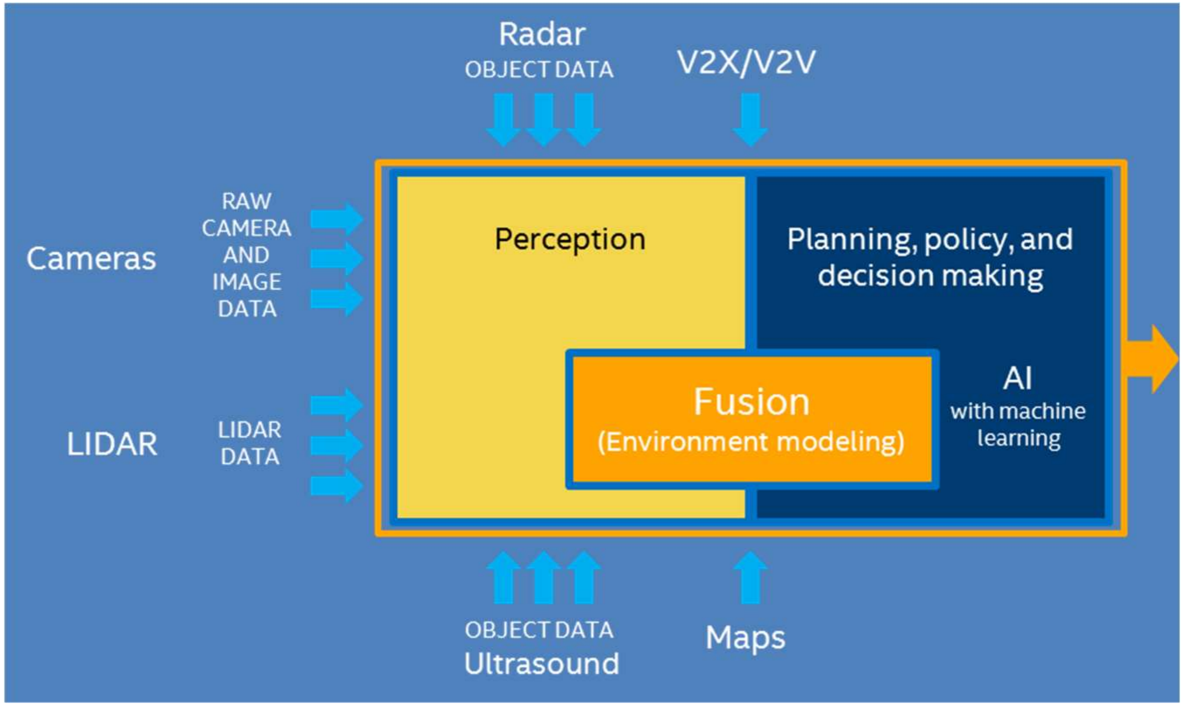
Context-awareness vehicle perception

Autonomous vehicle perception based on multi-sensor fusion:
VideoCameras, Lidar, Radar, Ultrasounds

Fusion with V2X and V2V information



Level of autonomy (state of art)

SAE Level	Name	Narrative Definition	Execution of Steering and Acceleration/ Deceleration	Monitoring of Driving Environment	Fallback Performance of Dynamic Driving Task	System Capability (Driving Modes)
Human driver monitors the driving environment						
0	**No Automation**	The full-time performance by the human driver of all aspects of the dynamic driving task, even when enhanced by warning or intervention systems	Human Driver	Human Driver	Human Driver	N/A
1	**Driver Assistance**	The driving mode-specific execution by a driver assistance system of either steering or acceleration/deceleration using information about the driving environment and with the expectation that the human driver perform all remaining aspects of the dynamic driving task	Human Driver and System	Human Driver	Human Driver	Some Driving Modes
2	**Partial Automation**	The driving mode-specific execution by one or more driver assistance systems of both steering and acceleration/deceleration using information about the driving environment and with the expectation that the human driver perform all remaining aspects of the dynamic driving task	**System**	Human Driver	Human Driver	Some Driving Modes
Automated driving system ("system") monitors the driving environment						
3	**Conditional Automation**	The driving mode-specific performance by an automated driving system of all aspects of the dynamic driving task with the expectation that the human driver will respond appropriately to a request to intervene	System	**System**	Human Driver	Some Driving Modes
4	**High Automation**	The driving mode-specific performance by an automated driving system of the dynamic driving task, even if a human driver does not respond appropriately to a request to intervene	System	System	**System**	Some Driving Modes
5	**Full Automation**	The full-time performance by an automated driving system of all aspects of the dynamic driving task under all roadway and environmental conditions that can be managed by a human driver	System	System	System	**All Driving Modes**

Context-awareness vehicle perception

Radar (Master of Motion Measures)

Active EM sensor. Robust in harsh conditions. Long Range. Limited accuracy

LRR4, range: up to 250 m, ± 5 m/s, accuracy: ±0.1 m, ±0.1 m/s H/V-FOV $30^0/5^0$

Lidar (Master of 3D mapping)

Active Light sensor. Mid Range, good accuracy. 360^0 H-FOV

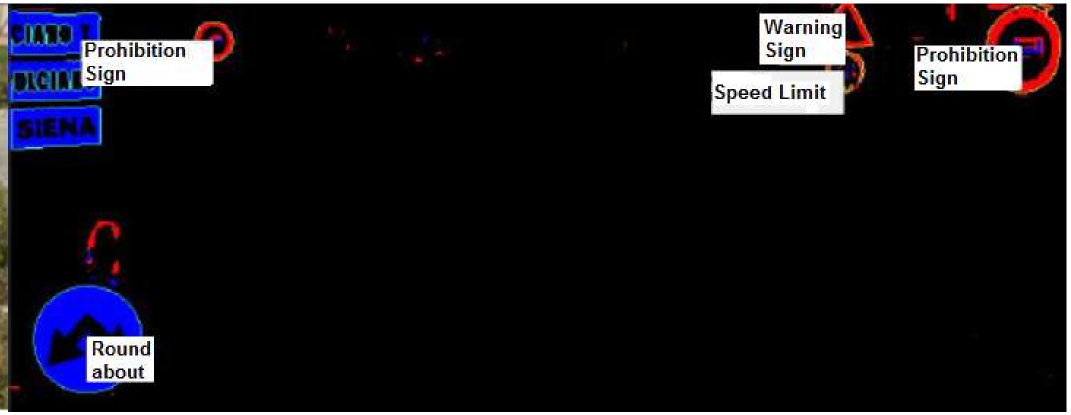
HDL-32/64: up to 100 m, 0.02 m and 0.1^0 accuracy. Limited by cost

Velodyne

Camera (Master of Classification)

Passive. See colors & textures. Cheap. IR sensors needed for night vision

JRTIP2016 640x480 automotive camera & FPGA, recognition at 15 m, <100 ms



Real-time Radar distance/speed measurements

X-band Radar for harbor surveillance information system

- Detection & tracking of ships/yachts ingress/egress
- Long distance up to 1.5 km
- 1 Radar for a small harbor
- Network of Radars for large port areas (increase the covered area)
- 1 Tx + 1 Rx speed and distance estimation
- Multiple-channels for speed, distance, angle estimation
- Custom microwave board for imaging sensor front-end in X-band
- DSP via software on a GPP for off-line analysis
- **Real-time DSP to be implemented on FPGA or GPU, FPGA mandatory if power efficiency and compact size are key issues**

Collaboration with CNIT/RASS (Berizzi, Martorella, Lischi, Massini)

Real-time Radar distance/speed measurements

X-band Radar for railway crossing safety and parking/road crossing safety

- Obstacle detection on a railroad or urban road crossing
- Up to 4 Radar nodes for high SIL (Safety Integrity Level) in automated railroad crossing
- Max detection distances up to 200-300 m
- 1 Tx + 1 Rx for speed and distance estimation
- 1 Tx + 3 Rx for speed, distance, azimuth/elevation angle estimation
- **Real-time power-efficient and compact Radar image processing on FPGA platforms**
- **Custom microwave board for X-band transceiver**

Collaboration with I.D.S. spa

IDS
INGEGNERIA DEI SISTEMI

X-band FMCW Radar vs. LIDAR

	Max Distance	Resolution	Power	Cost
HDL-32 [1]	100 m	2 cm	12 W	10000 USD
VLP-16 [2]	100 m	3 cm	8 W	<8000 USD
This work (harbour)	1.5 Km	37.5 cm	12 W	< 1000 USD
This work (railroad&urban road crossing, parking)	300 m	37.5 cm	< 8 W (5 Ch) < 3 W (2 Ch)	<500 USD

Radar vs. Lidar or Video (CMOS or CCD) sensors is more robust for bad weather and bad light conditions

Radar vs. Lidar allows for long ranges at lower cost

Research trends on LIDAR

Supplier	Type	HFOV in deg	VFOV in deg	Scanning Freq.	Cost	Range
Osram/Infineon/ Innoluce	Scanning,MEMS	120, (res. 0.1)	20 (res. 0.5)	<2kHz	40 USD	200m
Quanergy	Scanning, OPA	120	120	N/A	250 USD	150m
Velodyne (VLP-16)	Scanning mechanical	360 (res 0.1-0.4)	30 (res. 2)	5-20Hz	7999 USD	300m
LeddarTech (LeddarVu)	Solid-state	100	0.3-3	N/A	750 USD	60m
Microvision(PSE-0400Li-101)	Scanning MEMS	90 (res. 0.18)	30 (res. 0.08)	30Hz	N/A	15m

Lidar used by Google's autonomous car → 70000 USD!!!!

Low cost Lidars are under development

Micro-mirrors (MOEMS) used for low-cost scanning (without mechanical/electric-motor parts)

Research on low-cost laser

Velodyne

Research on low-cost Lidar

Supplier	Type	HFOV in deg	VFOV in deg	Scanning Freq.	Cost	Range
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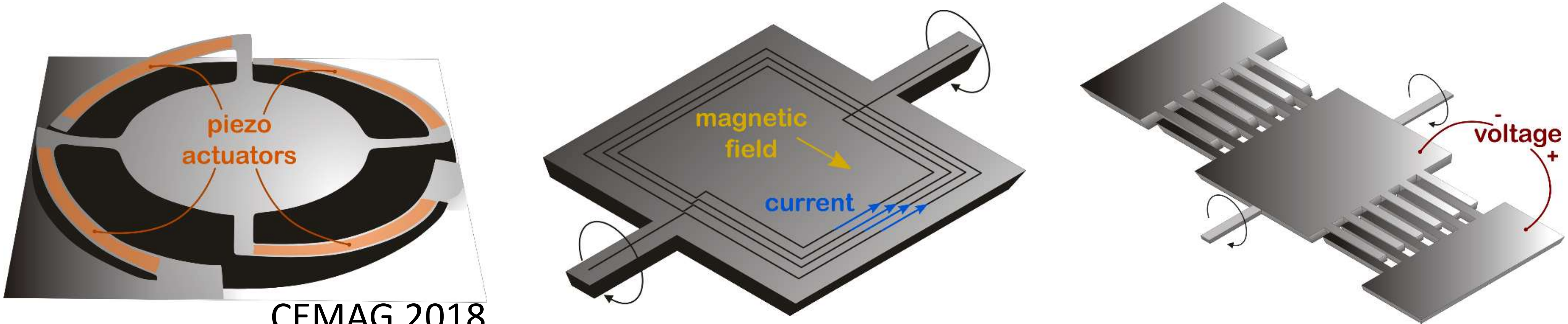
LeddarTech (LeddarVu)	Solid-state	100	0.3-3	N/A	750 USD	60m
ASC (Peregrine)	Solid-state	up to 60 (res. 0.5)	up to 15 (res. 0.5)	20 Hz	N/A	N/A
Microvision(PSE-0400Li-101)	Scanning MEMS	90 (res. 0.18)	30 (res. 0.08)	30Hz	N/A	15m



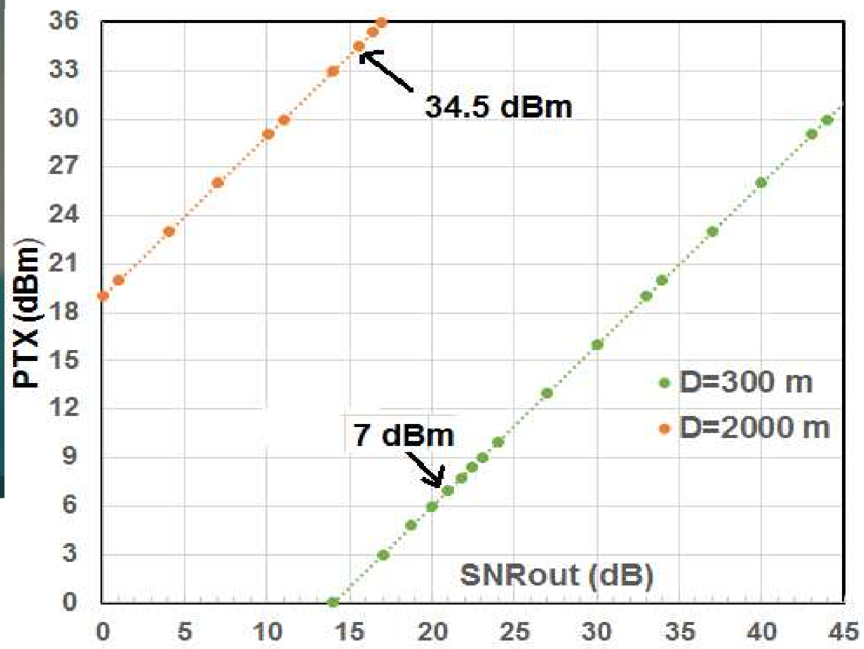
CEMAG 2018

Image by A. Nannini

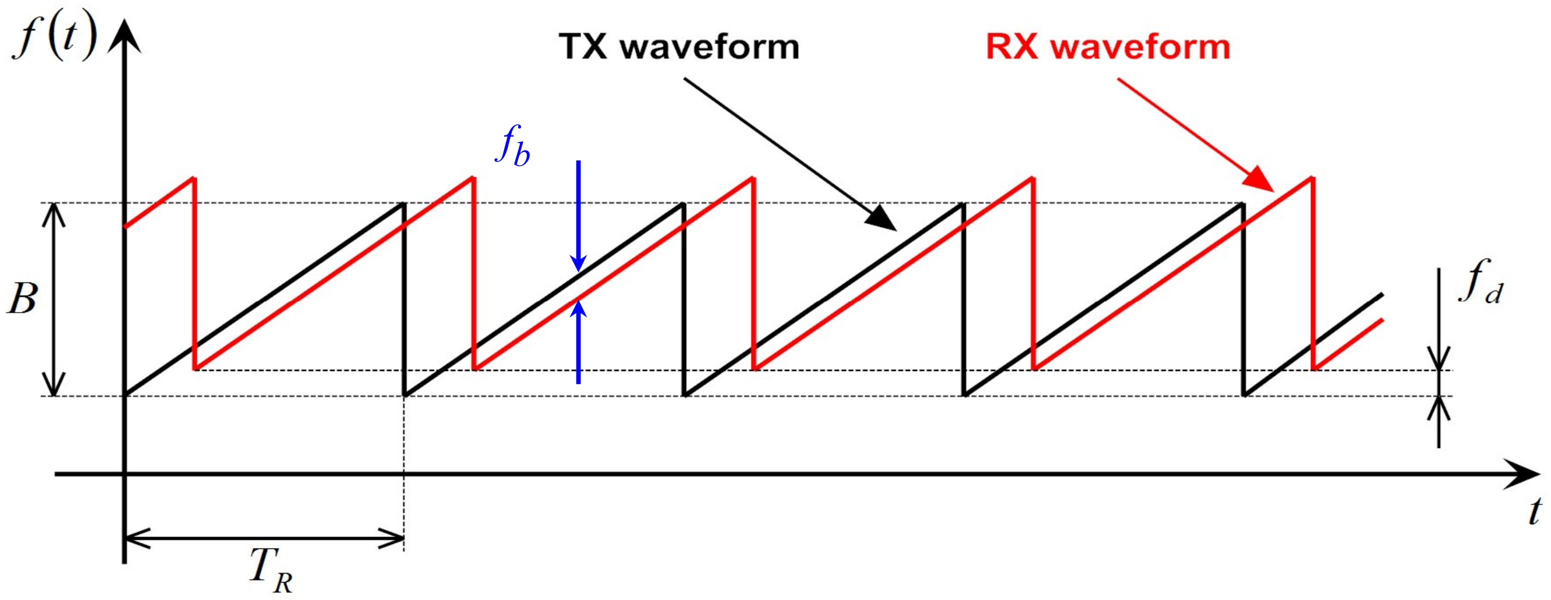
3D scanning Lidar using MOEMS micro-mirrors: scanning micro-mirrors with three different actuations schemes: (top) electrostatic, (center) magnetic, (bottom) piezoelectric

