Departamento de
electrónica

Universidad
de Alcalá

Acoustic
Local Positioning Systems

Jesús Ureña Ureña (UAH)
Álvaro Hernández Alonso (UAH)
Fernando J. Álvarez Franco (UEX)

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GEINTRA Research Group

Electronic Engineering Applied to Intelligent Spaces and Transport Group
www.geintra-uah.org
jesus.urena@uah.es

geintra

University of Extremadura

fafranco@unex.es

UNIVERSITY OF ALCALÁ

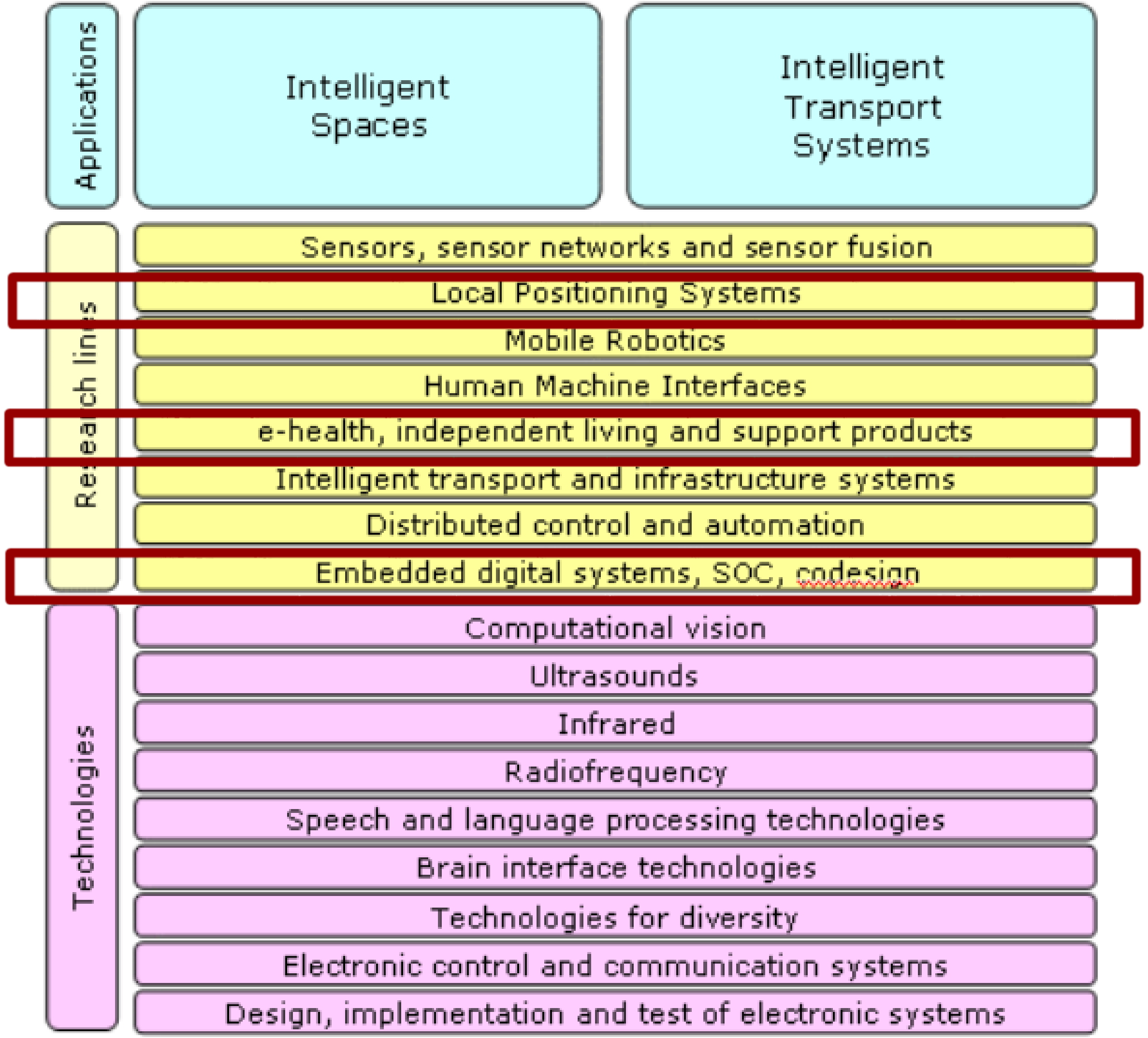
- Long-history University (founded in 1499 by Cardinal Cisneros)
- It was declared by UNESCO a World Heritage Site in December 1998

GEINTRA RESEARCH GROUP

- Smart Spaces and Intelligent Transport Research Group
  - Faculty members: 24
  - Non-permanent staff: 42 (currently)

- RF&US Subgroup
  - Faculty members: 7
  - Non-permanent staff: 12

Activity areas



Applications
- Intelligent Spaces
- Intelligent Transport Systems

Research lines
- Sensors, sensor networks and sensor fusion
- Local Positioning Systems
- Mobile Robotics
- Human Machine Interfaces
- e-health, independent living and support products
- Intelligent transport and infrastructure systems
- Distributed control and automation
- Embedded digital systems, SOC, codesign

Technologies
- Computational vision
- Ultrasounds
- Infrared
- Radiofrequency
- Speech and language processing technologies
- Brain interface technologies
- Technologies for diversity
- Electronic control and communication systems
- Design, implementation and test of electronic systems

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Departamento de

electrónica

Introduction to ALPS

- APS: Any system that makes use of mechanical waves to determine the location of a person/object.

- First APSs were developed in the 60s of the former century in underwater environments…

Nuclear bomb recovered in 1966 by the US Navy in the Spanish coast, after a B-52 crash

Introduction to ALPS

- Since then, underwater APS have been widely used in a variety of applications:

Marine archaeology, gas exploration, salvage operations…

- The high popularity of underwater APS is a consequence of the difficulty to use EM signals is seawater:

$$s \approx 4 \text{ S/m} \;\rightarrow\; a \approx 0.004\sqrt{f} \text{ Np/m}$$

Frequency	35 dB Penetration depth
10 kHz (VLF)	31.6 m
1 MHz (AM)	1 m
100 MHz (FM)	0.1 m
2.4 GHz (WiFi)	0.02 m

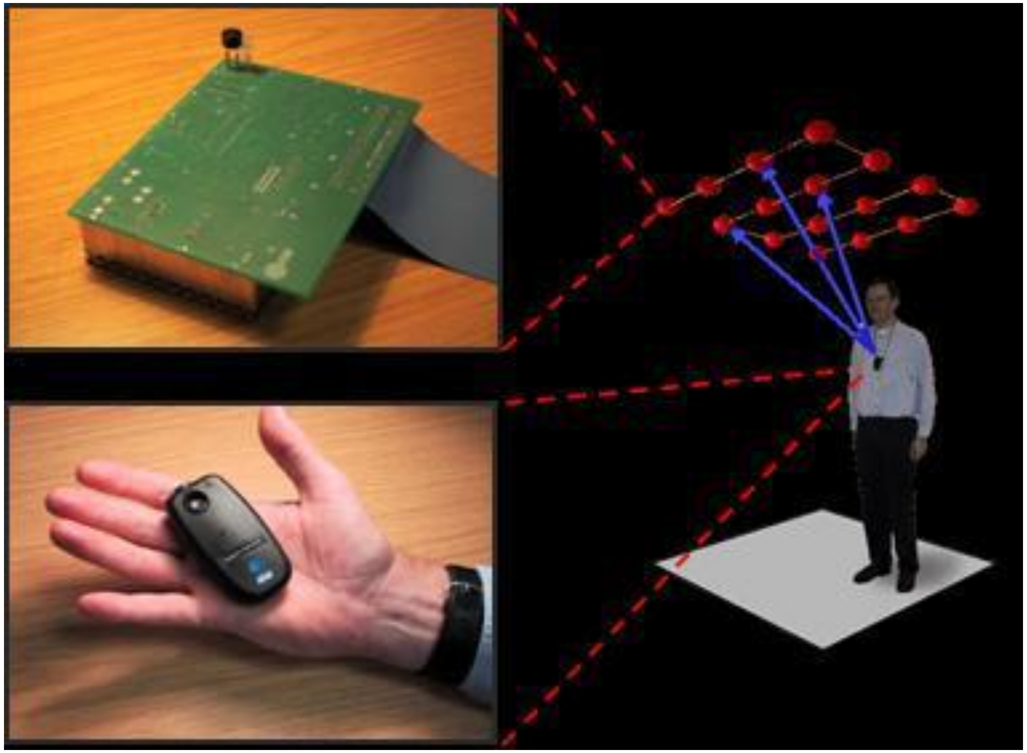
An acoustic 10 kHz signal would have an equivalent penetration depth ≈ **34.3 km!**

Introduction to ALPS

- Nevertheless, our interest here is focused on airborne APS.
- These systems started being developed in the late 80s of the former century…

ACTIVE BAT
(AT&T Labs Cambridge,
2001)

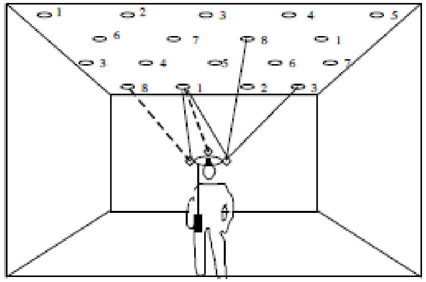
Centralized
Spherical lateration (TOA)
A 433 MHz RF signal is used to request the US emission of a bat (40 kHz for 50 us)
Update rate of 50 Hz



Source: www.uk.research.att.com/bat/

Narrowband Ultrasonic LPSs

- 1st: Lincoln Wand, MIT, Roberts 1966.
  - Pen with an ultrasonic emitter to create a wide bandwidth pulse of sound (20 kHz to 100 kHz). TOF to four microphones.
- Constellation, MIT & Intersense, 1998
  - Ultrasonic LPS + inertial monitoring unit
  - Virtual Reality head tracker application
  - 161 citations
  - 2mm