Specification for a transport-surveillance Radar

Max. distance coverage	*300 m, 2000 m*
Range resolution	*40 cm*
Max speed	*40 m/s*
Target RCS	*≈ $1 \div 10^4$ m^2*
SNR after DSP	*> 15 dB*



Linear-FMCW waveform: moving target



For a moving target:

$$R(t) \cong R_0 + v_r t$$

Doppler frequency: $$f_d = -\frac{2v_r}{\lambda_0}$$

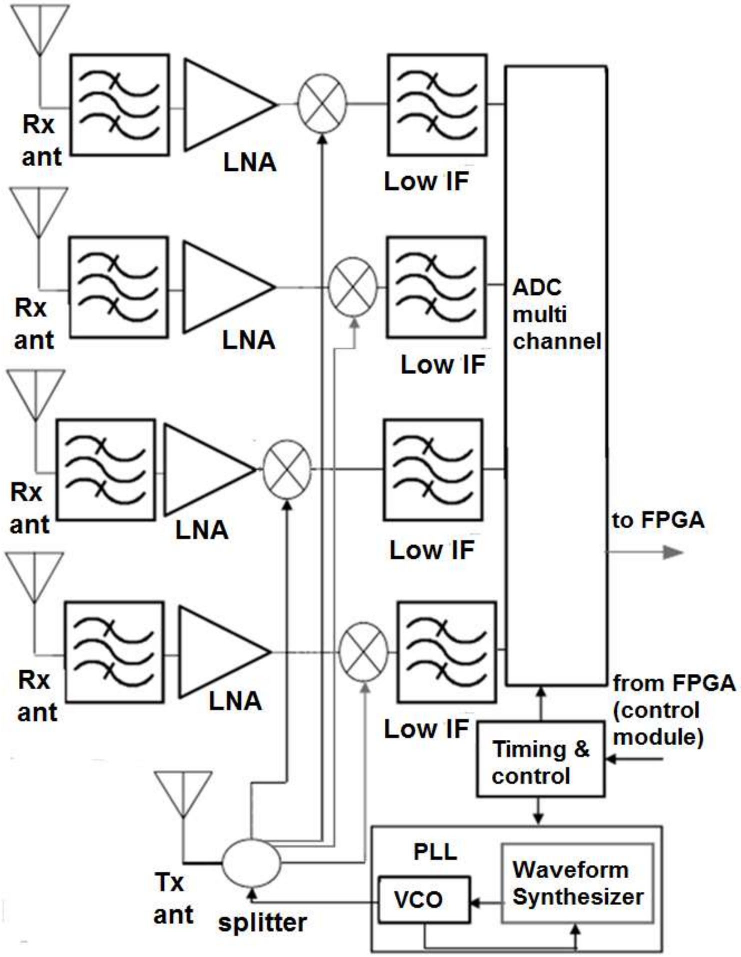
Range frequency: $$f_r = \alpha\tau = \frac{B}{T_R}\frac{2R_0}{c}$$

Beat frequency: $$f_b = f_r + f_d$$

Range-Doppler coupling effect

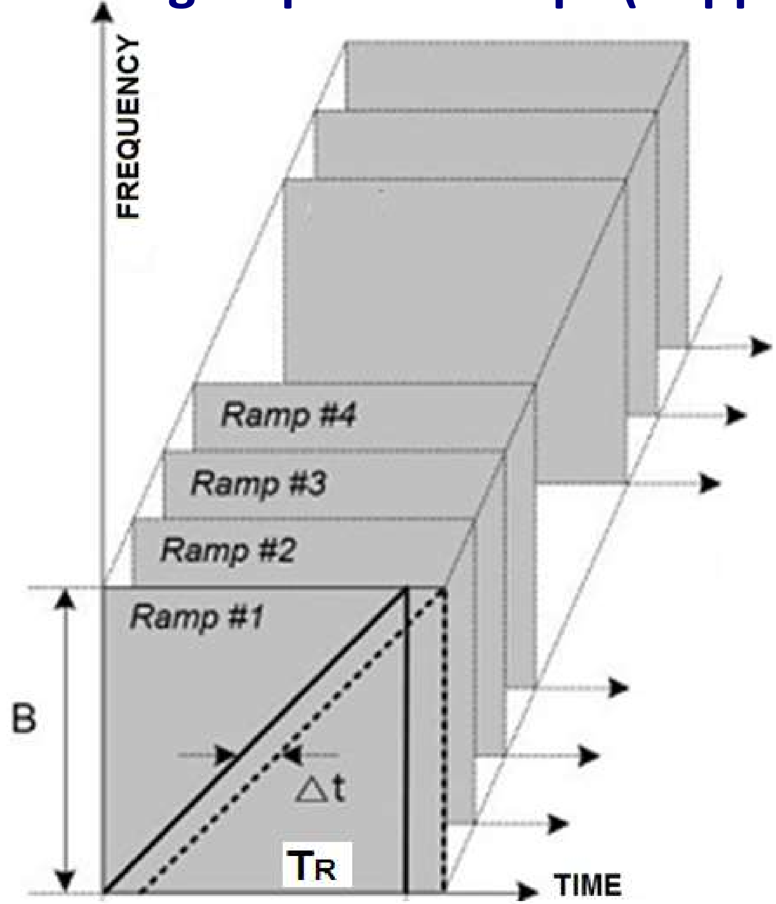
X-band Radar transceiver architecture

Scalable number of RX channels



2D FFT frequency analysis

- for each sweep (range)
- for each group of M ramps (doppler)

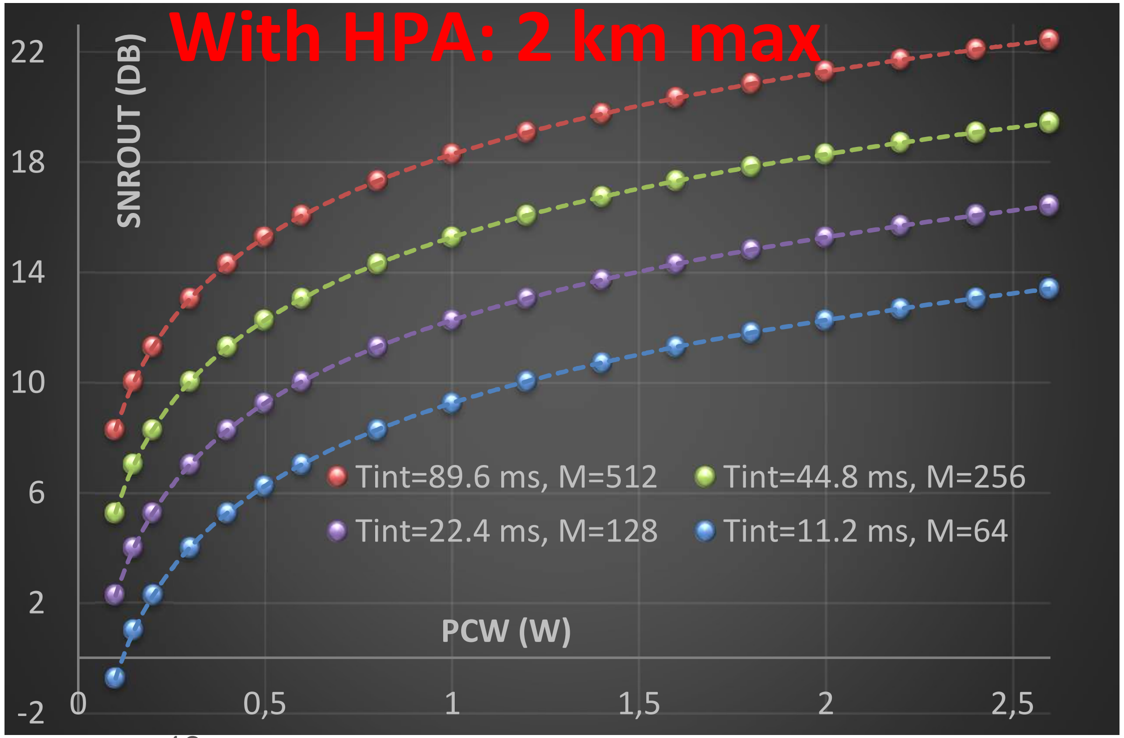


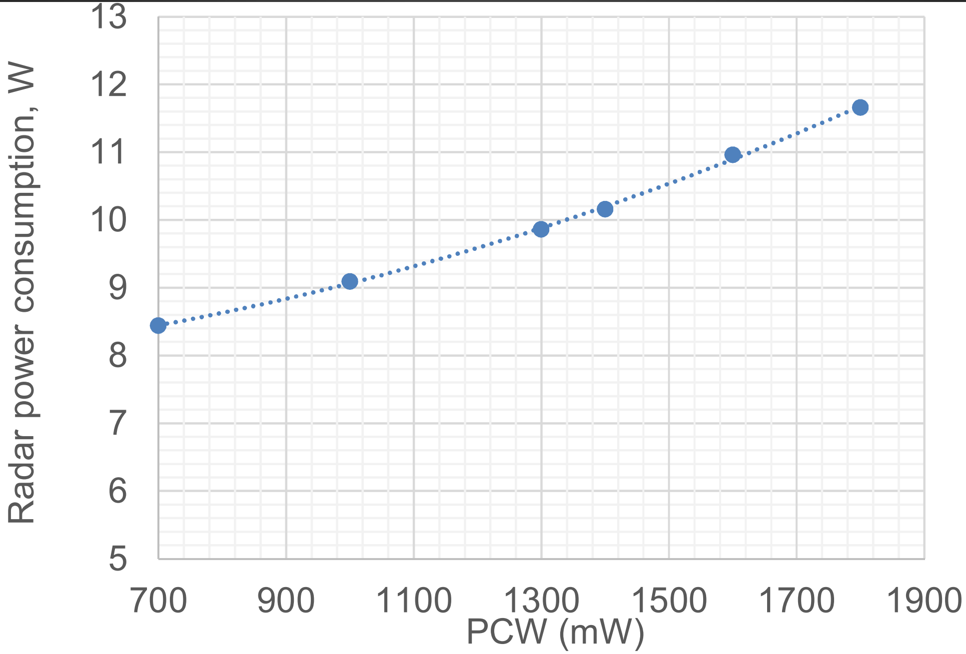
High-power stage HPA (34.5 dBm Pcw) to reach 2 Km

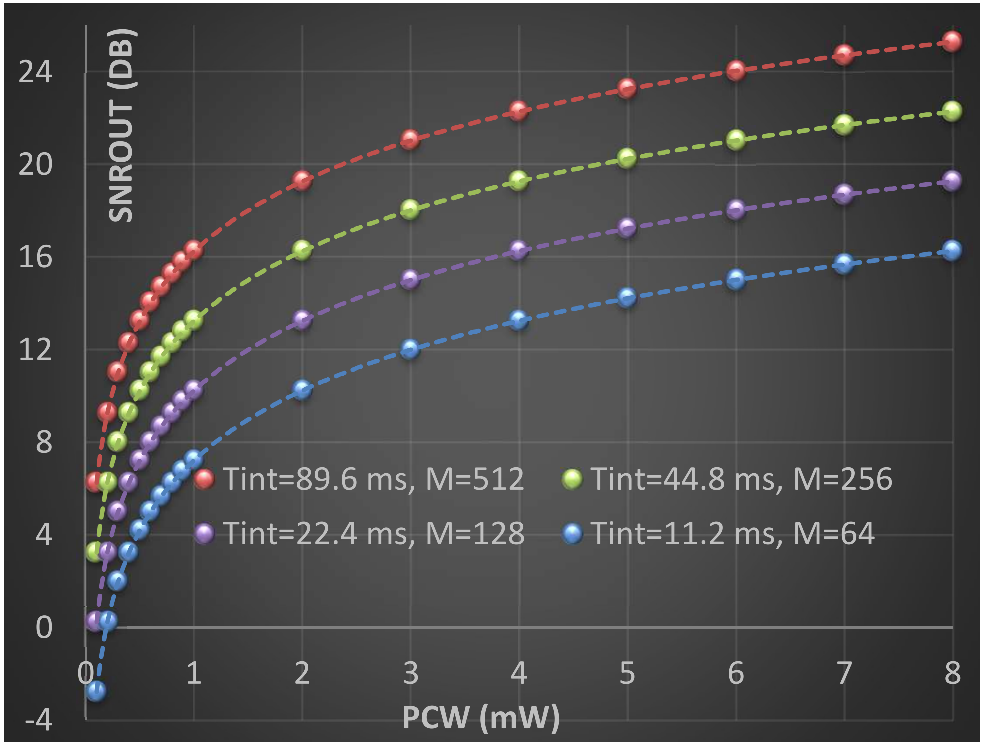
HPA by-passed (7 dBm Pcw) for low-power applications with 300 m target

Received SNR vs. Pcw

With HPA: 2 km max

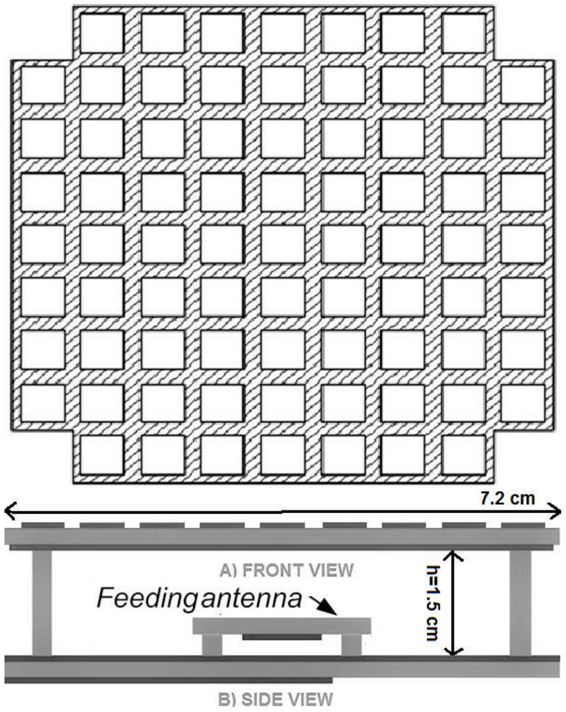




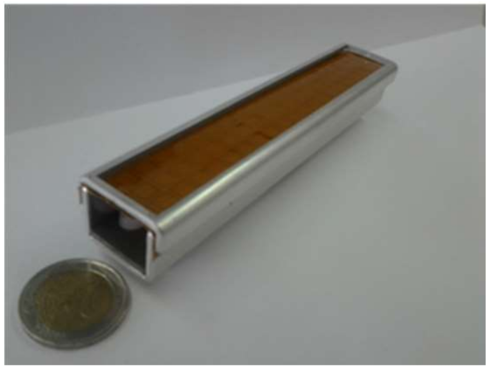


Without HPA: 300 m max

Fabry-Perot resonating antenna

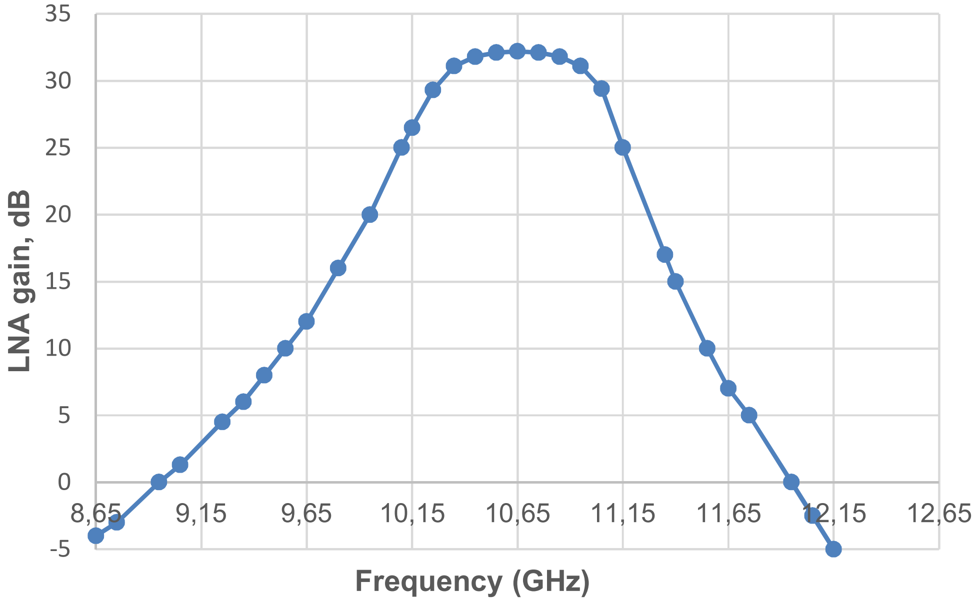


Prototype developed by the Electromagnetic fields and microwaves Lab. of the Department of Information Engineering of the University of Pisa.

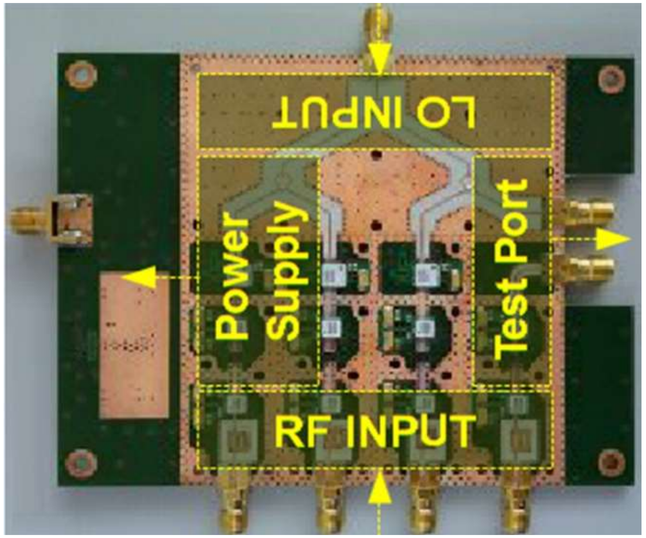


Central frequency	10.65 GHz
Bandwidth	300 MHz-500 MHz
Transmitted power	up to 33 dBm
System losses	8 dB
Noise figure	4.2 dB
SFDR	65 dBc
Sampling frequency	Up to 46 MS/s
ADC resolution	12 bit/14 bit
Antenna technology	Fabry-Perot resonator
Antenna polarization	H-linear
Antenna azimuth HPBW	60°
Antenna elevation HPBW	20°
Antenna gain	13 dBi
Receiving channels	1 to 4

Receiver with COTS LNA (from Hittite, now Analog Devices) & Microwave Board



Gain (S21) of the LNA and input filter

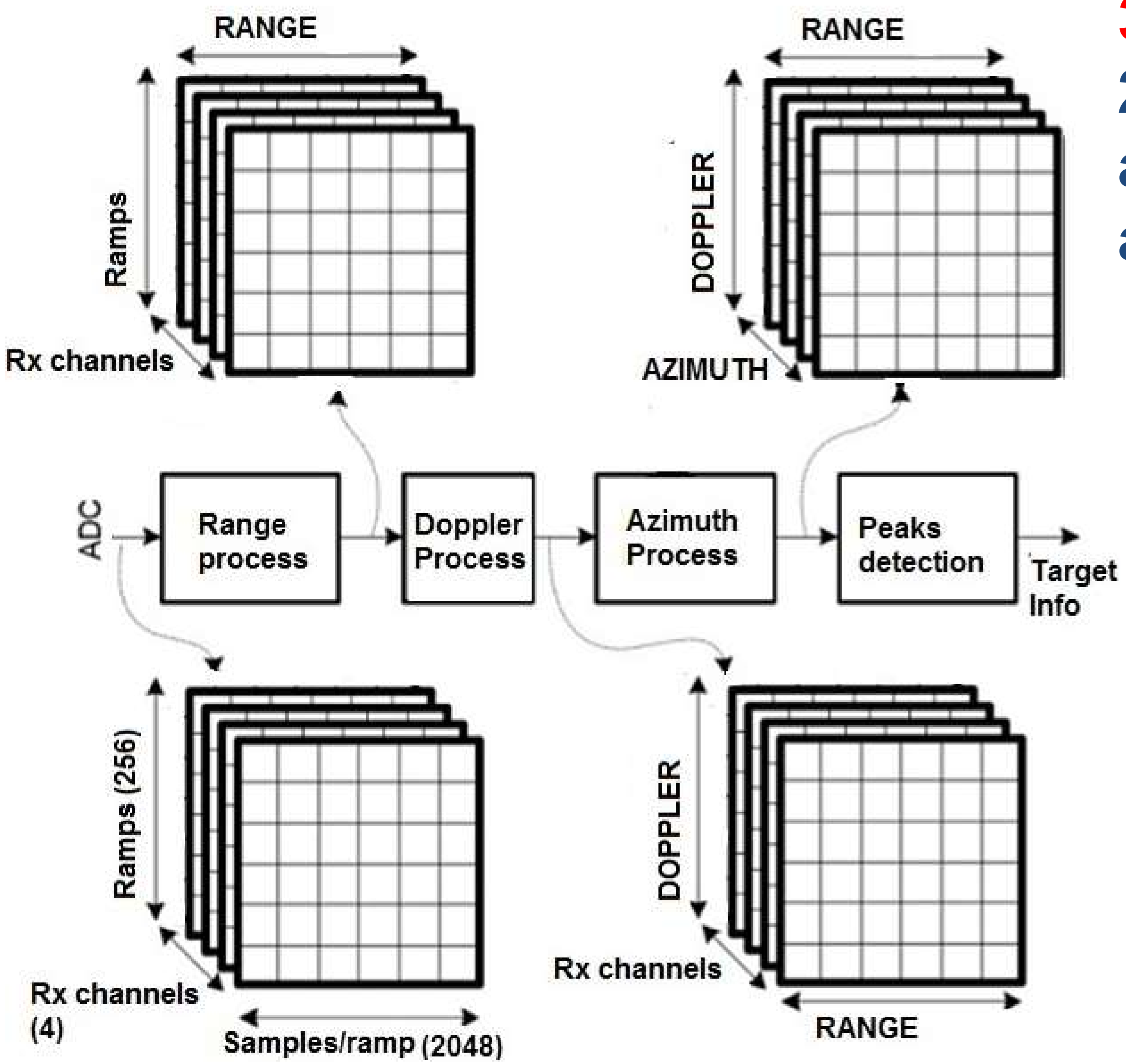


Measurement range R affected by channel impairments, HW performance, target cross-section; resolution d_R depends on sweep band B (4 cm for 77-81 GHz LRR)

$$R = \sqrt[4]{\frac{P_{CW}\lambda^2 G_{ant}^{\,2}}{(4\pi)^3}\frac{1}{L}\frac{\sigma}{SNR_{dig}}\frac{1}{k_B T N_F \Delta f}}$$

$$d_R = c/2B$$

FPGA-based signal processing

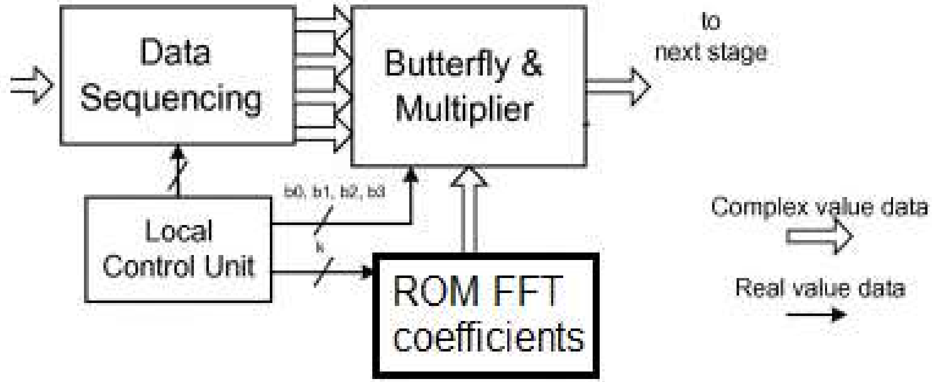


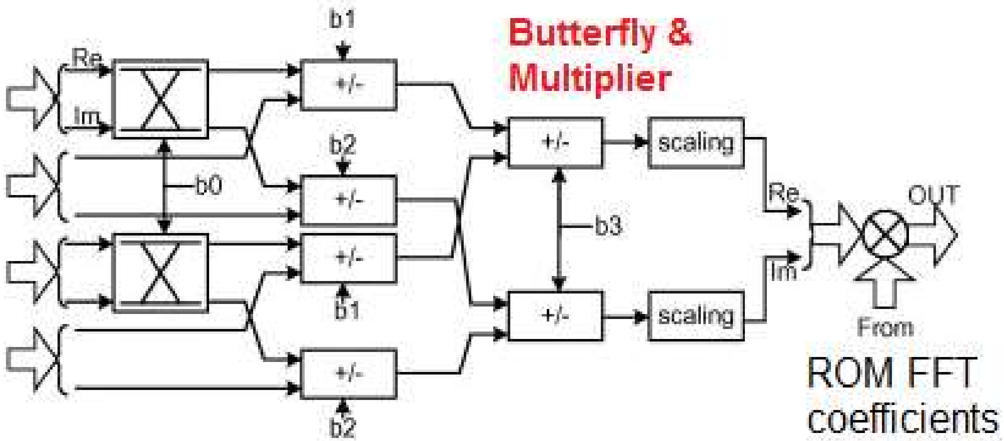
3D FFT range-Doppler: 2D FFT processing + 3rd FFT along the 4 RX channels for azimuth and peak estimation

Memory storage: 2M words of 24 bits (12 bits Re & Im data)

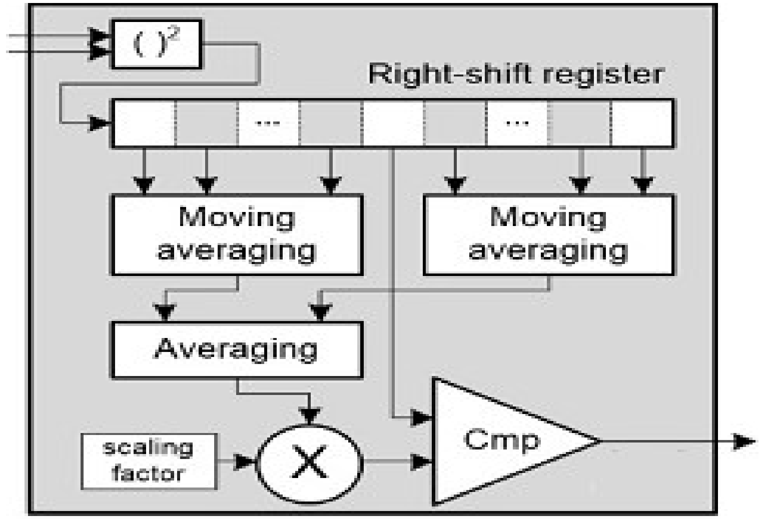
Memory buffering since data transfer & storage may become the bottleneck

HDL blocks for FPGA-based signal processing





FFT core based on a multi Radix-4 stages

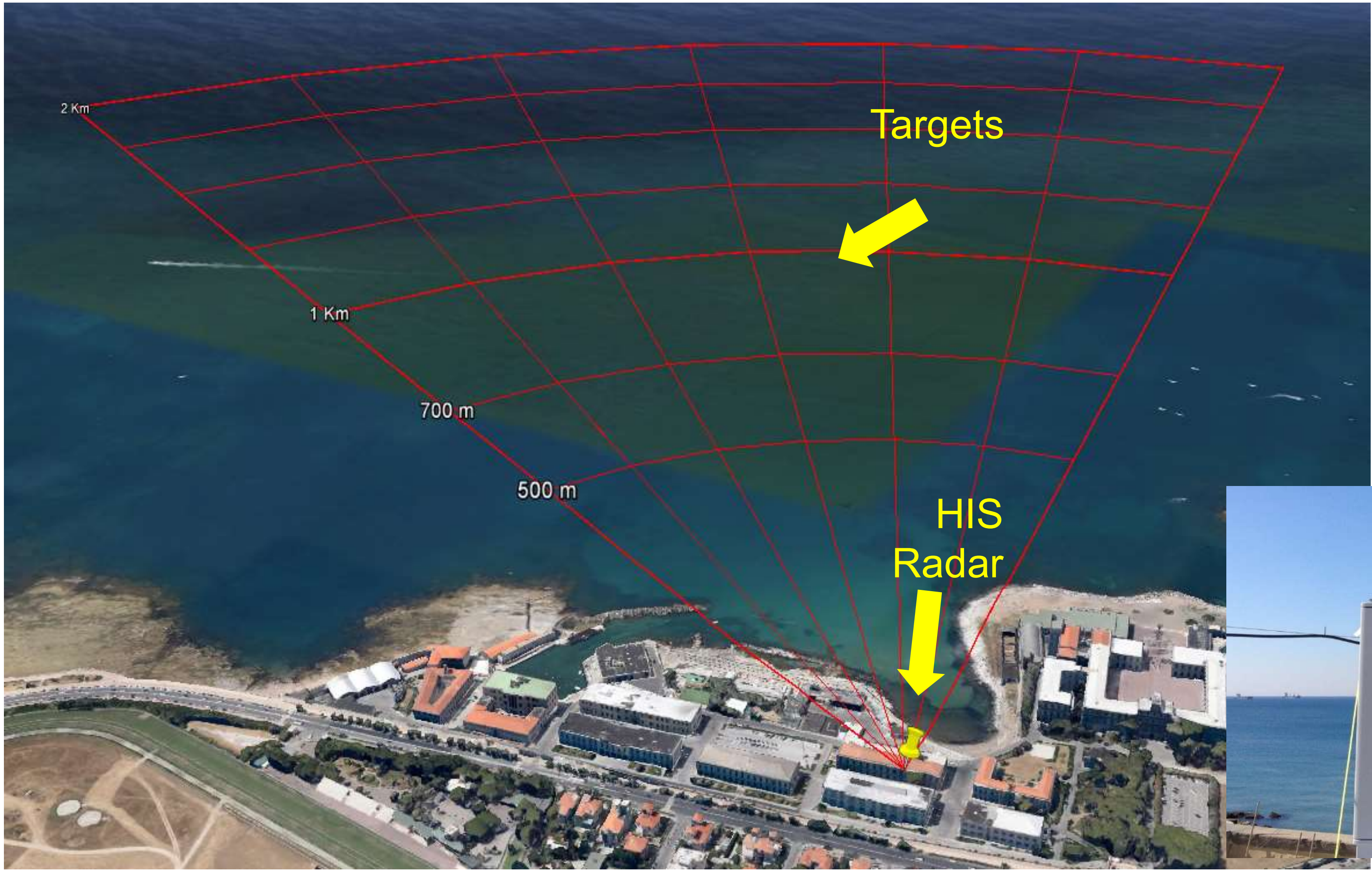


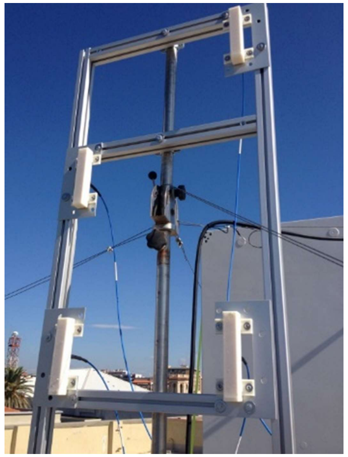
CA-CFAR HDL circuit

Device	FF	DSPslice	LUTs	Mem block	RX Channels
XA7A100T	32.4%	88.3%	35.6%	96%	4
Zynq-XA7Z020	40.9%	93.7%	45.7%	93%	4

Artix-7 FPGA and Zynq FPSoC

Experimental setup and Measurements

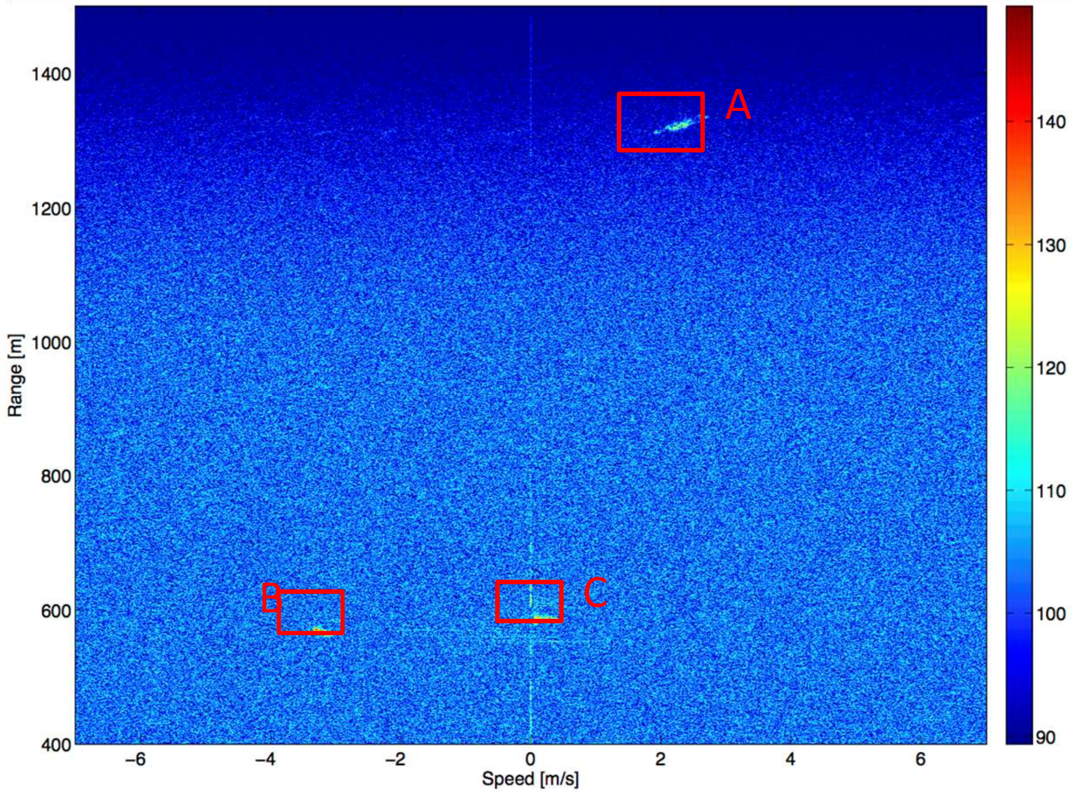




Experimental setup for the NATO-SET196 trials, 29/09-03/10 2014, Istituto Vallauri, Livorno, Italy.