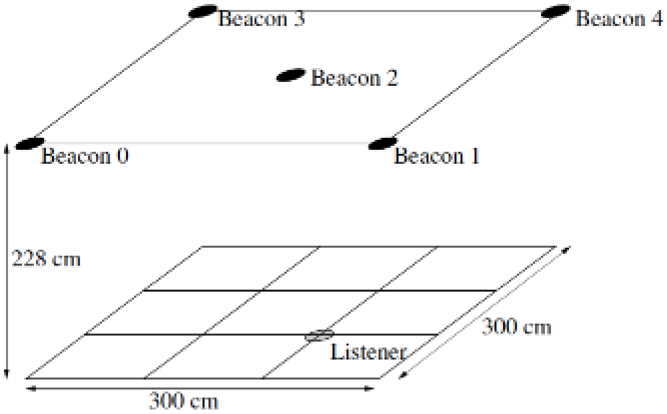
- Bats, AT&T, 1999
  - Office application, MD is emitter
  - 1250 citations
  - 9 cm

- Cricket, MIT, 2000
  - "The Cricket Location-Support System"
  - 2691 citations
  - 2 cm

Introduction to ALPS

CRICKET
(MIT, 2005)

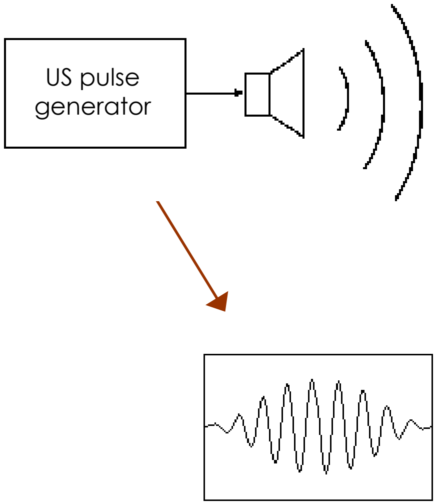
Loosely centralized
Spherical lateration (TOA)
Independent beacons transmit a 433 MHz RF signal to inform about their position together with a 40 kHz US pulse of 125 us
Specific algorithmic is developed to eliminate interference.

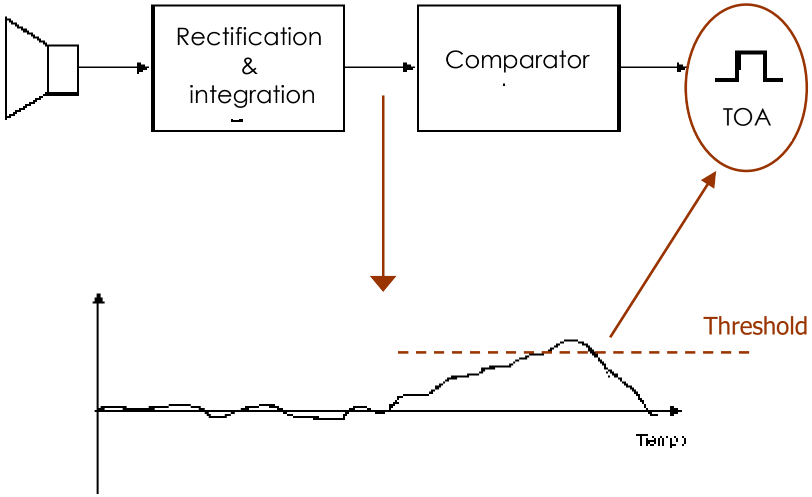


Source: http://nms.csail.mit.edu/papers/bodhi-thesis.pdf

Introduction to ALPS

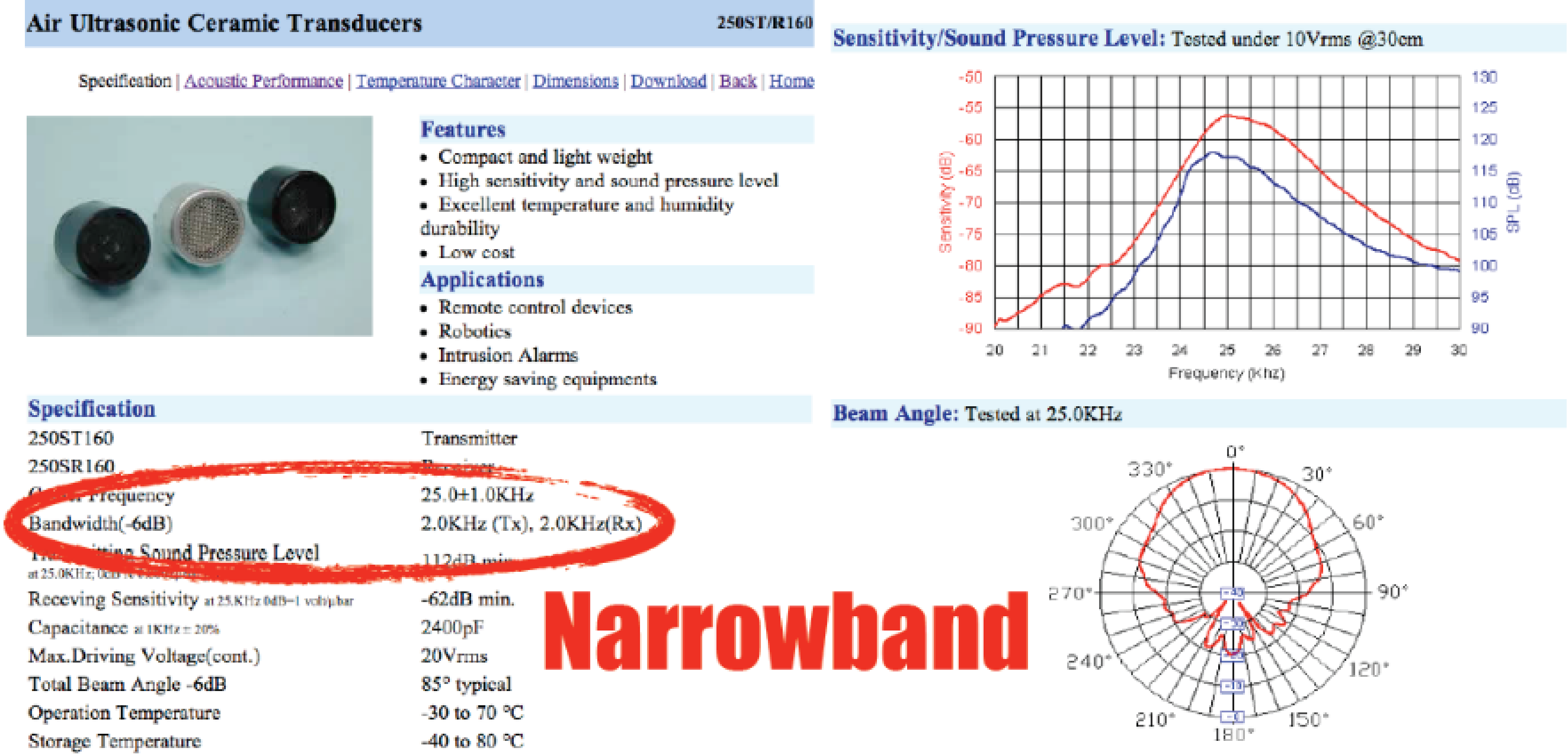
- All these systems are now considered narrow-frequency systems, based on envelope detection:





- Common drawbacks:
  - Low accuracy
  - Low robustness against in-band noise
  - Low update rate

Ultrasonic Transducers



Air Ultrasonic Ceramic Transducers **250ST/R160**

Specification | Acoustic Performance | Temperature Character | Dimensions | Download | Back | Home

Features

- Compact and light weight
- High sensitivity and sound pressure level
- Excellent temperature and humidity durability
- Low cost

Applications

- Remote control devices
- Robotics
- Intrusion Alarms
- Energy saving equipments

Specification

250ST160	Transmitter
250SR160	Receiver
Center Frequency	25.0±1.0KHz
Bandwidth(-6dB)	2.0KHz (Tx), 2.0KHz(Rx)
Transmitting Sound Pressure Level at 25.0KHz; 0dB re [illegible]	112dB min.
Receving Sensitivity at 25.KHz 0dB=1 volt/µbar	-62dB min.
Capacitance at 1KHz ± 20%	2400pF
Max.Driving Voltage(cont.)	20Vrms
Total Beam Angle -6dB	85° typical
Operation Temperature	-30 to 70 °C
Storage Temperature	-40 to 80 °C

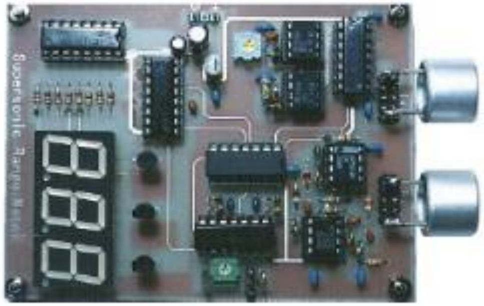
Sensitivity/Sound Pressure Level: Tested under 10Vrms @30cm

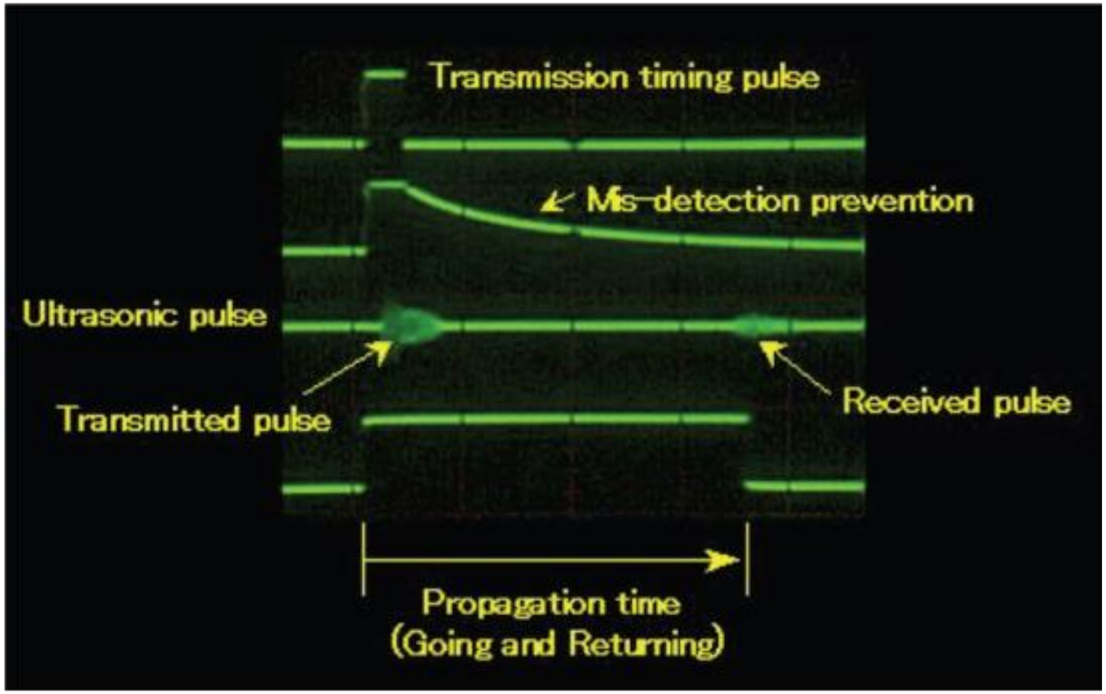
Beam Angle: Tested at 25.0KHz

Narrowband

Range Finder

- Tx: Electrical pulse => ultrasonic pulse or “ping”
- Rx: ultrasonic pulse => electrical pulse => threshold detect