Targets & Range-Doppler map

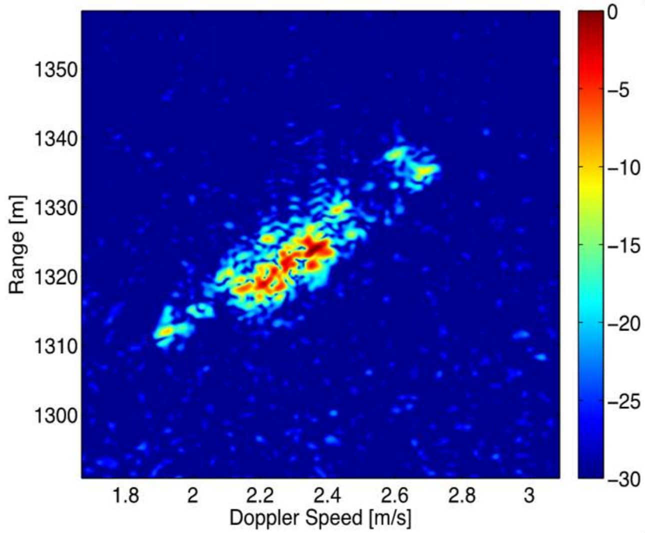
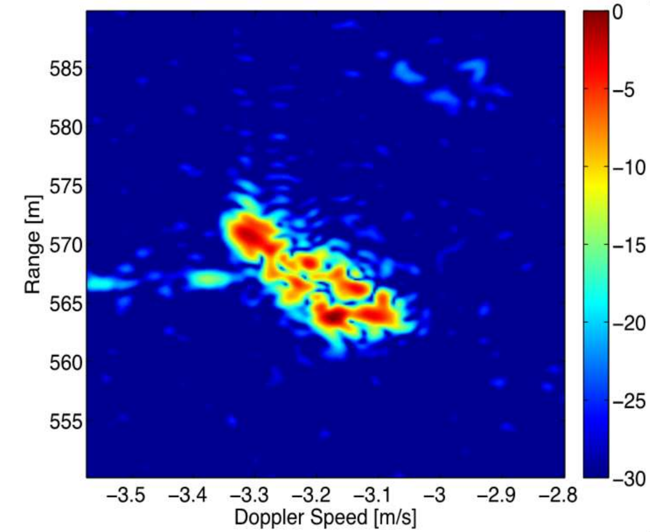
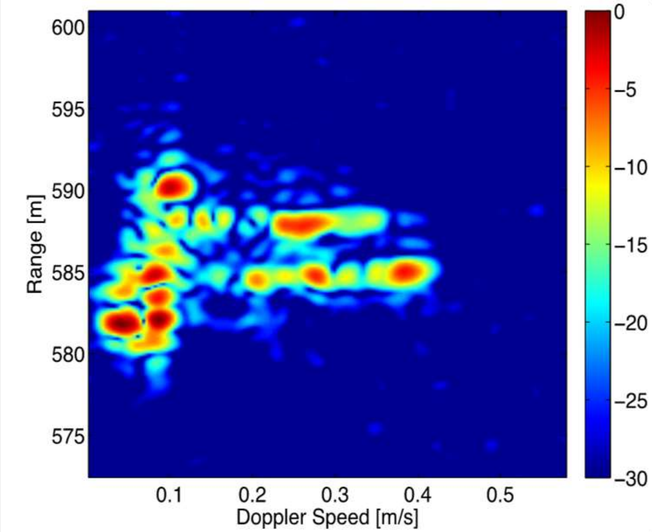
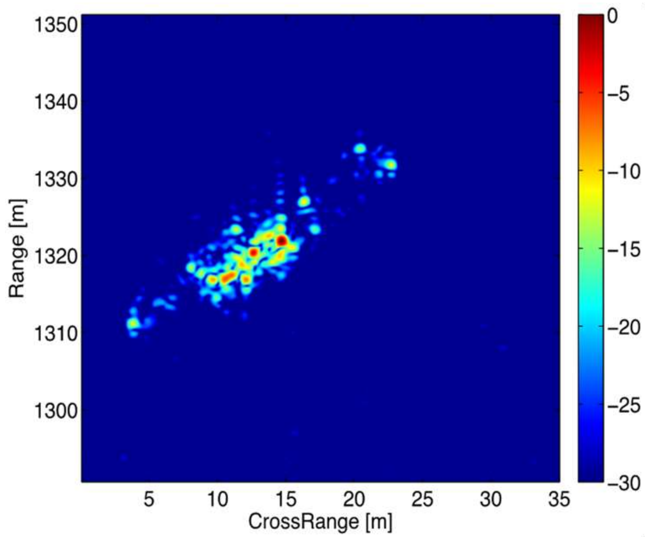
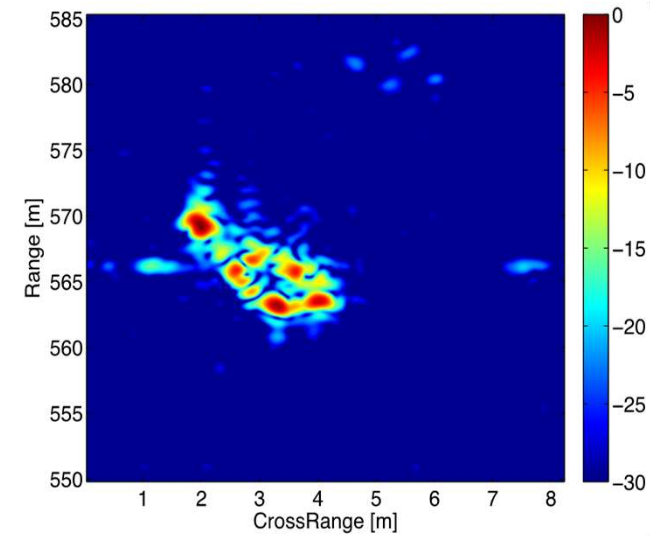
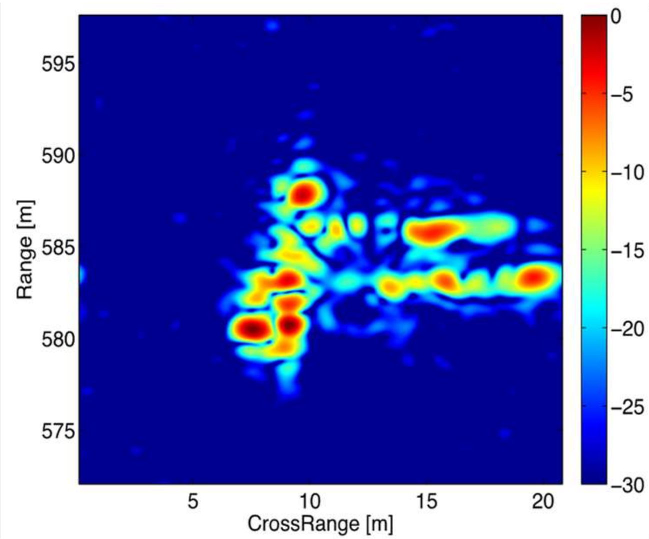
		
A. Length: 332.5 m, Width: 6.47 m • Material: wood and iron	B. Length: 8.5 m, Width: 2.3 m • Material: fiberglass and iron	C. Length: 13.20 m, Height: 13 m • Material: wood



- $P_T = 33\ dBm$
- $B = 300\ MHz$
- $PRF = 1\ kHz$
- $CPI = 1\ s$

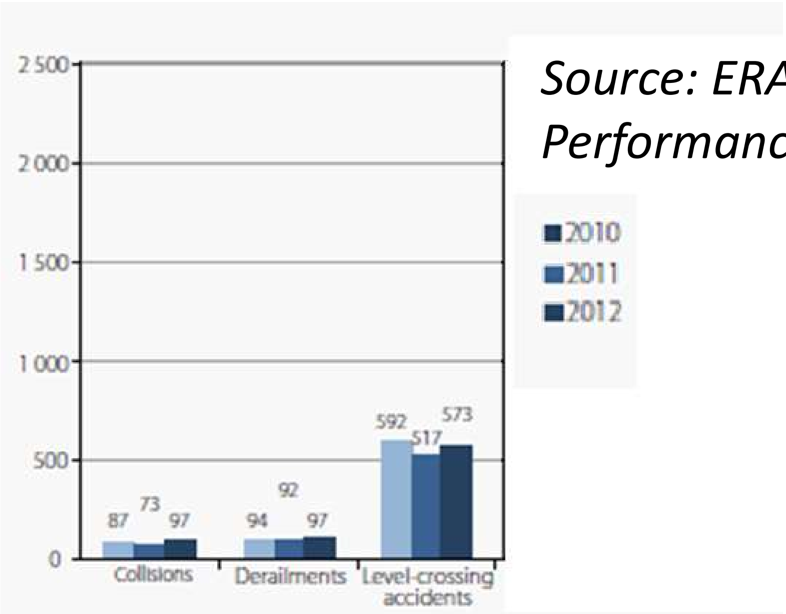
2D-ISAR images (off-line processing)

Thanks to S. Lischi, R. Massini

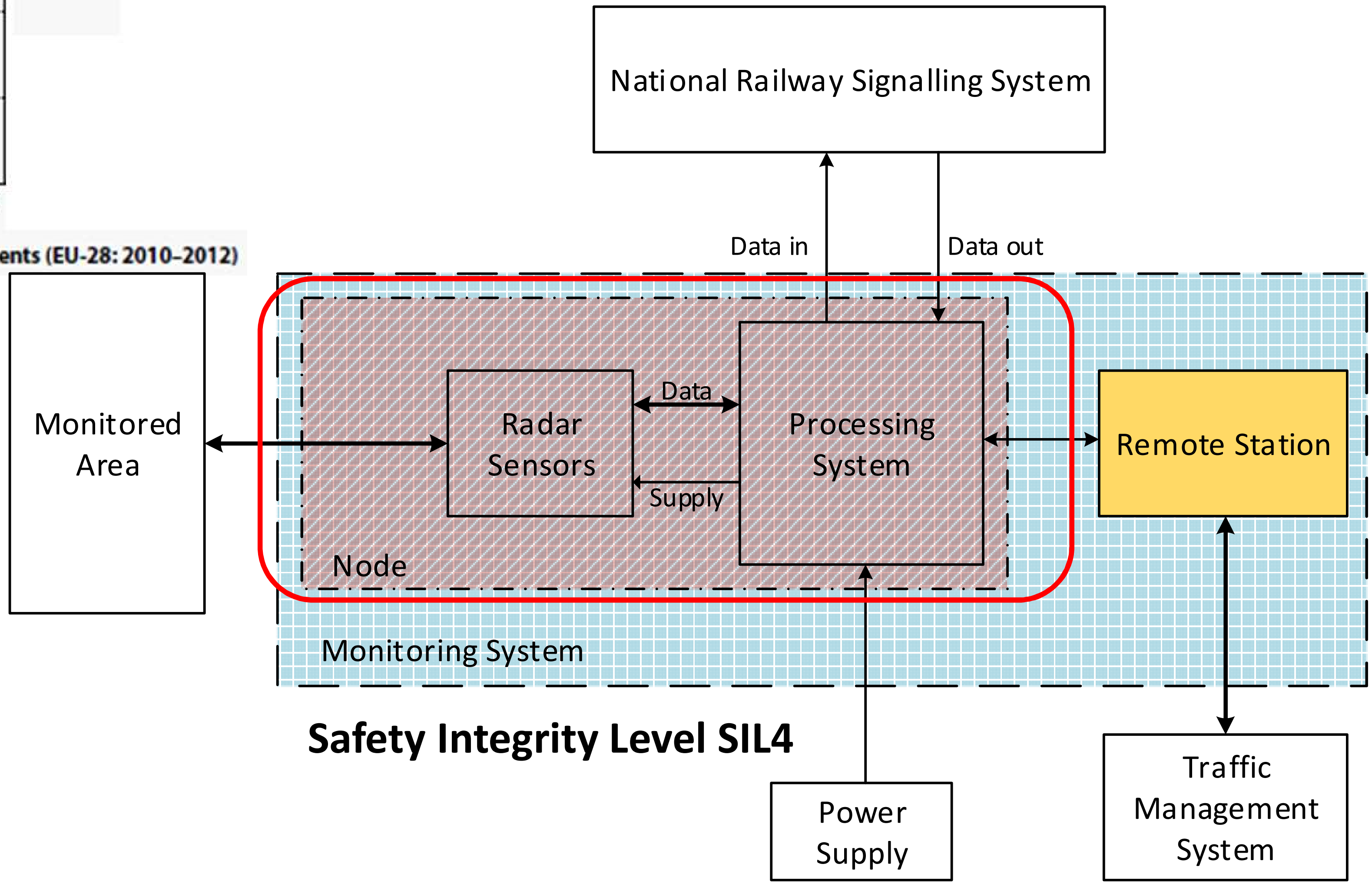
	Target A	Target B	Target C
Range-Doppler crop			
2D-ISAR			

Railway accidents in EU

Source: ERA – Railway Safety Performance Report 2014

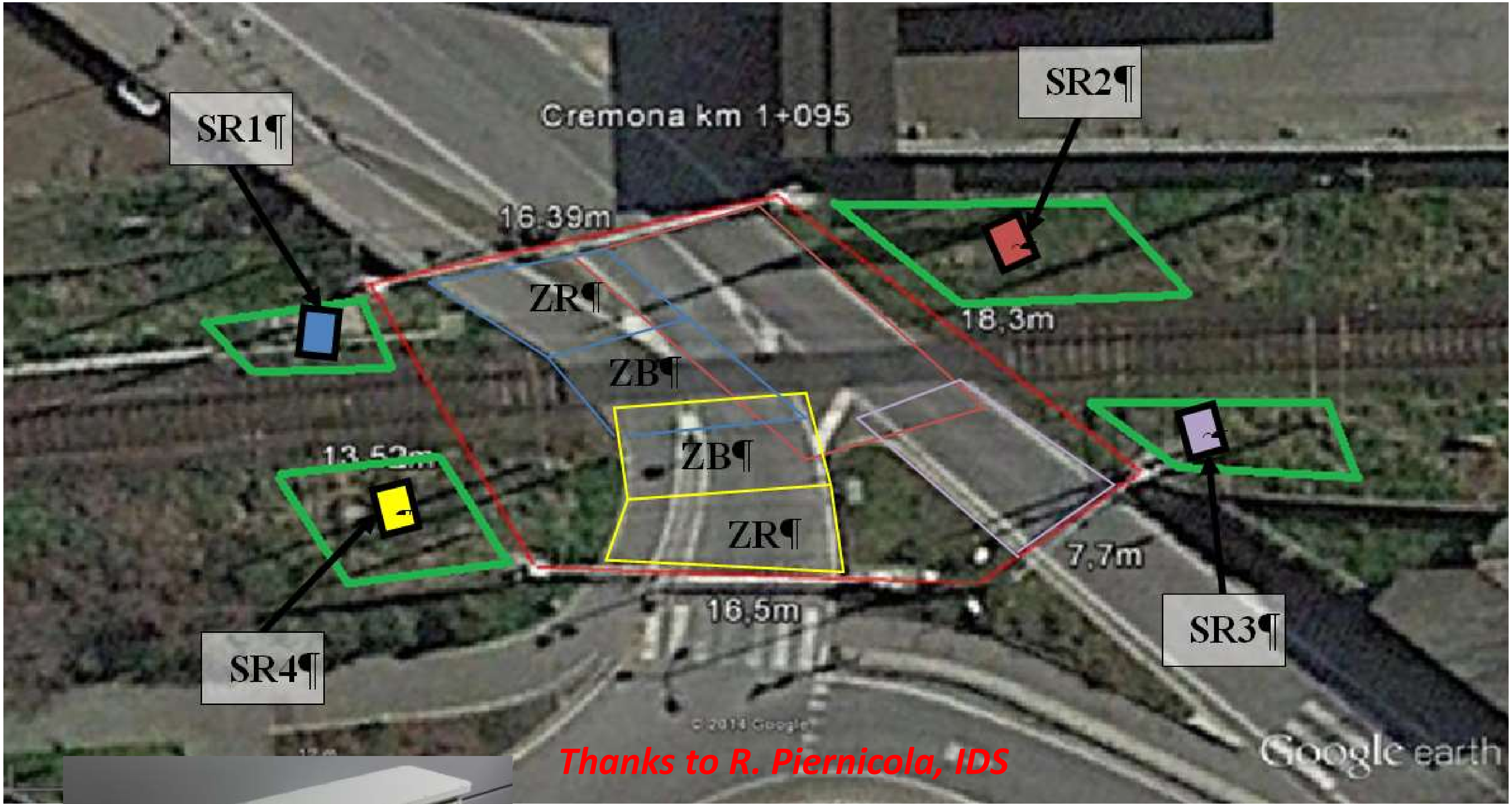


Significant accidents per type of accidents (EU-28: 2010–2012)

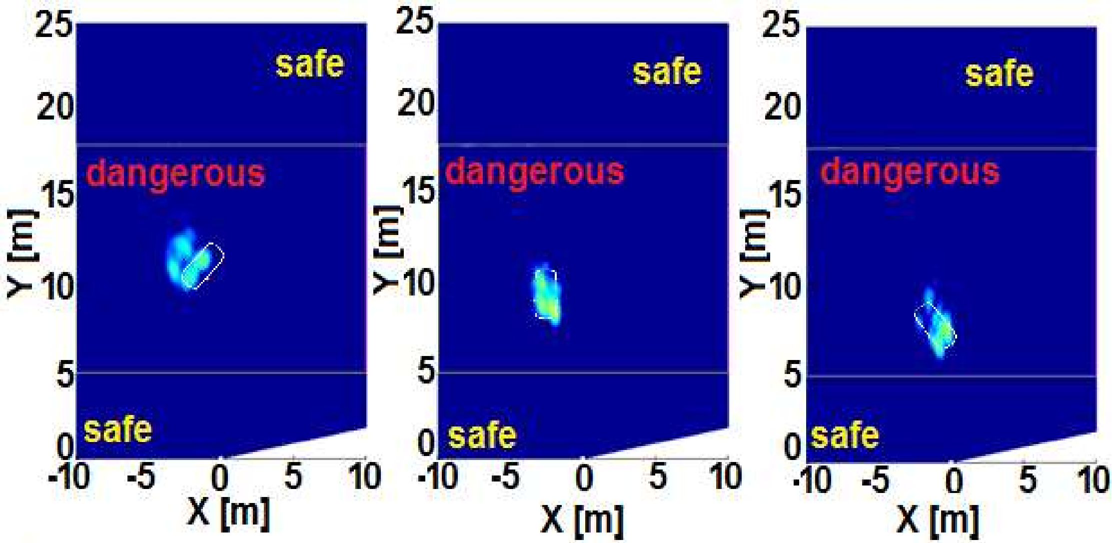


Safety Integrity Level SIL4

Example of installation on a roadcrossing



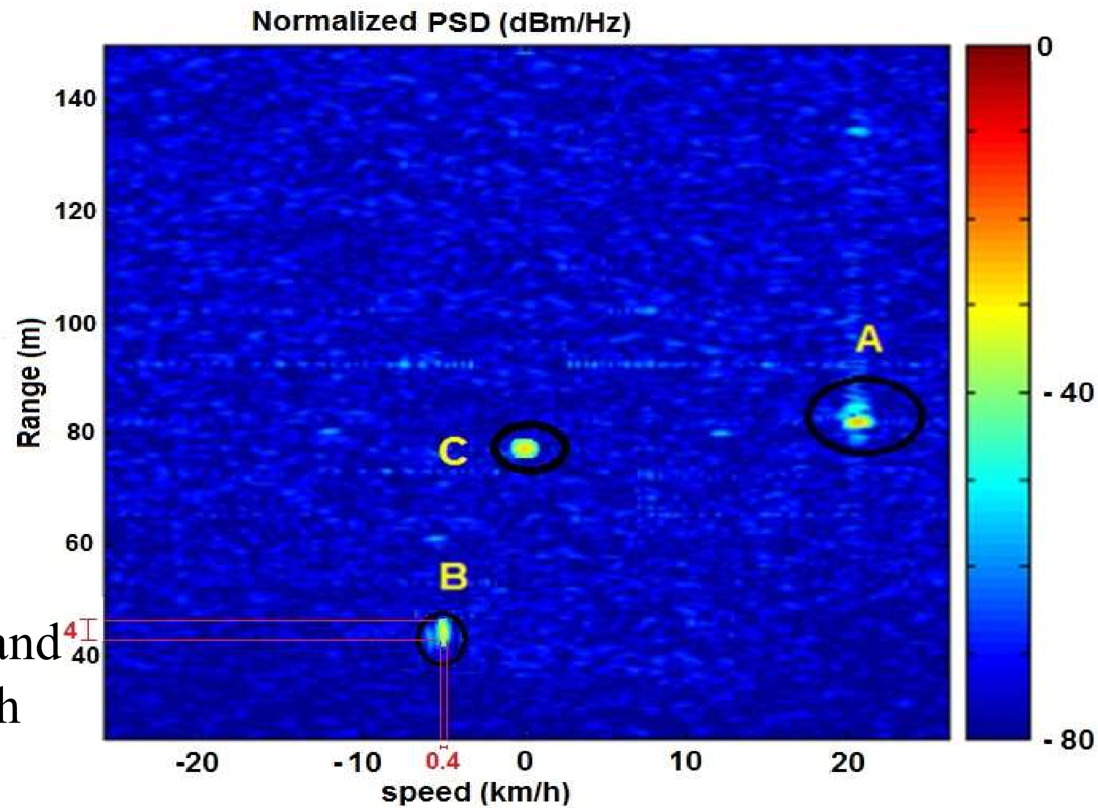
Real-time level-crossing & parking monitoring



Thanks to
R. Piernicola, IDS

A: moving vehicle
B: biker
C: still vehicle

Detected targets appear like an oval due to the target physical size and to the Radar resolution limits in distance and speed. A post-processing step on the range-doppler image allows extracting size along radial axis (4 m for the Target B, 30 cm resolution limit) and speed (5.5 km/h for the Target B, with 0.4 km/h uncertainty, due to the speed resolution limit)



State-of-art comparison: surveillance mobility Radar

	Freq, GHz	Type	Power cost	Range, Output power	Channels
This work	10.3-10.8	FMCW	< 8 W	300 m, 5 mW	5
IEEE TBSC2011	3.1-10.6	Pulsed UWB	73 mW	<1 m, 7 pJ/pulse	2
MOTL 2013	22-26	Pulsed UWB	N/A	N/A, 2 mW	2
TERMA2015	12-18	Pulsed	130 W	Min. 1 m/Max. 4 km, 8 W	N/A
TERMA2015	9.375	Pulsed	N/A	45 km, 32 kW	N/A
EURAD2014	10.5-10.8	FMCW	>100 W	1200 m, 2 W	3
IEEETIM 2014	2.48 - 2.56	FMCW	N/A	20-100m, 0.1 W	N/A

1 channel	Freq, GHz	Type	Power cost	Range	Output power
This work	10.3-10.8	FMCW	11.86 W	1.5 km	2 W
			2.56 W	300 m	5 mW
IEEE TBSC2011	3.1-10.6	PulsedUWB	73 mW	<1 m	7 pJ/pulse
ACMMobicom 2015	60	FMCW	N/A	<3.5 m	N/A
MOTL2013	22-26	PulsedUWB	N/A	N/A	2 mW
TERMA2015	12-18	Pulsed	130 W	4 km	8 W
TERMA2015	9.375	Pulsed	N/A	45 km	32 kW
AWC2015	2.48-2.56	FMCW	N/A	100m	100 mW
AMS2013	9.4	FMCW	650 W	50 km	100 W

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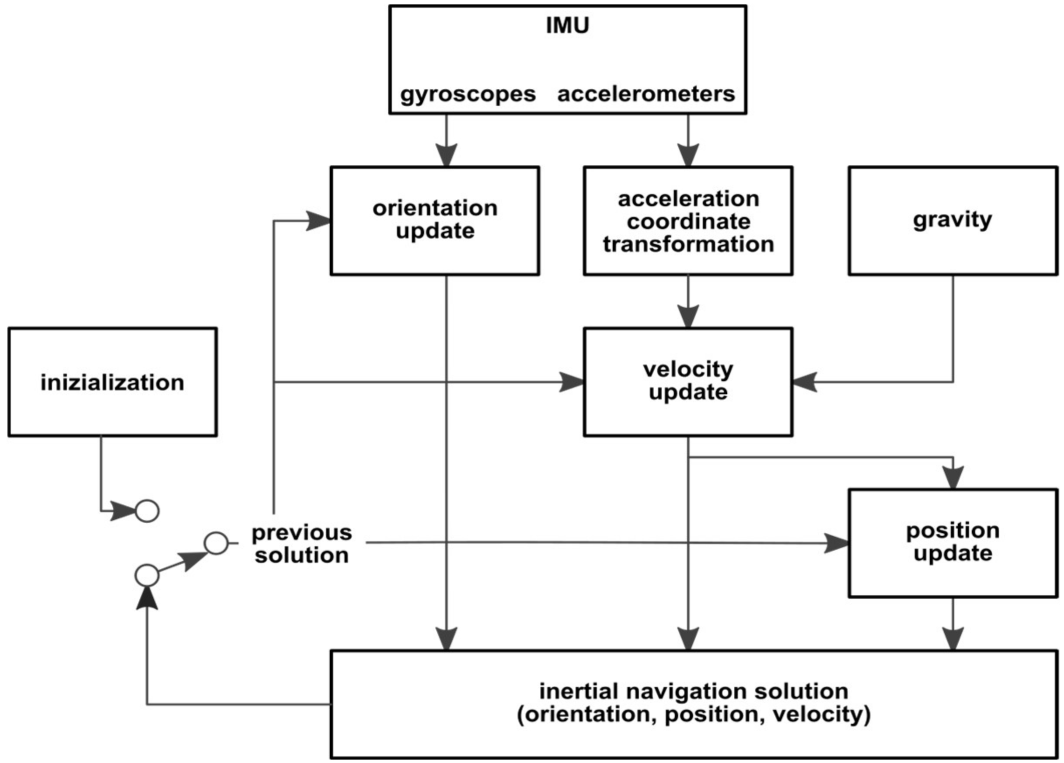
Inertial Navigation System

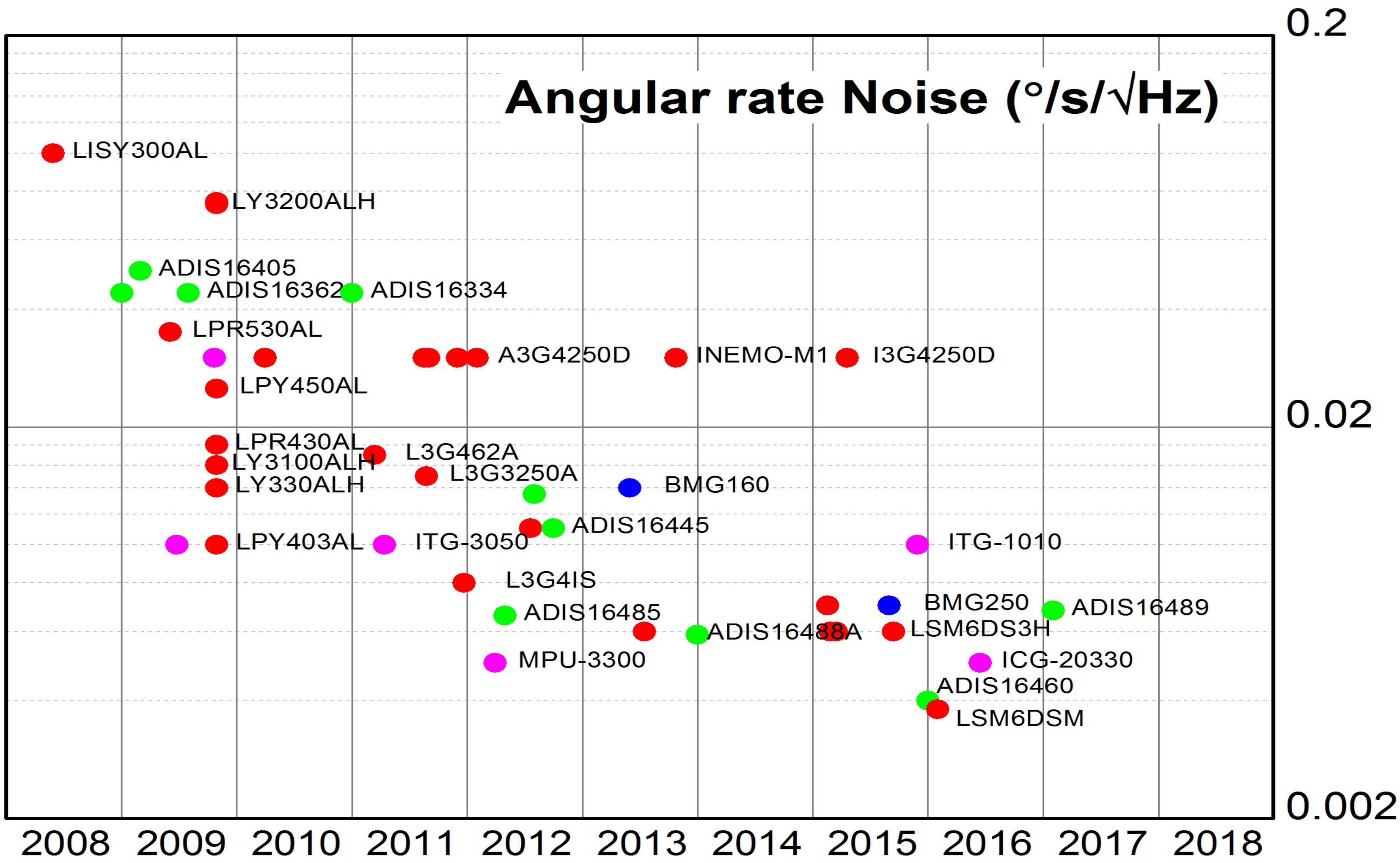
Bias as a limit of navigation & positioning accuracy



IMU grades by bias values

IMU grade	Acceleration bias (mg)	Angular rate bias (deg/hr)
Strategic	$10^{-3} - 10^{-2}$	$10^{-4} - 10^{-3}$
Navigation	$10^{-2} - 1$	$10^{-3} - 0.1$
Tactical	1 – 30	0.1 – 30
Consumer	>30	>30