“Ultrasonic tracking localization system based on DSP”

www.piclist.com

Ranging

- Ranging is based on:

$$\hat{r} = \frac{1}{2}(t_a - t_e)c$$

$\hat{r}$ = estimated range

t_a = Time Of Arrival (TOA) of signal

t_e = Time Of Emission (TOE) of signal

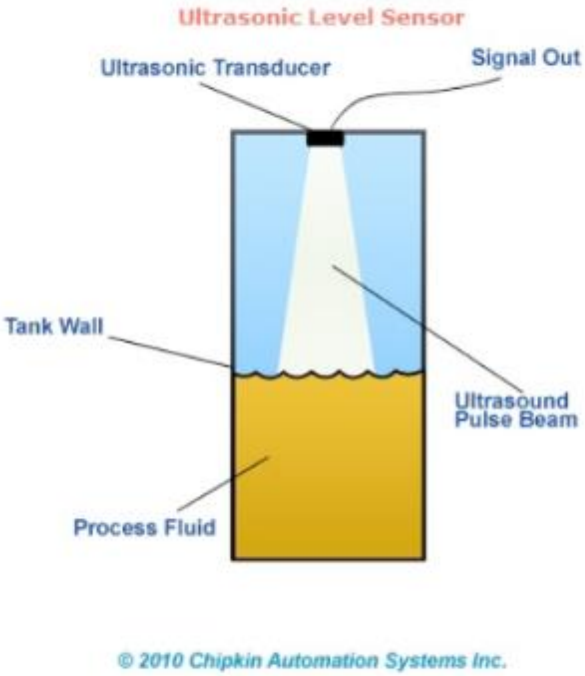
$t_f = t_a - t_e$ = Time Of Flight (TOF) of signal

c = speed of signal

- For sound: $c = 343$ m/s
- For light & radio signals: $c = 299{,}792{,}458$ m/s

- For a given time precision, ultrasonic signals give a much better range precision.

Ultrasonic Range Finders



Level Sensors

Car Reverse Parking Radar

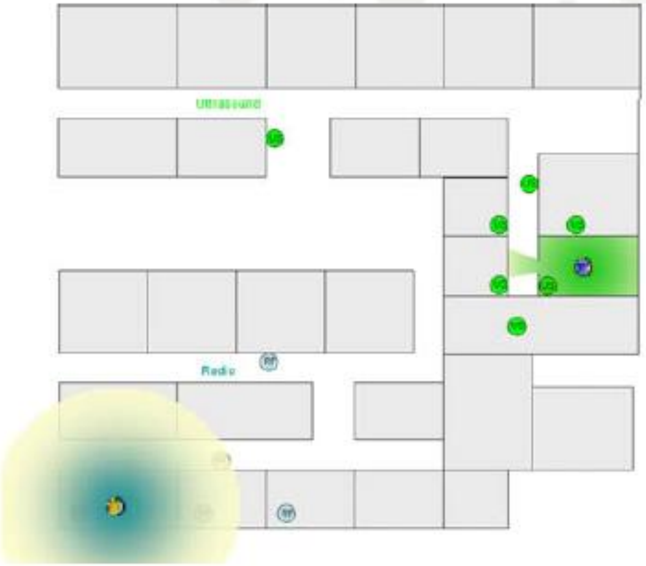
Parking Sensor

Commercial Narrowband LPSs

Sonitor Technologies

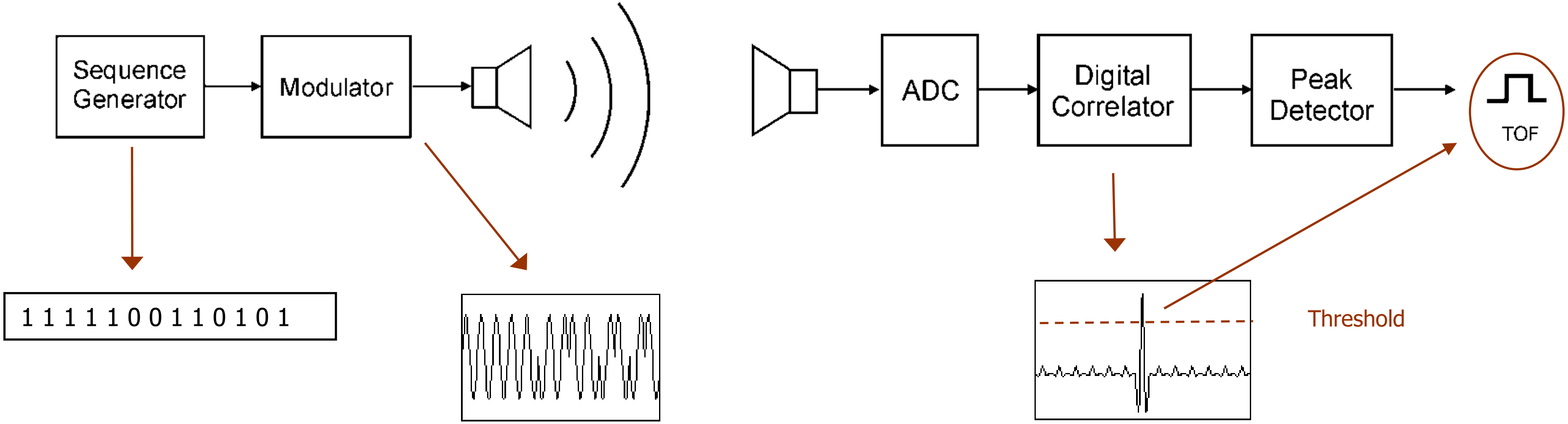
- Scientific American: A Positioning System That Goes Where GPS Can't, January, 2008
- Sonitor Technologies: now at more than 30 hospitals in the US
  - Patient tracking
  - Equipment tracking

RFID vs Ultrasound



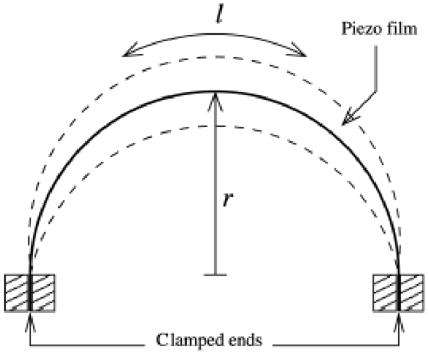
- Ultrasonic Identification (USID)
- Researching infectious disease surveillance

- These problems are overcome by introducing spread-spectrum techniques already applied in radar systems.



Wideband Ultrasonic Transducers

- EMFi
  - high polarization voltages => power consumption issues
- Piezoelectric film (polyvinylidene flouride) (PVDF)
  - E.g. MSI US40KT-01 40kHz centre frequency 8kHz bandwidth
  - E.g. Hazas and Ward, “A Novel Broadband Ultrasonic Location System”, 2002.
  - Custom, can be expensive



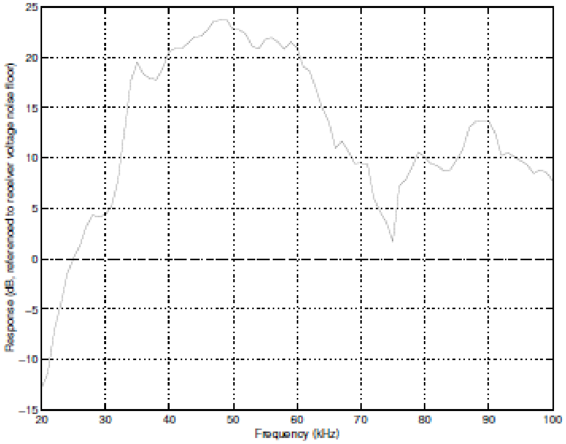


Fig. 6. Ultrasonic channel bandwidth at one metre (receiver noise floor shown as a dashed line)

Introduction to ALPS

- At the beginning of this century, the first broadband systems begin to develop.

UNIV. CAMBRIDGE, 2002

Centralized system (Privacy-oriented in 2003)
511-bit Gold code BPSK modulated with 2.5 cycles of a 50 kHz carrier (25.6 ms)

Spherical lateration

Accuracy around 2 cm

Source: http://comp.eprints.lancs.ac.uk/1610/1/Hazas02_ANovelBULS.pdf

Introduction to ALPS

- At the beginning of this century, the first broadband systems begin to develop.

UAH & CSIC & UEX, 2007

Privacy oriented

255-bit Kasami codes BPSK modulated with 1 cycle of a 50 kHz carrier (5.1 ms)

Hyperbolic Lateration

Reported errors in the range of mm

Introduction to ALPS

- The current tendency is oriented to the design of APS for portable devices (smartphones/tablets)
- This objective has two main implications: shifting down the operation frequency and adapting the signal processing algorithms to the limited computing capability of these devices.