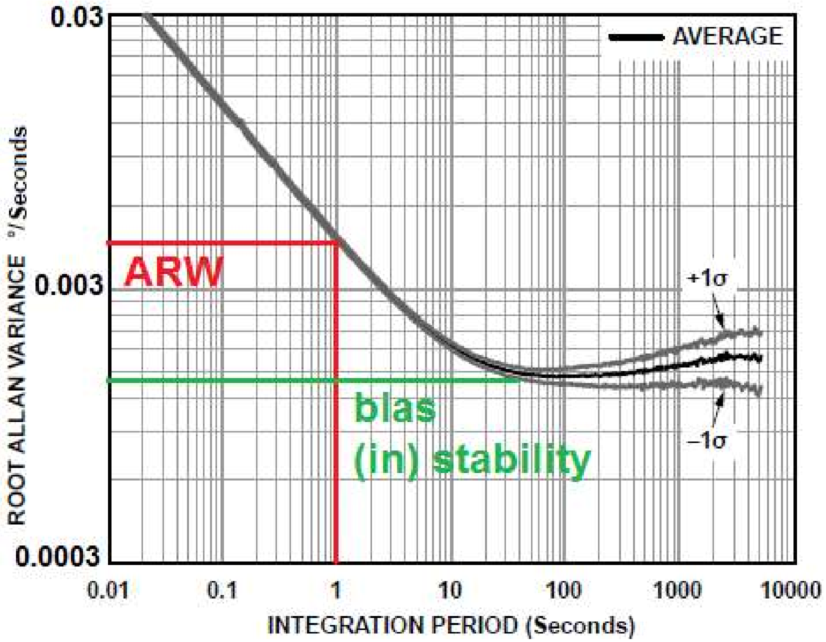
Inertial Navigation System



Noise spectral density of several recent different commercial gyroscopes, by year
Color marks the supplier *Thanks to F. Pieri*

ST, AD, Bosch, InvenSense

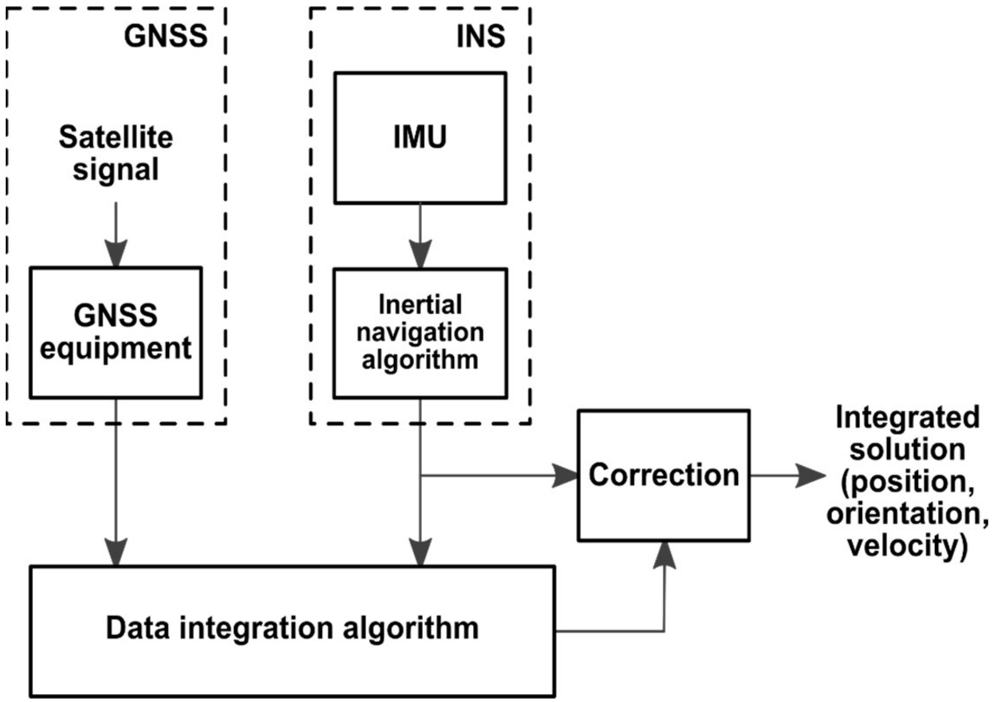
Inertial Navigation System



Ten-second position errors due to sensor bias

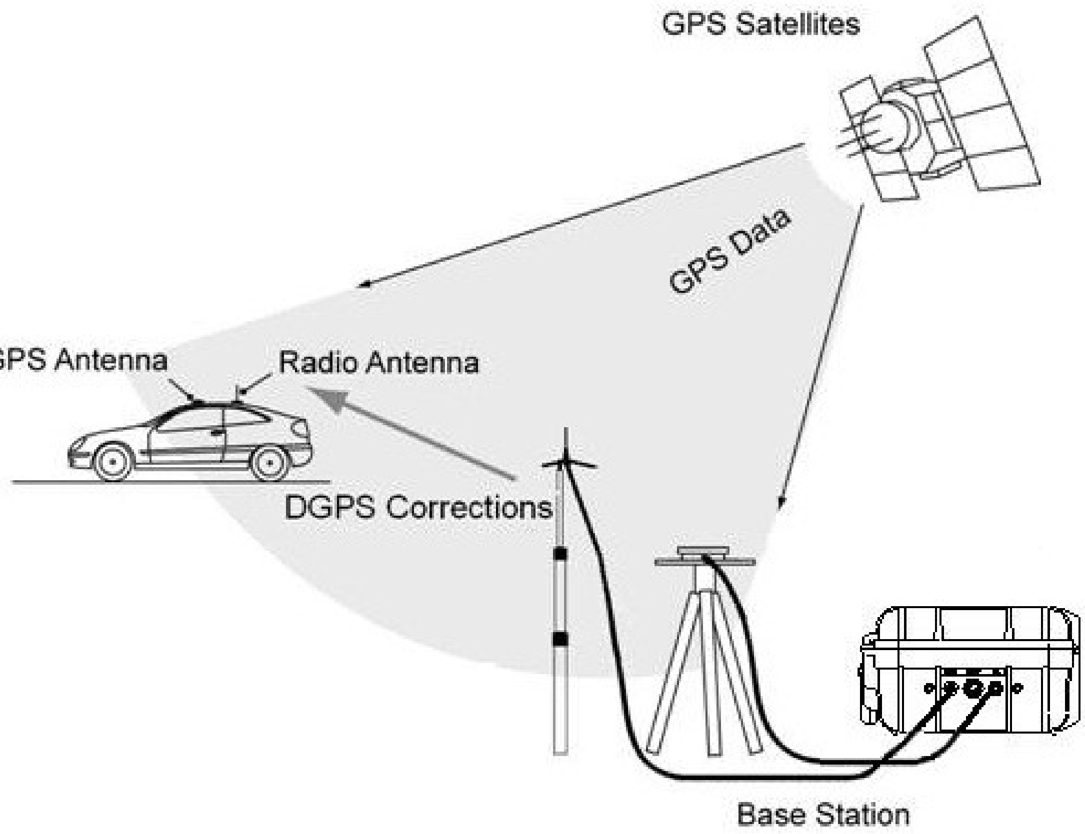
IMU grade	Due to acceleration bias (m)	Due to angular rate bias (m)
Strategic	$< 0.5\times10^{-3}$	$< 8\times10^{-6}$
Navigation	0.5×10^{-3}-0.5	8×10^{-6}-0.8×10^{-3}
Tactical	0.5-15	0.8×10^{-3} - 0.25
Consumer	> 15	> 0.25

Fusion of GNSS & IMU needed



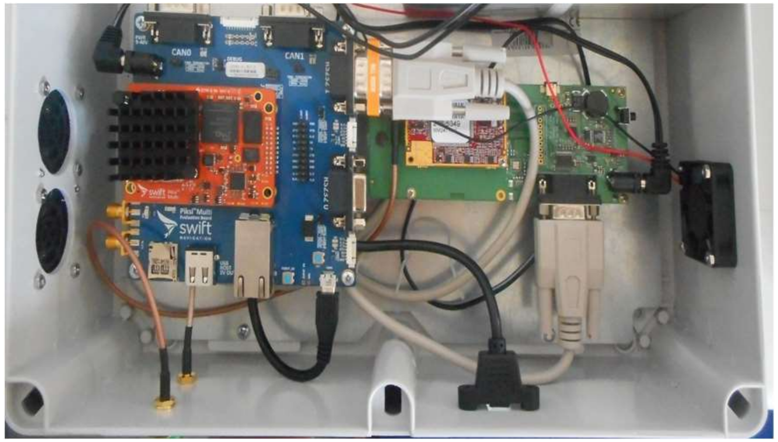
Still not–enough for cm accuracy in positioning/navigation

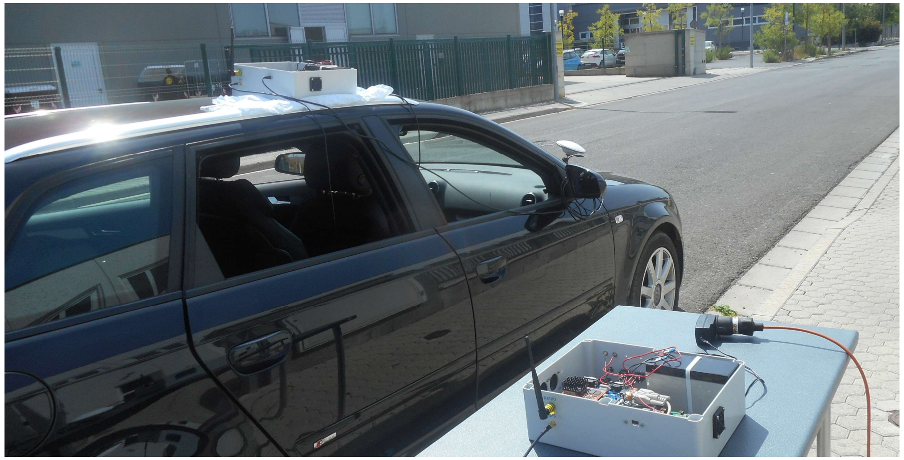
RTK: Fusion of Multiple-GNSS & IMU



The vehicle receives its GPS signal plus the GPS signal of a reference point through a vehicle to infrastructure communication link

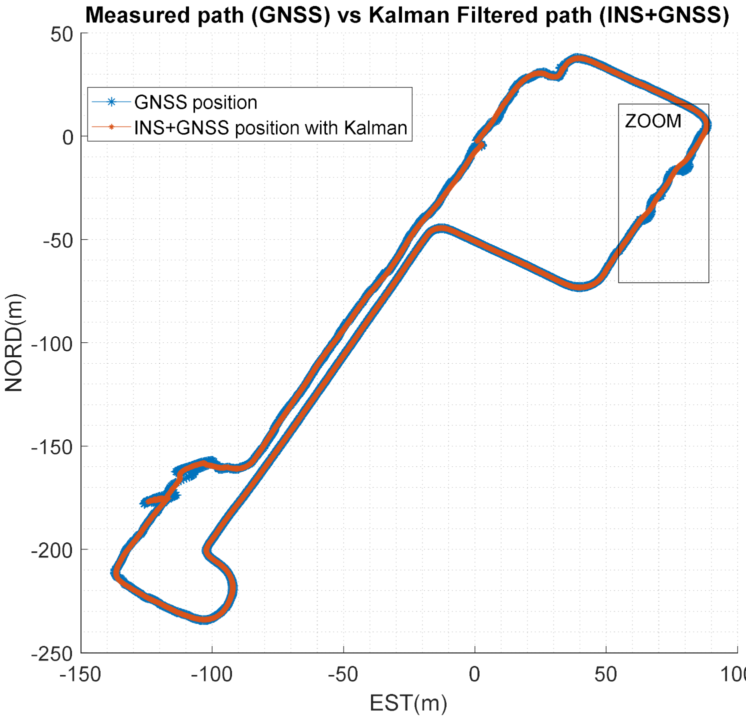
RTK: Fusion of Multiple-GNSS & IMU

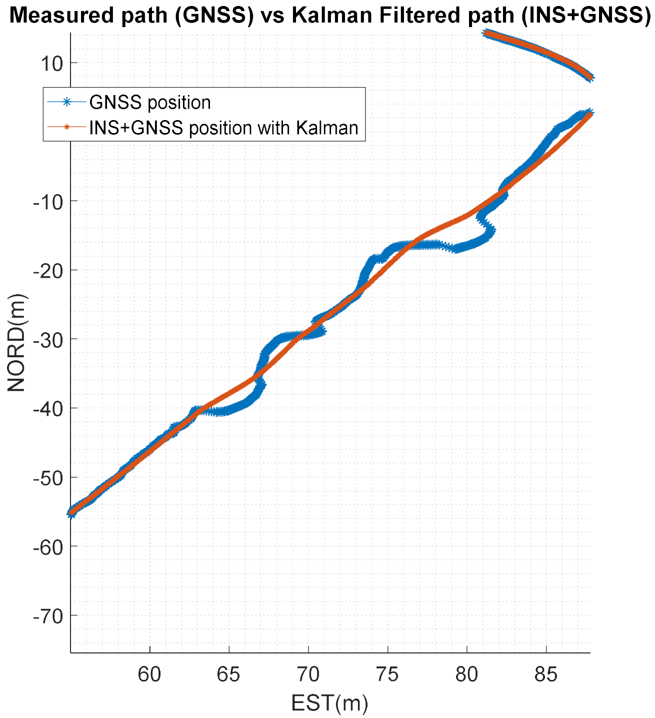




A prototype realized using COTS components (embedded signal using Kalman filter & fusion of 2 GPS data & on-board accelerometer and gyroscope) achieves an accuracy of 10 cm.
Implemented in collaboration UNIPI with PPC
Fully integrated system under development