BEEP SYSTEM, 2005

PDA HP iPAQ 5550

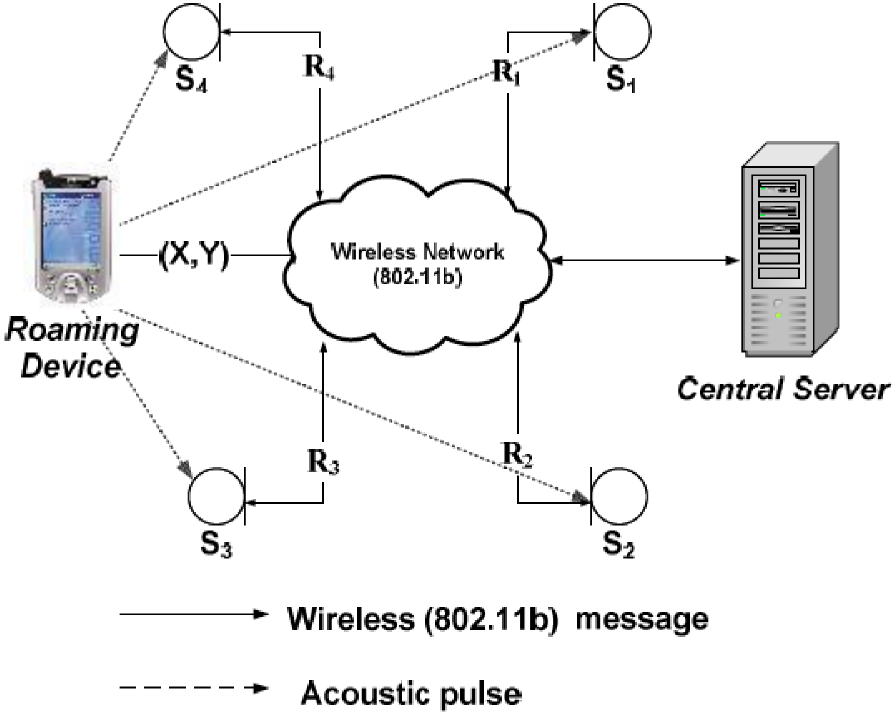
Acoustic sensors connected to central server

Centralized system

Acoustic pulses of 4.01 kHz and 100 ms

Spherical lateration

Accuracy around 1 m



Introduction to ALPS

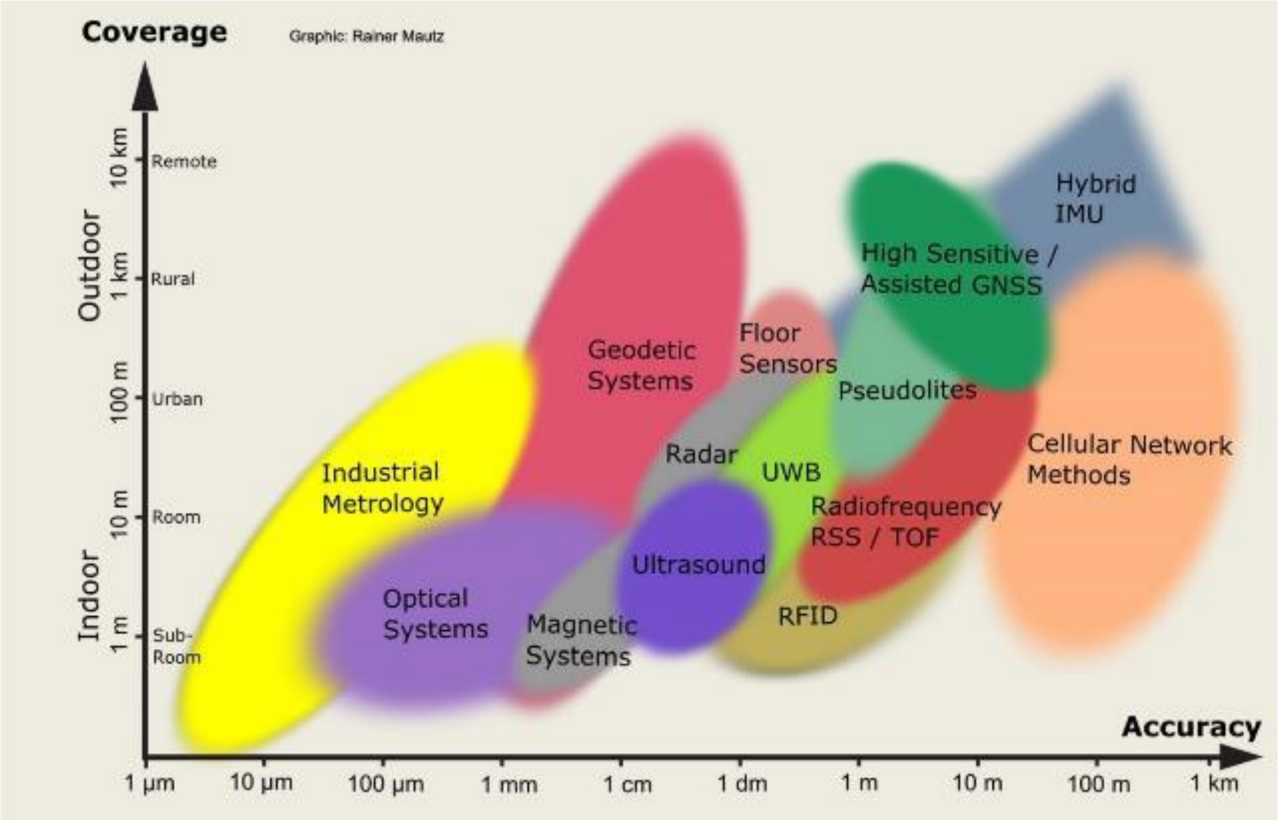
- The current tendency is oriented to the design of APS for portable devices (smartphones/tablets)

GISS-UEx, 2016

Privacy oriented
iPad Air 2
63 bit Kasami codes BPSK modulated with 1 cycle of a 16 kHz carrier (3.9 ms)
Hyperbolic lateration
Multipath and MAI cancellation algorithms
Accuracy around 8 cm

Introduction to ALPS

- Today acoustic systems are considered a classical solution within LPS.
- Although not majority, it is an important technology in the field.



Source: R. Mautz, Indoor Positioning Technologies, Institute of Geodesy and Photogrammetry, Department of Civil, Environmental and Geomatic Engineering, ETH Zurich, 2012.

IPIN Conference	Percentage of APS papers
2010	7,58%
2011	10,57%
2012	9,09%
2013	7,69%
2014	2,91%
2015	5,06%
2016	10,32%

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POSITIONING

- Typical observables used to compute the user position are:
  - Power (RSS)
  - Time of Arrival (TOA)
  - Time Difference of Arrival (TDOA)
  - Angle of Arrival (AOA)
  - Proximity (Cell ID)
  - Fingerprinting

- From all of them, those typically used in APS are
  - ➢ Time of Arrival (TOA): Trilatelation or Spherical lateration
  - ➢ Time Difference of Arrival (TDOA): Multilateration or Hyperbolic Lateration

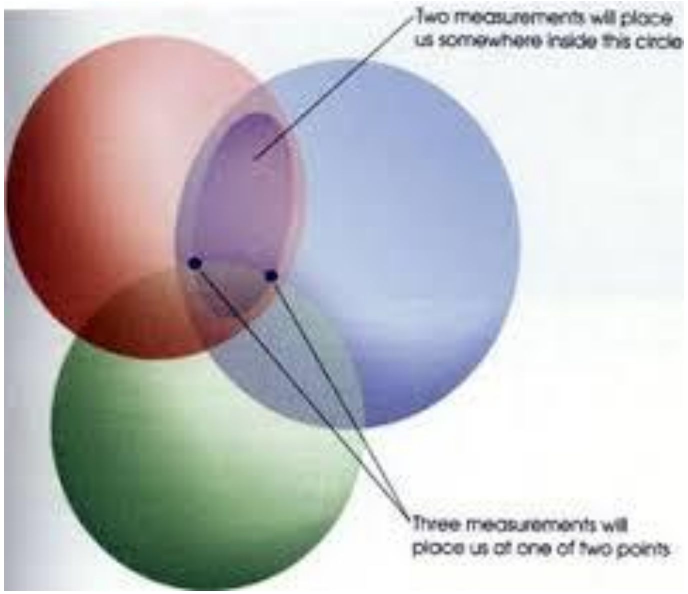
POSITIONING

TOAs-based positioning: Spherical Lateration

- TOAs are converted into absolute distances to the reference points (beacons): $d_i = c \cdot (TOA_i - t_{TX})$

- Location is then obtained as the intersection of the spherical surfaces defined by these distances:

$$d_i = \|\vec{r}_i - \vec{r}\| = \sqrt{(x_i - x)^2 + (y_i - y)^2 + (z_i - z)^2}$$



Source: ORPALIS

- In 3D geometry, a minimum of 3 TOAs are neccessary to narrow the possible locations down to two (from which only one is usually coherent)

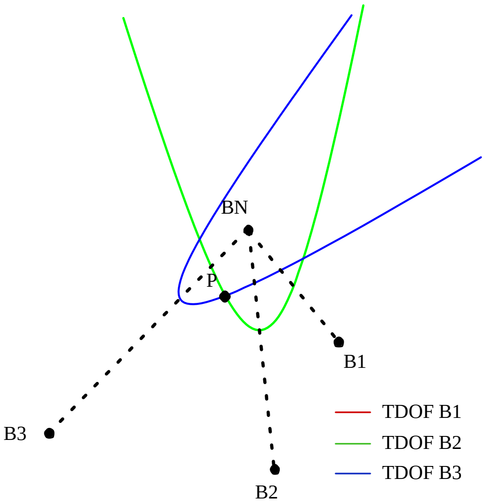
- The problem of this positioning method is that the receiver must know the precise moment of emission, and TX-RX clocks must be synchronized.

POSITIONING

TDOAs-based positioning: Hyperbolic Lateration

- TDOAs are converted into differential distances to pairs of reference points (beacons):

$$d_{ij} = c \cdot TDOA_{ij}$$



- Location is then obtained as the intersection of the hyperbolic surfaces defined by these differential distances:

$$d_i - d_j = \|\vec{r}_i - \vec{r}\| - \|\vec{r}_j - \vec{r}\| =$$

$$= \sqrt{(x_i - x)^2 + (y_i - y)^2 + (z_i - z)^2} - \sqrt{(x_j - x)^2 + (y_j - y)^2 + (z_j - z)^2}$$

- In 3D geometry, a minimum of 3 TDOAs (4 beacons) are necessary to narrow the possible locations down to two (from which only one is usually coherent)

- In this positioning method only emitters must be synchronized.

POSITIONING

Positioning Equations Solutions

- In both lateration methods, the position is given by the solution of a system of non-linear equations:

$$d_1 = \|\vec{r}_1 - \vec{r}\| = \sqrt{(x_1 - x)^2 + (y_1 - y)^2 + (z_1 - z)^2}$$
$$d_2 = \|\vec{r}_2 - \vec{r}\| = \sqrt{(x_2 - x)^2 + (y_2 - y)^2 + (z_2 - z)^2}$$
$$d_3 = \|\vec{r}_3 - \vec{r}\| = \sqrt{(x_3 - x)^2 + (y_3 - y)^2 + (z_3 - z)^2}$$

- There are two main strategies to solve this type of systems:

Method	Linarization strategy	Advantages	Disadvantages
Closed-solution	Introduction of new unknowns	Fast	• Less precise • Needs more beacons
Iterative	Linearization from an initial estimate	More precise	• Slower • Needs an initial estimation

Closed solution methods: the Bancroft method

- Squaring the previous equations we ha $d_i^2 = (x_i - x)^2 + (y_i - y)^2 + (z_i - z)^2$
- Rearranging terms: $d_i^2 - x_i^2 - y_i^2 - z_i^2 = -2x_i x - 2y_i y - 2z_i z + x^2 + y^2 + z^2$
- And introducing the new variable *B* = $x^2+y^2+z^2$ we obtain the following system of 4 linear equations for the 4 unknowns (*x*, *y*, *z*, *B*)

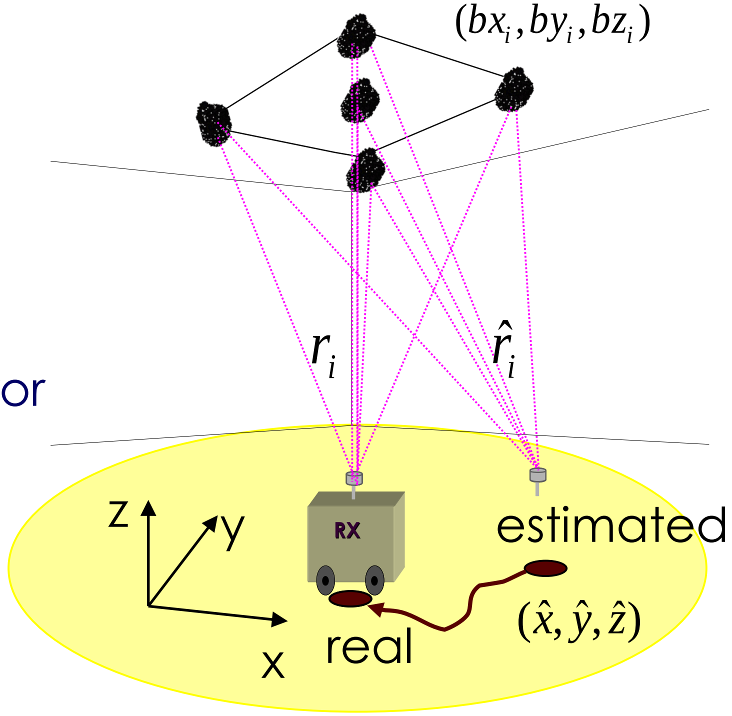
$$\begin{bmatrix} -2x_1 & -2y_1 & -2z_1 & +1 \\ -2x_1 & -2y_1 & -2z_1 & +1 \\ -2x_1 & -2y_1 & -2z_1 & +1 \\ -2x_1 & -2y_1 & -2z_1 & +1 \end{bmatrix} \times \begin{bmatrix} x \\ y \\ z \\ B \end{bmatrix} = \begin{bmatrix} d_1^2 - x_1^2 - y_1^2 - z_1^2 \\ d_2^2 - x_2^2 - y_2^2 - z_2^2 \\ d_3^2 - x_3^2 - y_3^2 - z_3^2 \\ d_4^2 - x_4^2 - y_4^2 - z_4^2 \end{bmatrix}$$

- Note that by squaring the equations we also square the noise contribution, thus causing a lack in precision.

Iterative methods: the Gauss-Newton algorithm (spherical case)

Initial Data:

- Estimated Mobile Position (**emp**): $(\hat{x}, \hat{y}, \hat{z})$
- Beacon positions: (bx_i, by_i, bz_i)
- Measured Distances from the beacons: r_i



Goal: To minimize the mean quadratic error of distances:

$$F(x,y,z) = \sum_{i=1}^{n} \left(\hat{r}_i - r_i\right)^2 = \sum_{i=1}^{n} \left[f_i(x,y,z)\right]^2$$

with $f_i(\hat{x}, \hat{y}, \hat{z}) = \sqrt{(bx_i - \hat{x})^2 + (by_i - \hat{y})^2 + (bz_i - \hat{z})^2} - r_i$

Obtaining:

$$\mathbf{A} \cdot \mathbf{\Delta X} = \mathbf{B}$$

$$\mathbf{\Delta X} = \begin{pmatrix} \frac{\partial F}{\partial \hat{x}} \\ \frac{\partial F}{\partial \hat{y}} \\ \frac{\partial F}{\partial \hat{z}} \end{pmatrix}; \quad \mathbf{A} = \begin{pmatrix} \frac{\partial f_1}{\partial \hat{x}} & \frac{\partial f_1}{\partial \hat{y}} & \frac{\partial f_1}{\partial \hat{z}} \\ \frac{\partial f_2}{\partial \hat{x}} & \frac{\partial f_2}{\partial \hat{y}} & \frac{\partial f_2}{\partial \hat{z}} \\ \vdots & \vdots & \vdots \\ \frac{\partial f_n}{\partial \hat{x}} & \frac{\partial f_n}{\partial \hat{y}} & \frac{\partial f_n}{\partial \hat{z}} \end{pmatrix}; \quad \mathbf{B} = \begin{pmatrix} f_1 \\ f_2 \\ \vdots \\ f_n \end{pmatrix} \quad \textit{where} \quad \frac{\partial f_i}{\partial \hat{a}} = \frac{(\hat{a} - ba_i)}{\hat{r}_i}$$

$$f_i = \left(\hat{r}_i - r_i\right)$$

Solving by LMS:

$$\mathbf{\Delta X} = \left(\mathbf{A}^T \cdot \mathbf{A}\right)^{-1} \cdot \mathbf{A}^T \cdot \mathbf{B}$$

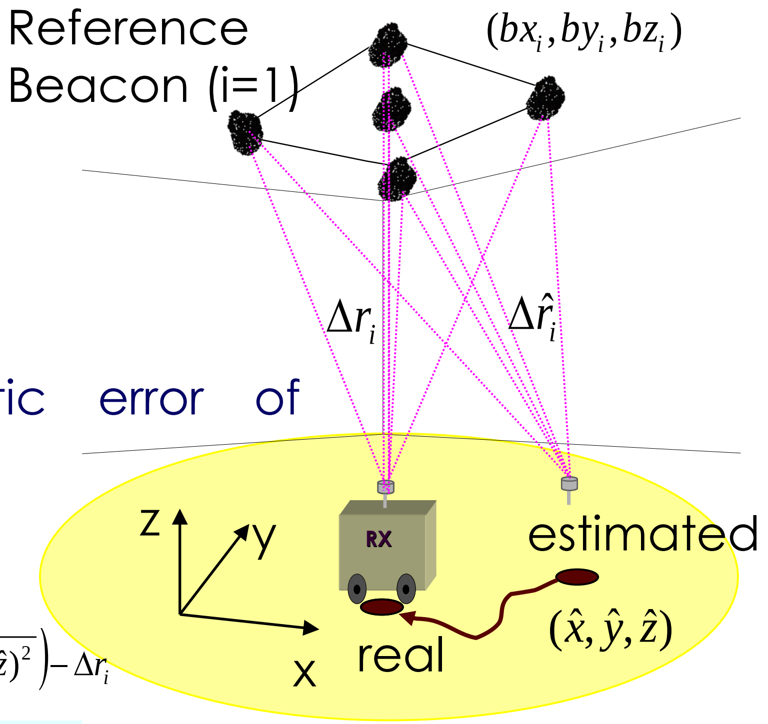
And iterating:

$\mathbf{emp}_{k+1} = \mathbf{emp}_k - \Delta \mathbf{X}_k$

Iterative methods: the Gauss-Newton algorithm (hyperbolic case)

Initial Data:

- Estimated Mobile Position (**emp**): $(\hat{x},\hat{y},\hat{z})$
- Beacon positions: (bx_i, by_i, bz_i)
- Measured Increment of Distances from the beacons (using one as reference): Δr_i



Goal: To minimize the mean quadratic error of incremental distances:

$$F(\hat{x},\hat{y},\hat{z}) = \sum_{i=2}^{n} \left(\Delta\hat{r}_i - \Delta r_i\right)^2 = \sum_{i=2}^{n} \left[f_i(\hat{x},\hat{y},\hat{z})\right]^2$$

with

$$f_i(\hat{x},\hat{y},\hat{z}) = \left(\sqrt{(bx_i-\hat{x})^2+(by_i-\hat{y})^2+(bz_i-\hat{z})^2} - \sqrt{(bx_1-\hat{x})^2+(by_1-\hat{y})^2+(bz_1-\hat{z})^2}\right) - \Delta r_i$$