RTK: Fusion of Multiple-GNSS & IMU





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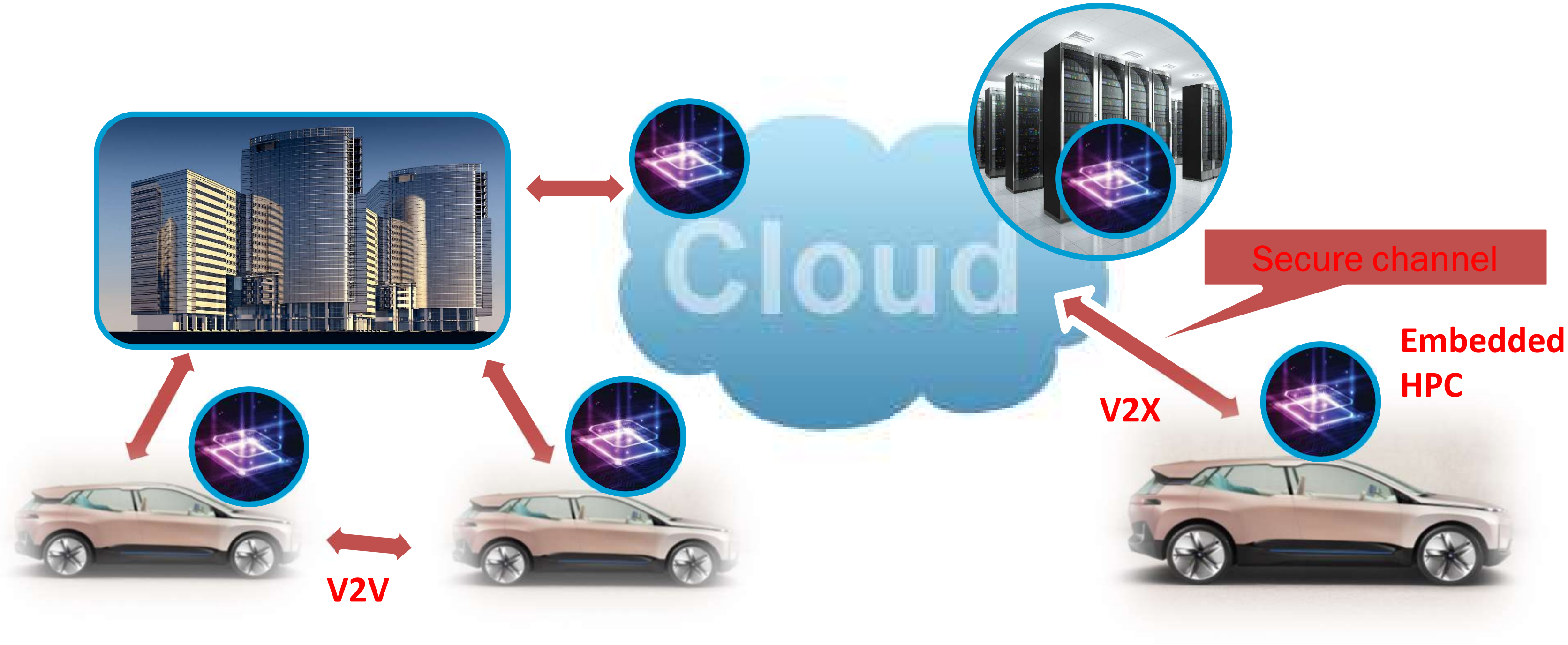
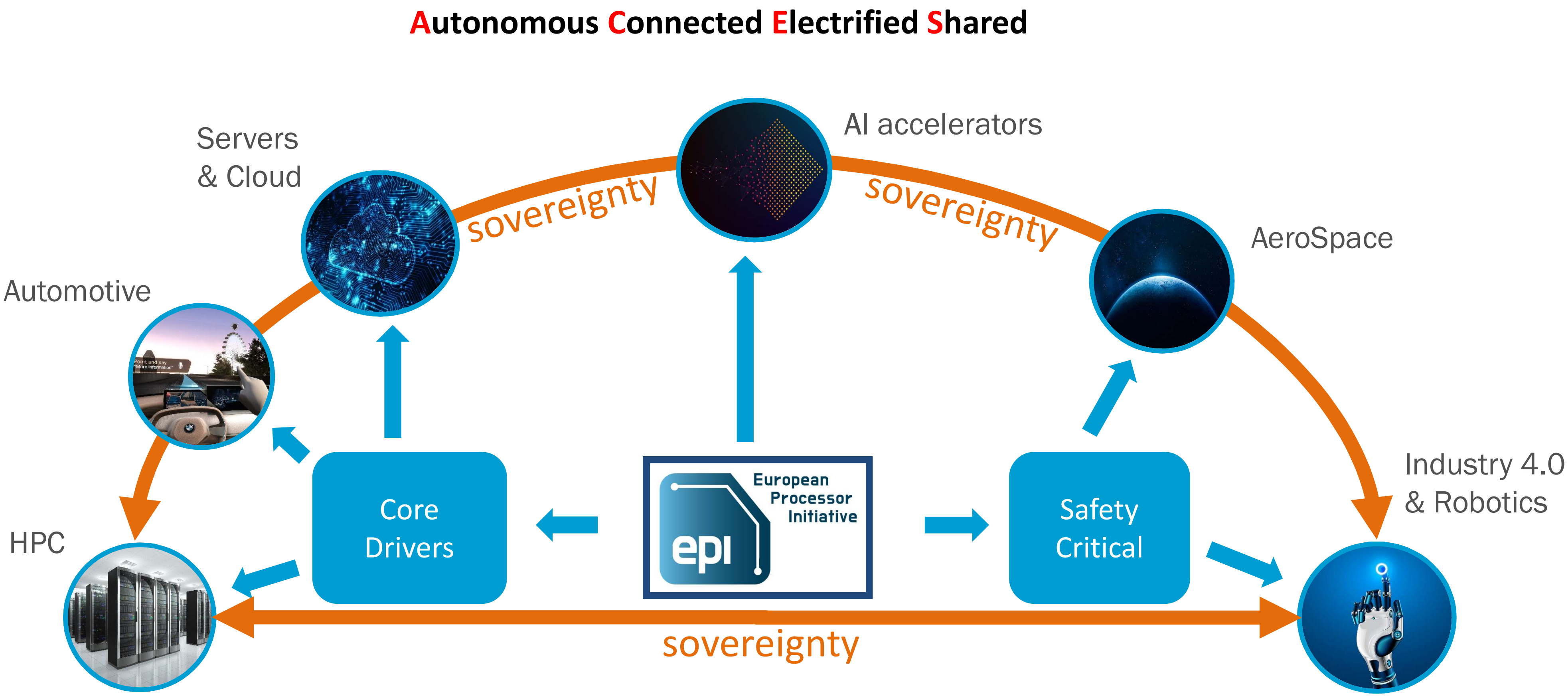
European Processor Initiative

Enabling **TE**chnologies for sm**A**rt vehicles and **M**obility (EPI SGA1 80 M€ + EPI SGA2 35 M€ project 2018-2023)



ACES Vehicles & Mobility

New eHPC ECU: Safe&secure MCU with high-SIL controlling EPI-like number crunchers (multi-core 64b GPP + accelerators)



EPI partners & HW/SW eco-system

Full HPC Environment for the Reference Platform

Lustre

Co-design exploration space

Automotive eHPC software support

Programming tools & Libraries: LLVM/GCC with OpenMP; OpenMPI; FFTW; BLIS; OpenBLAS, …

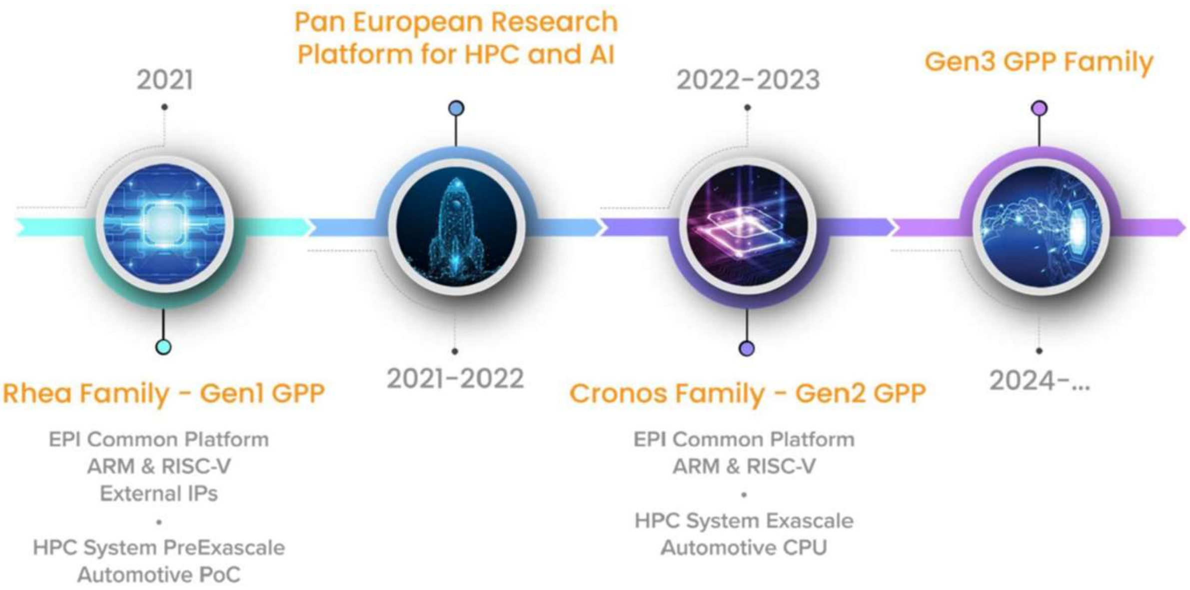
Security, Low-level software, power management

Linux Operating System

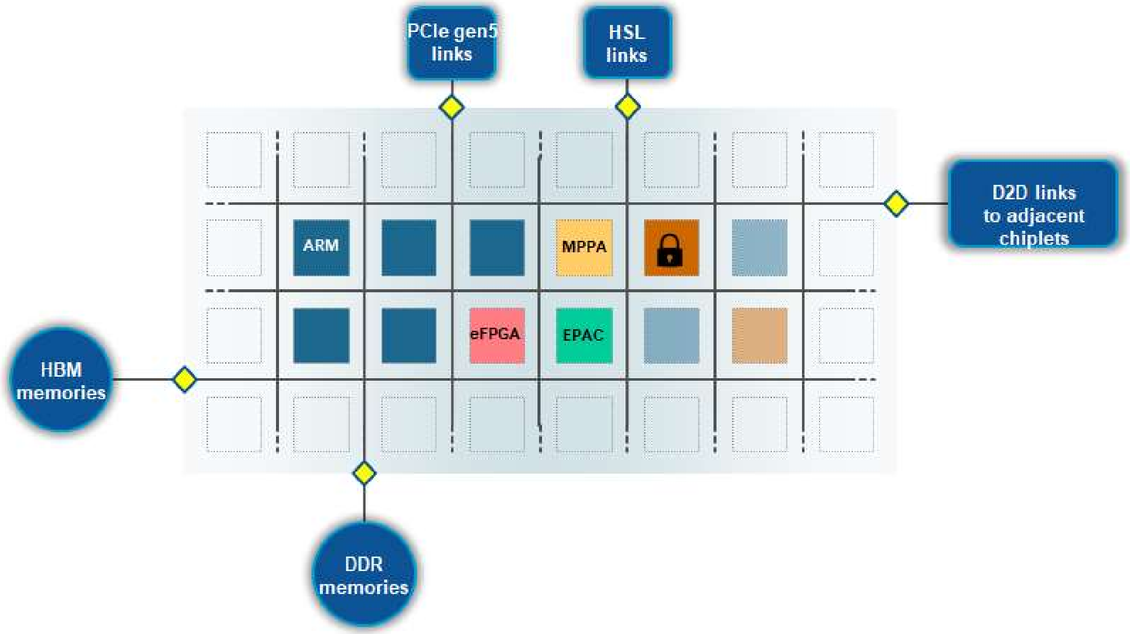
EPI Processor

EPI Reference Hardware

EPI Roadmap & Architecture



European Processor Initiative



- EPAC - EPI Accelerator
- MPPA - Multi-Purpose Processing Array
- eFPGA - embedded FPGA
- Cryptographic HW & SW (EU Sovereignty)

BSC KALRAY menta PROVE & RUN SIPEARL

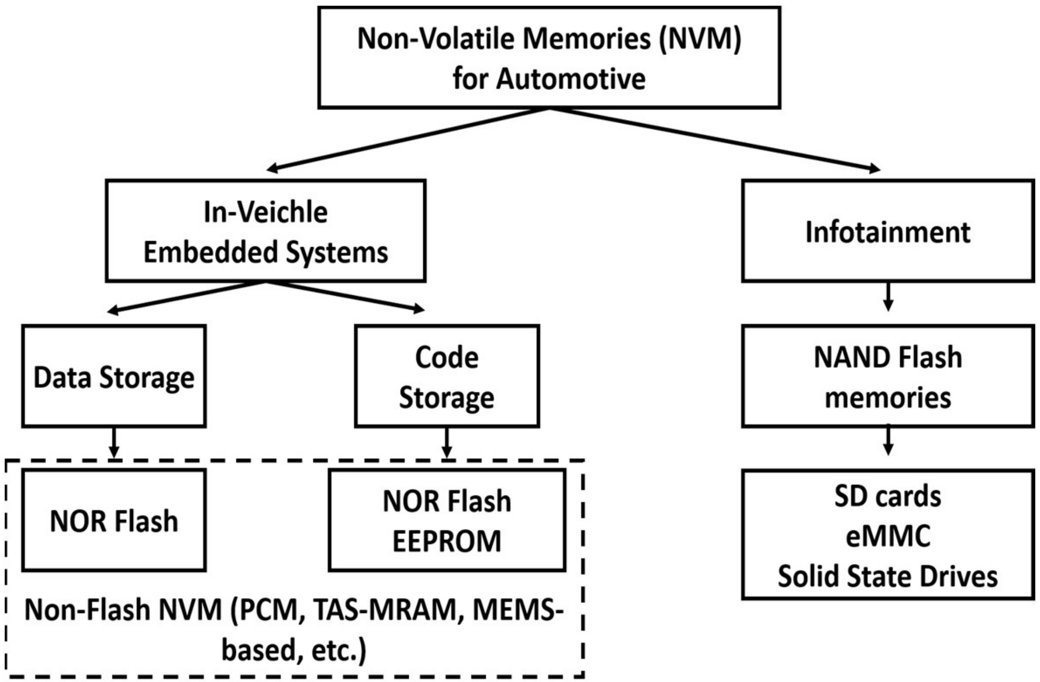
EPI RHEA chip (Multi-core ARM64b with SVE in 6 nm technology)

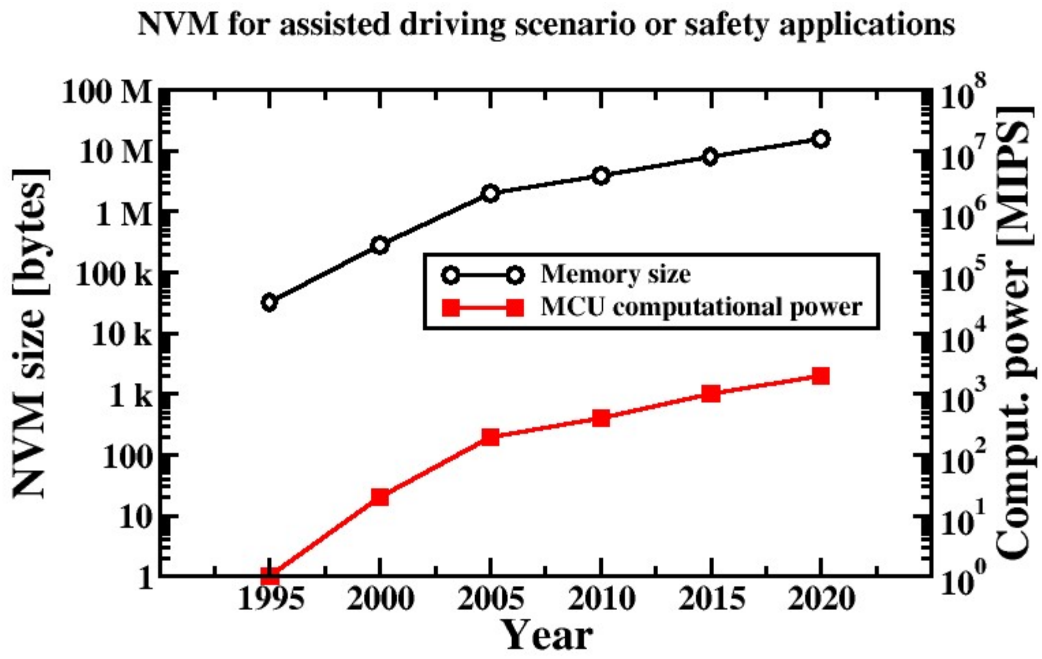
Memory needs for autonomous cars

- AVG INTERNET USER ~1.5 GB OF TRAFFIC PER DAY
- SMART HOSPITAL 3,000 GB PER DAY
- AUTONOMOUS VEHICLES 4,000 GB PER DAY… EACH
- AIRPLANE DATA 40,000 GB PER DAY
- SMART FACTORY 1,000,000 GB PER DAY

- TECHNICAL DATA
- SOCIETAL & CROWDSOURCED
- PERSONAL DATA

NV Memory automotive trends





Parameter	EEPROM	NOR Flash Code Storage	NOR Flash Data Storage	PCM	MEMS-based	RRAM CBRAM	TAS-MRAM
Endurance	500k	10k – 100k	500k – 1M	>1M	>1M	100k	>1M
Data Retention	>10 yrs/125 °C	10 yrs/125 °C	>10 yrs/125 °C	10 yrs/85 °C	>10 yrs/125°C	10 yrs/85 °C	>10 yrs/125 °C
Power consumption	Low	Low	Low	High (Write)	Low	Low	High
Read Latency	20 – 50 ns	< 20 ns	< 20 ns	> 20 ns	> 100 ns	> 20 ns	50 – 100 ns
Cost per bit	Medium/High	Medium	Medium	Low	High	Low	High

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Motivations

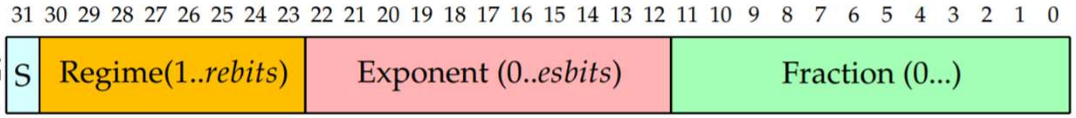
- In **Automotive** ML and DNNs must run in vehicle (relying on internet connection and remote services can not be mandatory)
- The representation chosen for real numbers has a high impact on the synthetized hardware (cores, SoC acceletarors, etc.) → Novel **posit** format as alternative to float (the cppPosit library developed in Pisa)
- FP representation (IEEE-754) has limitations: support to unnormalized numbers is tricky, representations wasted for Not-A-Number, inefficient use of same bits for the mantissa, both for small and large numbers