Obtaining:

$$\mathbf{A}\cdot\Delta\mathbf{X} = \mathbf{B}$$

$$\Delta\mathbf{X} = \begin{pmatrix} \frac{\partial F}{\partial \hat{x}} \\ \frac{\partial F}{\partial \hat{y}} \\ \frac{\partial F}{\partial \hat{z}} \end{pmatrix}; \quad \mathbf{A} = \begin{pmatrix} \frac{\partial f_1}{\partial \hat{x}} & \frac{\partial f_1}{\partial \hat{y}} & \frac{\partial f_1}{\partial \hat{z}} \\ \frac{\partial f_2}{\partial \hat{x}} & \frac{\partial f_2}{\partial \hat{y}} & \frac{\partial f_2}{\partial \hat{z}} \\ \vdots & \vdots & \vdots \\ \frac{\partial f_n}{\partial \hat{x}} & \frac{\partial f_n}{\partial \hat{y}} & \frac{\partial f_n}{\partial \hat{z}} \end{pmatrix}; \quad \mathbf{B} = \begin{pmatrix} f_1 \\ f_2 \\ \vdots \\ f_n \end{pmatrix} \quad where \quad \frac{\partial f_i}{\partial \hat{a}} = \frac{(\hat{a}-ba_i)}{\hat{r}_i} - \frac{(\hat{a}-ba_1)}{\hat{r}_1}$$

$$f_i = \left(\Delta\hat{r}_i - \Delta r_i\right)$$

Solving by LMS:

$$\Delta\mathbf{X} = \left(\mathbf{A}^T\cdot\mathbf{A}\right)^{-1}\cdot\mathbf{A}^T\cdot\mathbf{B}$$

And iterating:

emp$_{k+1}$ = **emp**$_k$ - **Δ****X**$_k$

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Departamento de
electrónica

Particularities of APS

1. High absorption, strongly dependent on Frequency, Temperature and Humidity (ISO-9613)

$$\alpha\ (Np/m) = f^2\left\{18.4\cdot10^{-12}\left(\frac{P}{P_r}\right)^{-1}\left(\frac{T}{T_{20}}\right)^{\frac{1}{2}} + \left(\frac{T}{T_{20}}\right)^{\frac{-5}{2}}\left[0.01275\frac{e^{-2239.1/T}}{f_{ro}+f^2/f_{ro}} + 0.1068\frac{e^{3352/T}}{f_{rn}+f^2/f_{rn}}\right]\right\}$$

f =40 kHz

	Air (T=20, H=50%)	**Seawater (T=8°C, S=35 ppt)**
Absorption	1.31 dB/m	11.3 dB/km
35dB penetration depth	26.6 m	3.1 km

Particularities of APS

2. Low propagation speed, strongly dependent on Temperature:

$$c = 331.23 \times \sqrt{1 + \frac{T}{273.15}}\ \text{m/s} \qquad c = 343\ \text{m/s}\ \ (T = 20^{\circ} C)$$

☺ High resolution:

d = 1cm
→

ΔTDV-US ≈ 29 µs

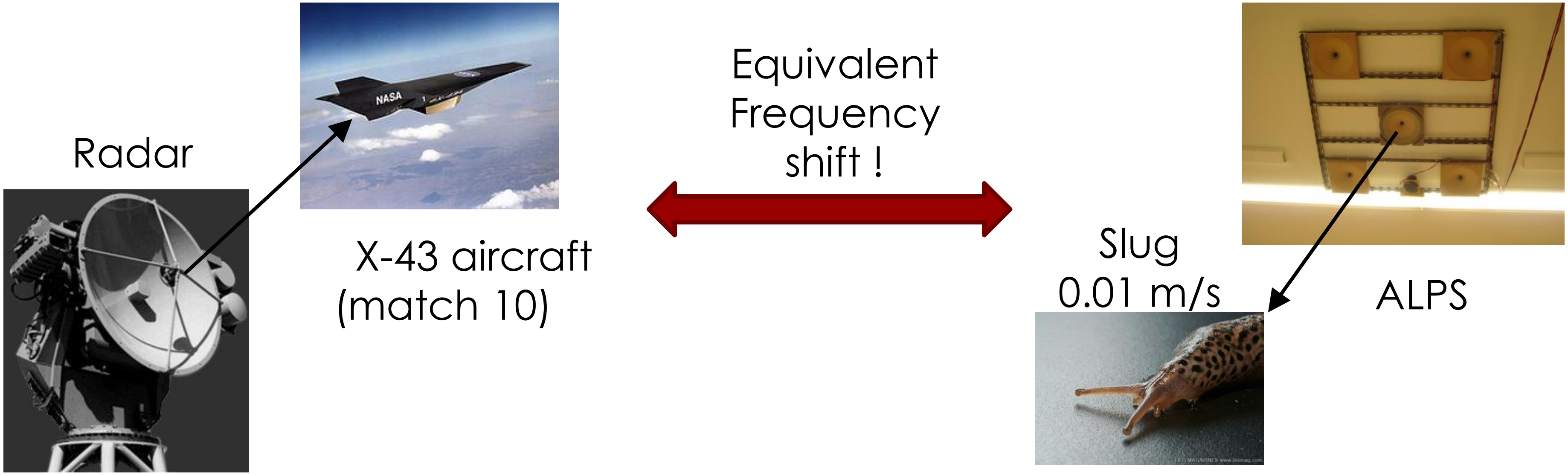
ΔTDV-RF ≈ 33 ps

POSITIONING

2. Low propagation speed, strongly dependent on Temperature:

$$c = 331.23 \times \sqrt{1 + \frac{T}{273.15}}\ \text{m/s} \qquad c = 343\ \text{m/s}\ \ (T = 20^{\circ} C)$$

Strong Doppler shift:



Radar

X-43 aircraft (match 10)

Equivalent Frequency shift !

Slug 0.01 m/s

ALPS

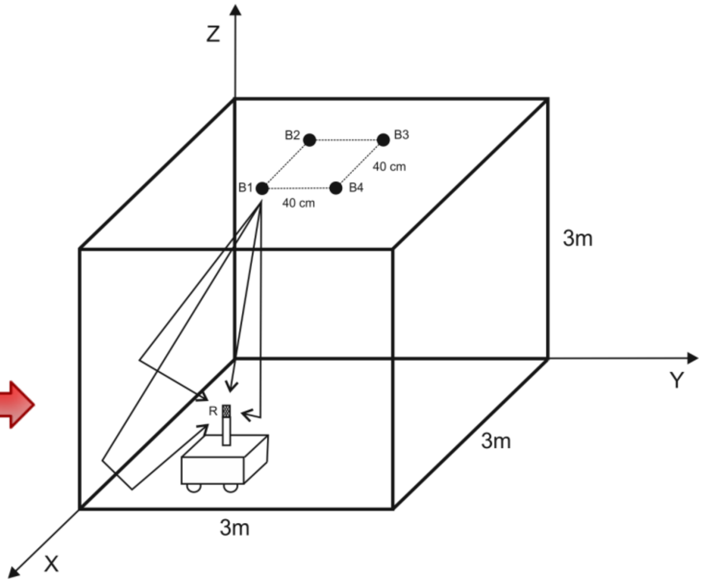
Particularities of APS

3. Very low acoustic impedance of the propagation medium:

Material	Acoustic impedance (Rayls)
Air	413
Wood	$1.57 \cdot 10^6$
Brick	$7.40 \cdot 10^6$
Marble	$10.5 \cdot 10^6$
Glass	$13.0 \cdot 10^6$

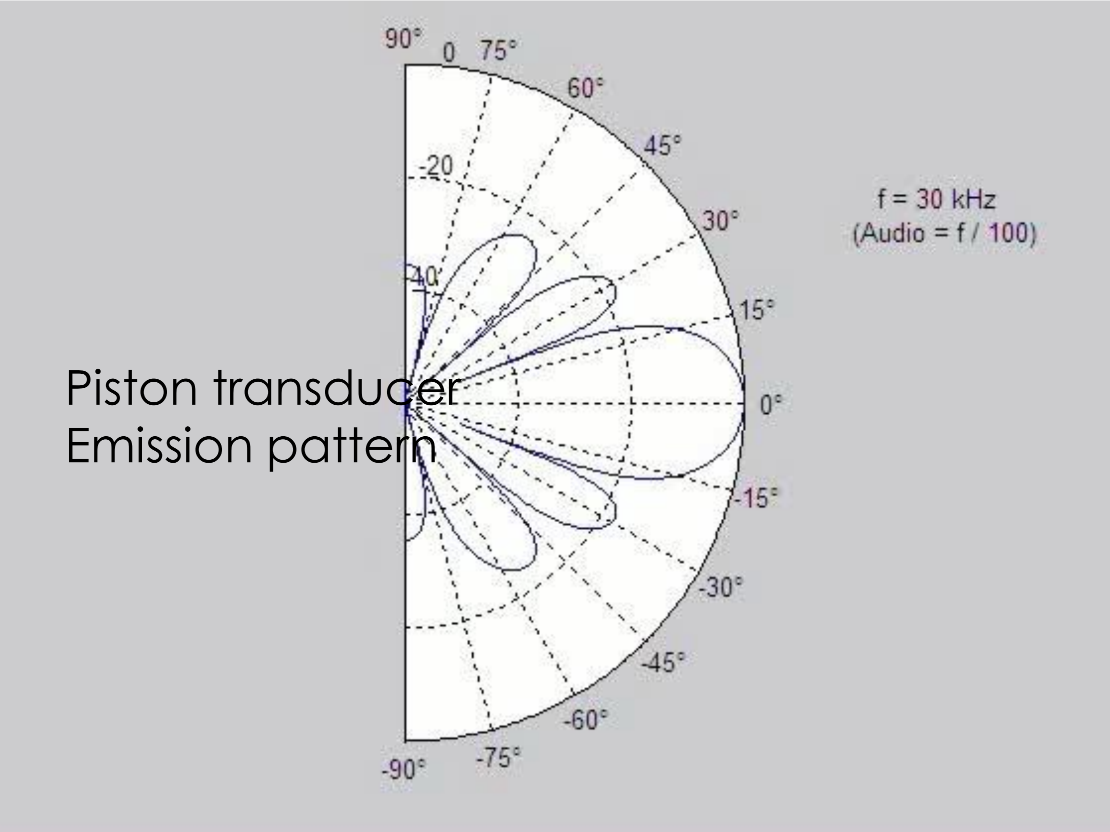
☺ Confined emissions

☹ Strong reflections (mostly specular) → Strong Multipath →



Particularities of APS

4. High directionality of acoustic transducers:



Piston transducer
Emission pattern

Big Brown Bat
(Eptesicus Fuscus)

🙂 Energy focusing

🙁 Coverage problems

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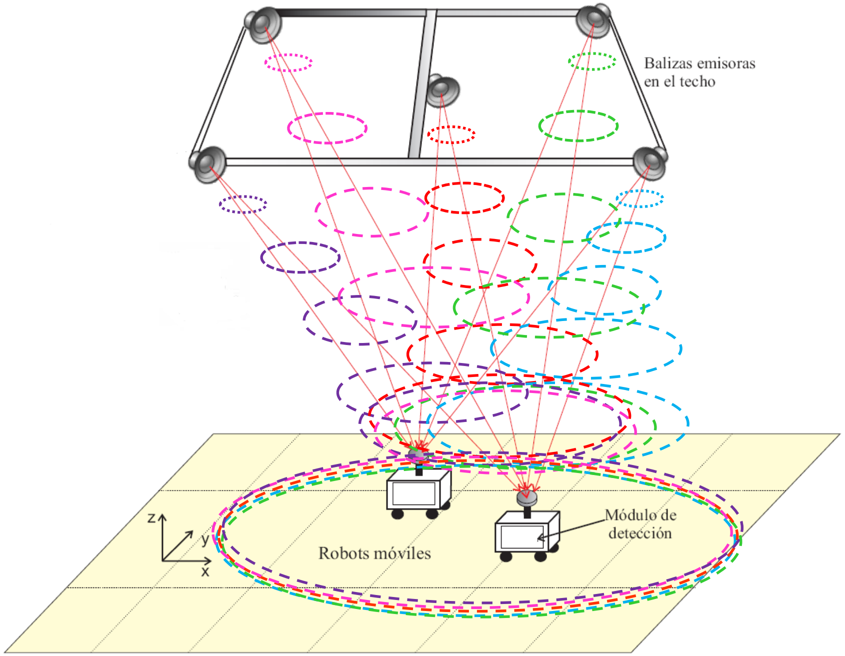
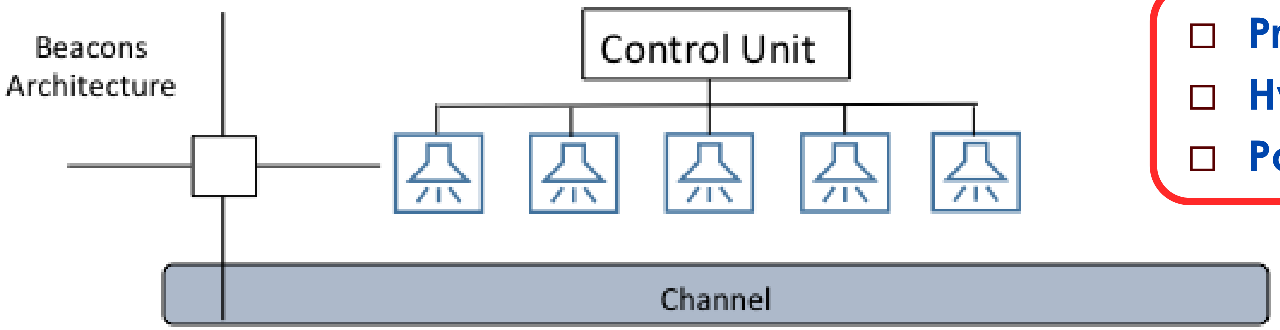
WISH LIST FOR AN ULPS

- Design of an U-LPS with wide coverage using coding techniques
  - Decentralized ULPS without emitter-receiver synchronism
  - Coverage improvement
  - Beacons’ emissions based on multi-access techniques
    - CDMA
    - Combined CDMA with TDMA
  - Improvement of immunity to:
    - ISI, MAI, noise
    - Near-far effect
    - Multi-path
  - Real-time operation

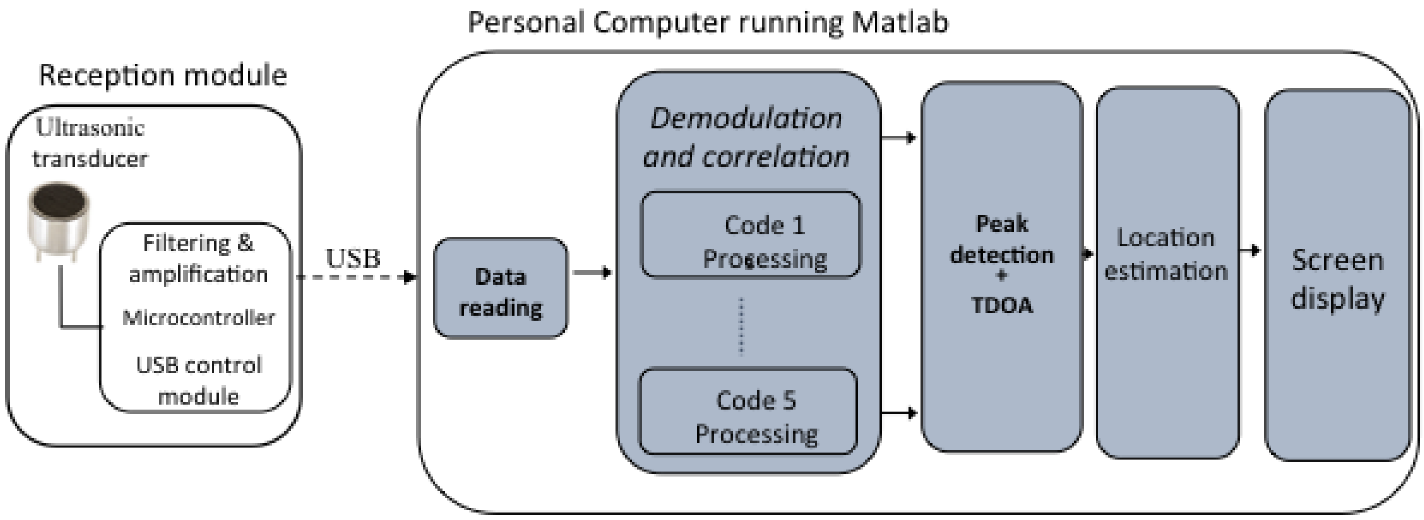


IMPLEMENTATION

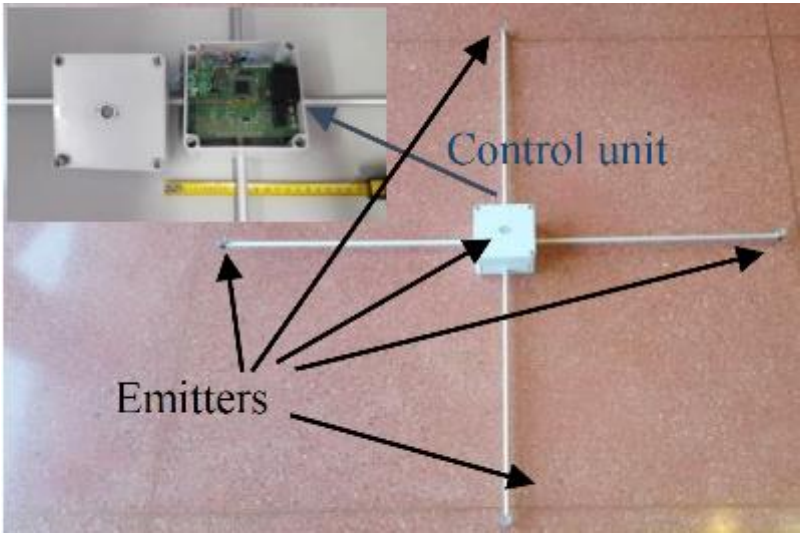
General Overview

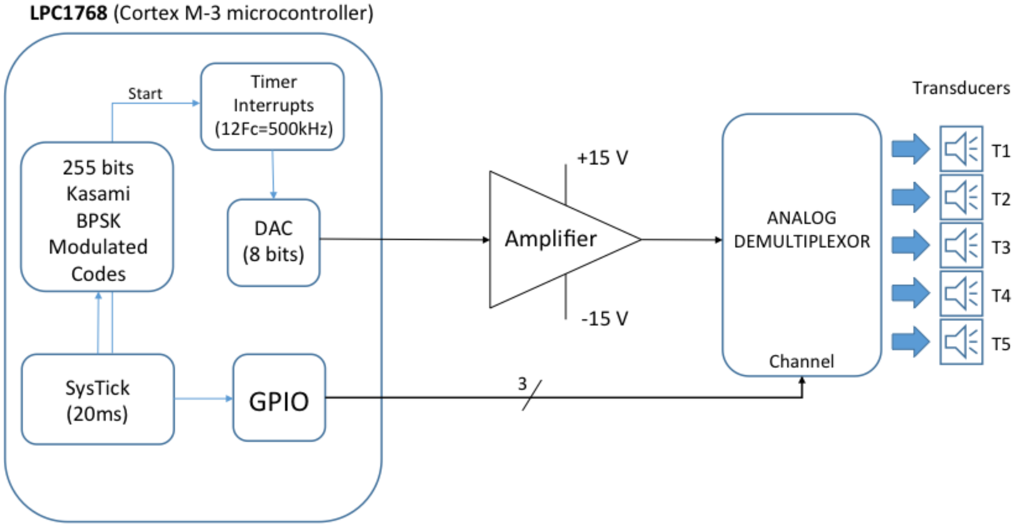


- ☐ **Privacy oriented**
- ☐ **Hyperbolic lateration**
- ☐ **Portable receiver**



Beacons architecture and emitter control unit





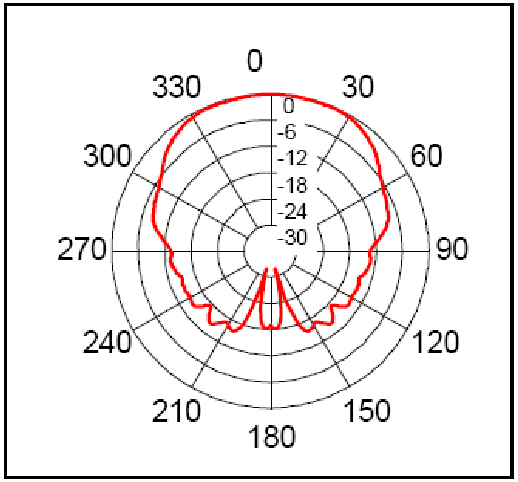
Five beacons (Prowave 328ST160) distributed in a 71 x 71 cm square structure to cover 30 m^2 with a carrier frequency of 41.67 kHz.