Computing Industry Looking for Alternatives to FP32/FP64

- **Intel/Google BFLOAT16** (equivalent to a standard single-precision floating-point value with a truncated mantissa field)
- **Intel flexpoint** (16bits size aiming at equivalent fp32 accuracy)
- **NVIDIA** concurrent execution in the new Turing SM of FP32/FP16 and INT32 to INT8 and INT4 precision modes
- **Tesla FSD chip** (Neural processing units use 8-bit by 8-bit integer multiply and a 32-bit integer addition)

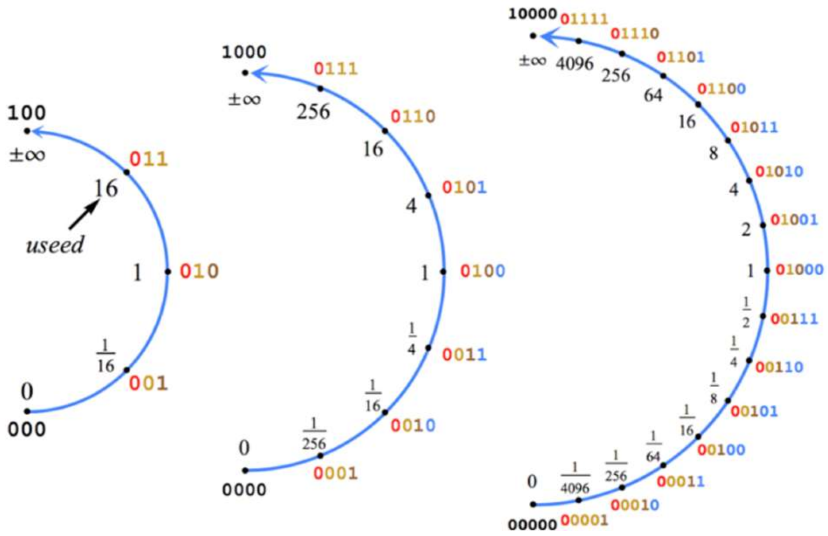
The Novel Posit Format

- Proposed by John Gustafson in 2017
- It is a compressed FP format (more mantiss low number and less for large numbers), wi fixed-length format
- No-need to use un-normalized floats (so, no extra-HW wasted to handle this exception)
- Only 1 representation wasted for Not-A-Real (NAR)
- Posit encoding allows comparing two posits reusing the same circuit used to compare two integers in 2's complement already present in the ALU



$$x = \begin{cases} 0, \text{ if p} = 0 \\ \text{NaR, if p} = -2^{(n-1)} \\ sign(p) \times u^k \times 2^e \times f, \text{ otherwise} \end{cases}$$

$$u = 2^{2^e}$$



State-Of-Art Posit CppPosit library, developed in Pisa (in C++, fully exploiting templates and several features of the C++14 standard)

Emulates a Posit Processing Unit (PPU) using:
- FPU and the ALU
- ALU alone (the FPU is emulated using softfloat)

The cpp-Posit Library developed in Pisa

- Supports also **TABULATED POSITS** (using LUT, e.g. 2 MB for POSITS10bits): this speedup the library, a mandatory feature to train DNNs
- Hierarchy of operations to

  L1 operations involve bit-manipulation of the posit, without decoding it, considering it as an integer. L1 operations are performed on ALU and are fast

  L2 operations involve unpacking the Posit into its four different fields, with no exponent computation

  L3 operations involve full exponent unpacking, but without the need to perform arithmetic operations on the unpacked fields (examples are converting to/from float, posit or fixed point)

  L4 operations require the unpacked version to perform SW/HW FP computing

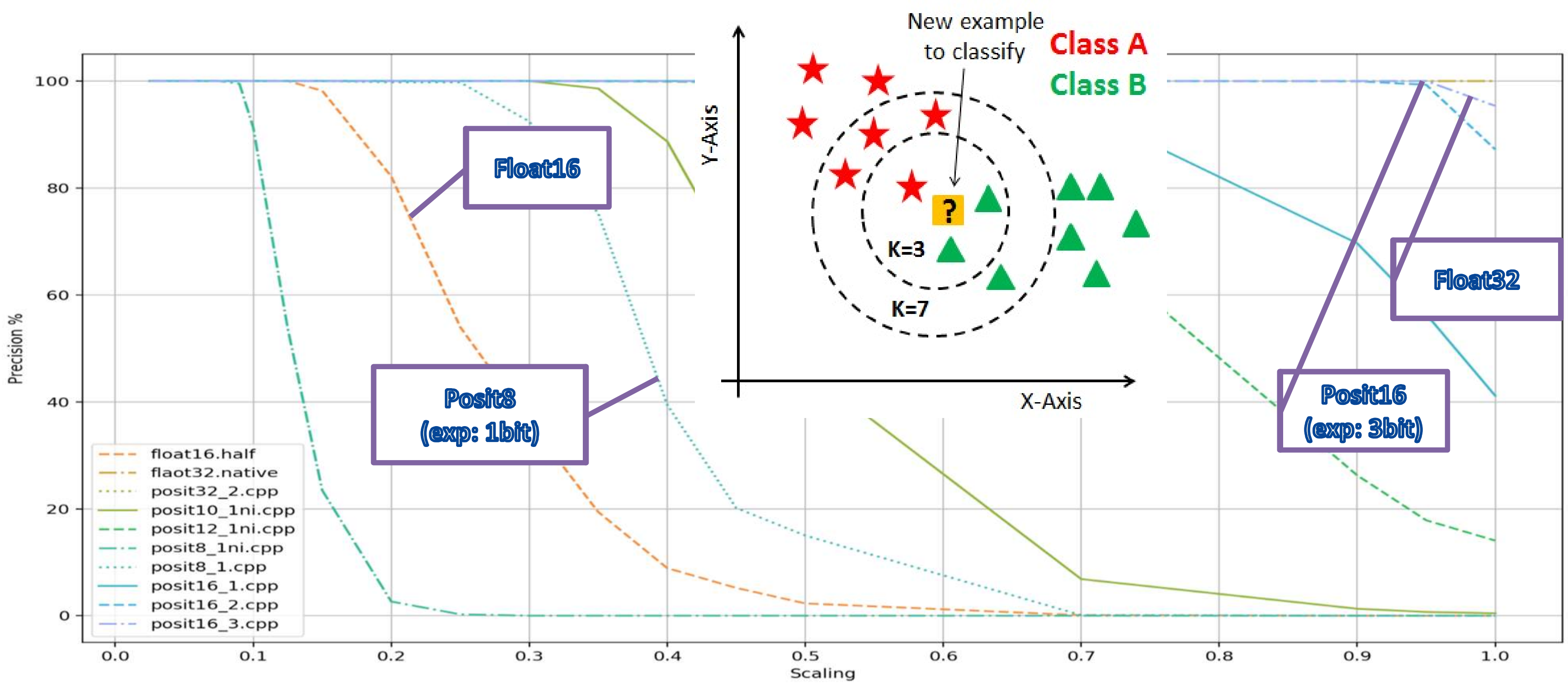
A Posit Processing Unit (PPU) can be synthesised e.g. using the Vivado toolkit:
the cppPosit library allows automatic HDL code generation starting from C++ code

The Cpp-Posit based K-NN Library

- UNIPI performed comparisons on Machine Learning (K-NN) and Deep Neural Networks for Image Classification (we extended the tiny-DNN C++ library)
- For K-NN 16b posit is as accurate as FP32, 8b posit is better than FP16
- For DNN (image classification) 10b posit is as accurate as FP32 (>98.5% of correct classification), 8b posit still provides very high accuracy (>97%)
- The K-NN algorithm searches for the K points in a dataset that are the closest to a given query point. K-NN can be computed in an exact or approximated manner.

• Implemented the approximated NN, using floats and posits

• Compared the 2 formats on 2 standard benchmarks: Fashion Mnist 784 Euclidean & SIFT-128-Euclidean



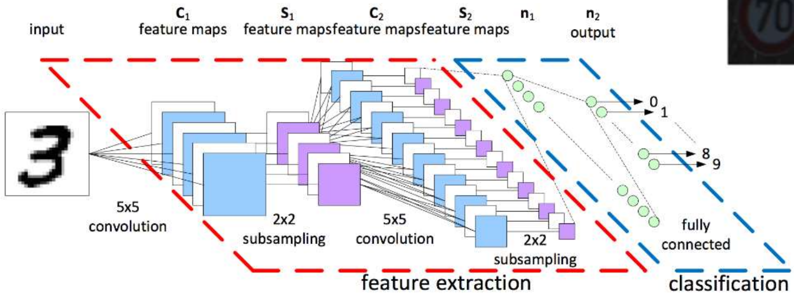
The scaling factor re-scales the dynamic range of the original dataset, without affecting relative dynamic.
Scale 1.0: original dataset. For a given scaling factor, the higher the precision, the better

Experiments with Deep-Neural Networks

- We integrated the cppPosit library with tiny-DNN open source C++ lib
- A posit12 DNN reaches the same accuracy of FP32
- To speedup the learning phase, we tabulated the posits (LUT)
- Acceptable performance can even be attained using an 8-bit

Data Type (tot_bits, exp_bits)	**Accuracy on 10,000 images**
Float32	98,88%
Posit16,2	98,88%
Posit14,2	98,85%
Posit12,2	98,66%
Posit10,0	**98,69%**
Posit8,0	**97,24%**

Type	Accuracy
Float32	94.0%
Posit16,0	94.0%
Posit14,0	94.0%
Posit12,0	94.0%
Posit10,0	94.0%
Posit8,0	93.8%



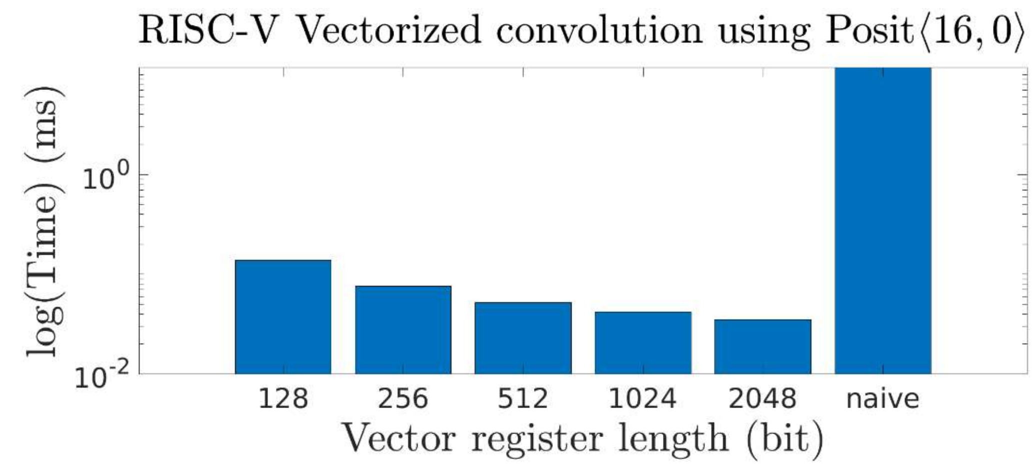
- **MNIST** dataset: 10 classes, 10,000 samples
- Convolutional Neural Network

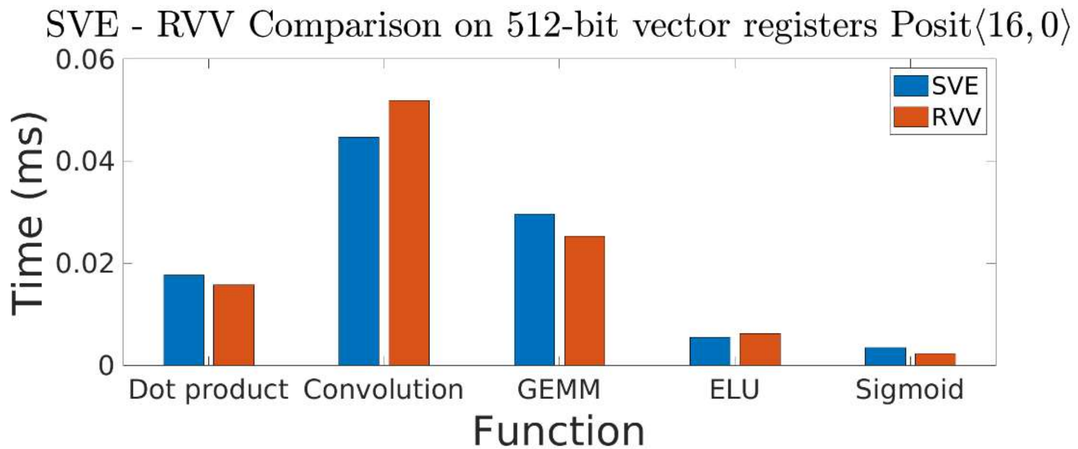
- Similar results obtained on **CIFAR10**.
- Currently investigating the **ImageNet** dataset, using the AlexNet pre-trained network

CppPosit on RISC-V and ARM SVE

Version	AlexNet	ResNet34	VGG16	VGG19	ResNet152
Naive	40.06	146.07	590.68	675.32	779.7
SVE128	2.76	10.07	40.74	46.57	53.77
SVE256	2.64	9.61	38.88	44.45	51.32
SVE512	2.54	8.93	36.12	41.30	47.68
SVE1024	2.44	8.92	36.06	41.23	47.60
SVE2048	2.34	8.90	35.97	41.13	47.48

Image processing time (in seconds) for various very DNN models using posit8

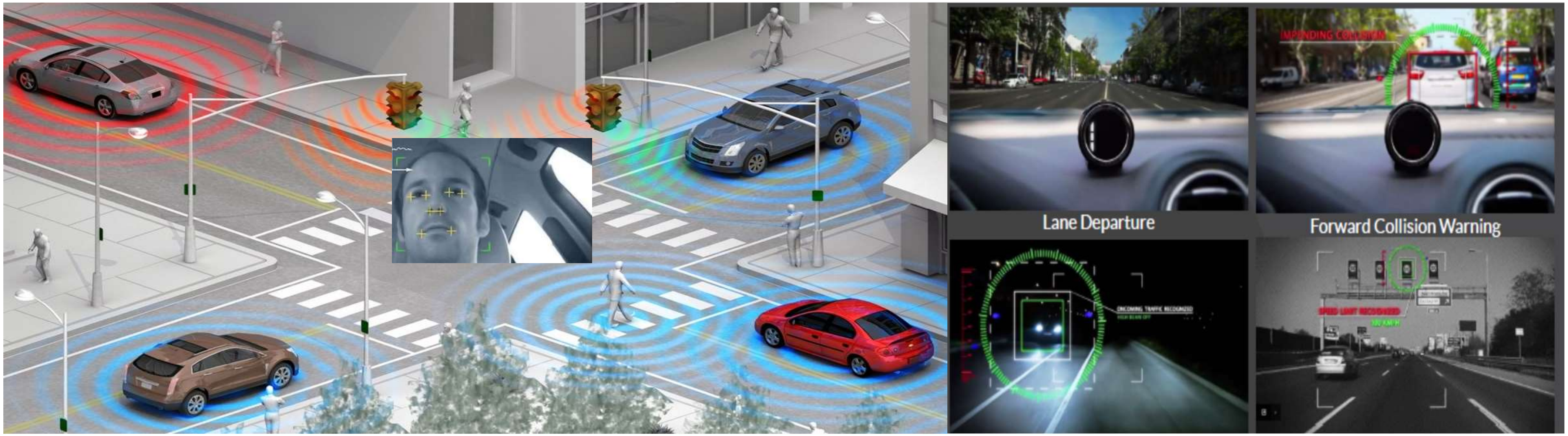




Conclusions

- Posits have the potential to overcome FP issues in ML and DNN
- Posits may reduce the bandwidth bottleneck (R/W from/to MEMs)
- Have beneficial effects on vectorizable applications, since data are generally shorter
- Posits are cache friendly, posit8/16 can replace FP16/FP32
- A posit library developed at UniPI (cppPosit) running on ARM v8 SVE and RISC-V with V extension

Conclusions & on-going activities



Smart vehicles and ITS are a huge R&D field for I&M

Minimizing bias and random errors in intertial sensors

Fusion of Radar, cameras, Lidar & intertial sensors for ADAS

Sensing technologies for natural HMI & contactless biometric measurements

V2X (802.11p) and Cellular-V2X (4GLTE/5G) wireless, robust and secure links

HW accelerators for ML and DNN for sensor fusion & classification

Innovative acquisition units for predictive diagnostic capabilities

Thanks for your attention

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https://www.youtube.com/watch?v=Bg8zw1SWiJA&feature=youtu.be

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