Emitter control unit:

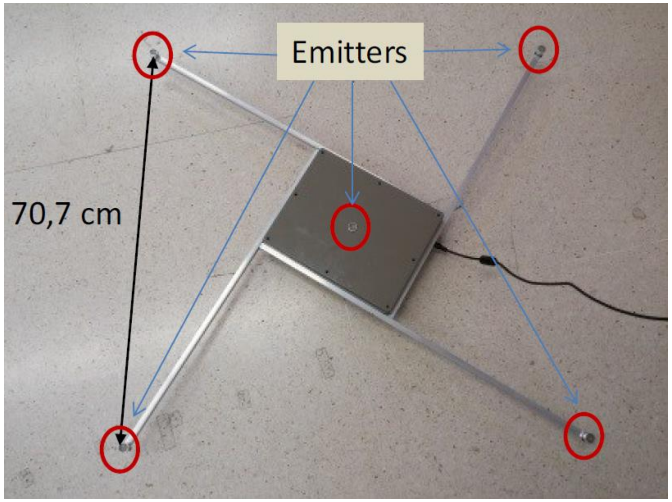
- Based on a LPC1768 uC that provides a wireless link to an external PC to configure different parameters.
- Only one DAC → Need to multiplex all the signals in the time domain

BEACON IMPLEMENTATION

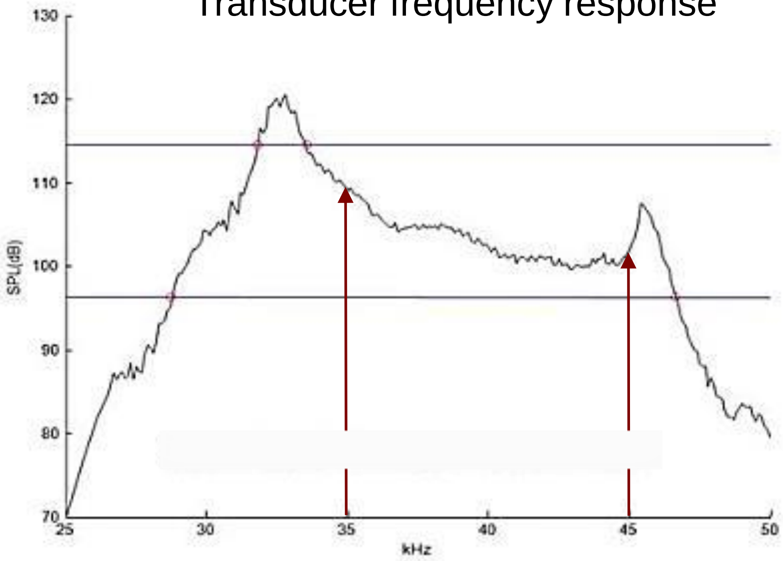
- Five ultrasonic transducers Prowave 328S160
  - Great bandwidth (≈10kHz)
  - Suitable phase response
  - Wide coverage area (emission pattern with ±80º)
  - BPSK Modulation carrier of 40kHz with a bandwidth of 18kHz



- Beacon unit installed at a height of 2.78m, approximated coverage area of 30m^2
  - 70.7x70.7cm square

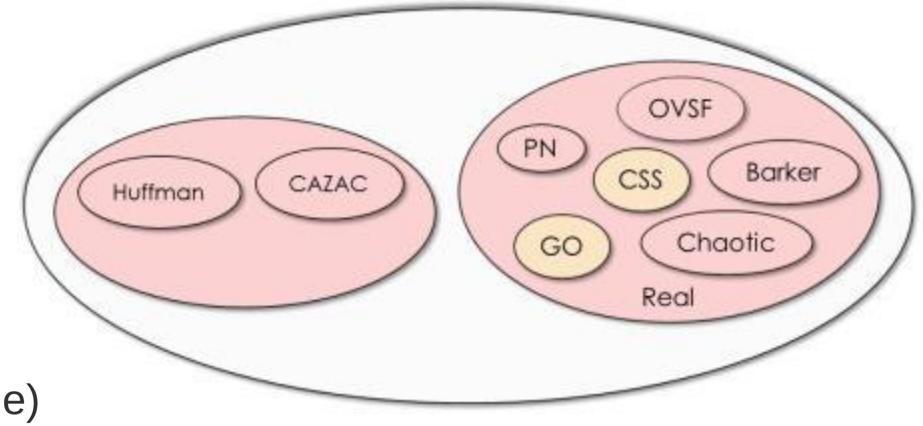


Transducer frequency response

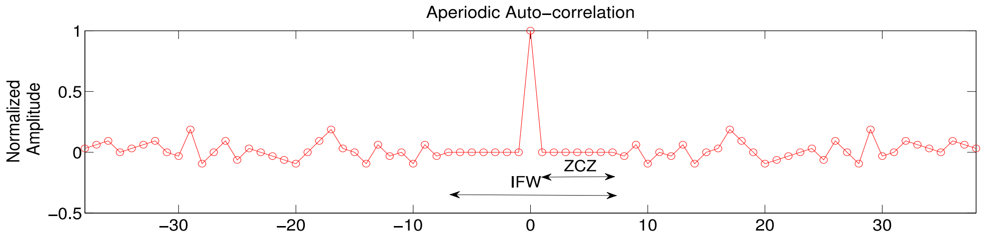


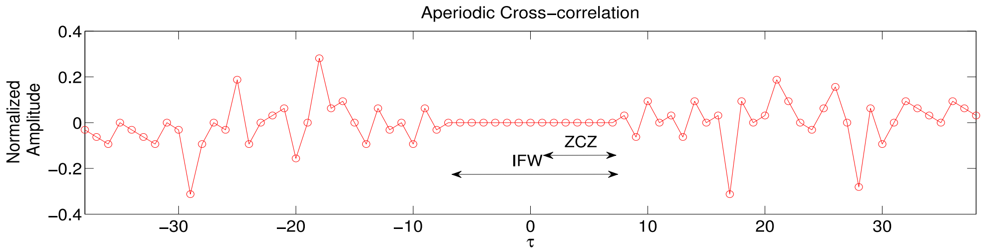
TIME-OF-FLIGHT (TOF) DETERMINATION

- Signal encoding:
  - Improve SNR
  - Improve the sensitivity
  - Detect overlapped echoes
  - Improve the operating frequency
  - Simultaneous transmission (multi-mode)



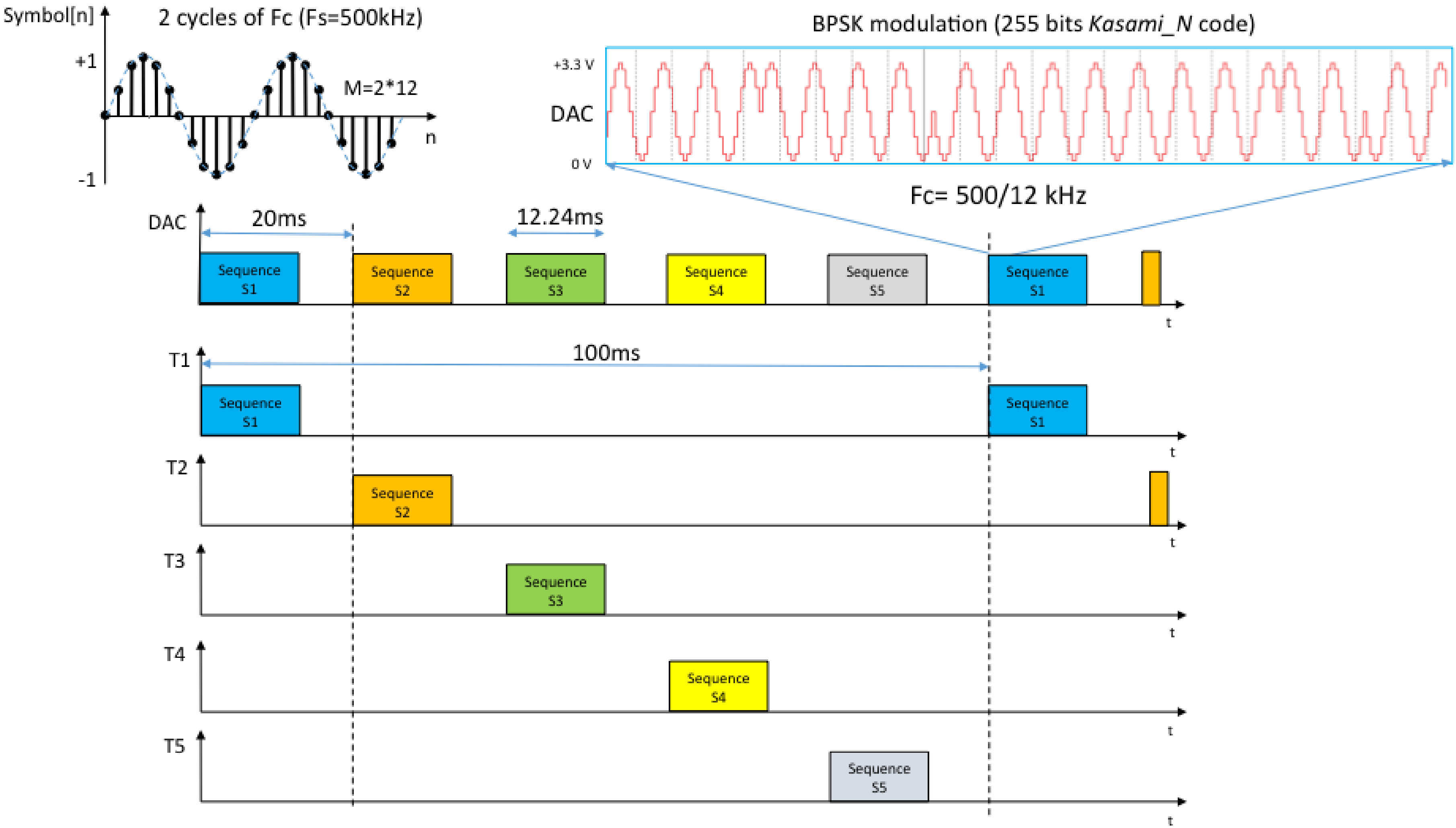
- Access scheme for ultrasonic beacons
  - Time multiplexing (TDMA)
  - Frequency multiplexing (FDMA) → difficult due to transducer bandwidth
  - **Code multiplexing (CDMA)** → mobile communications, GPS





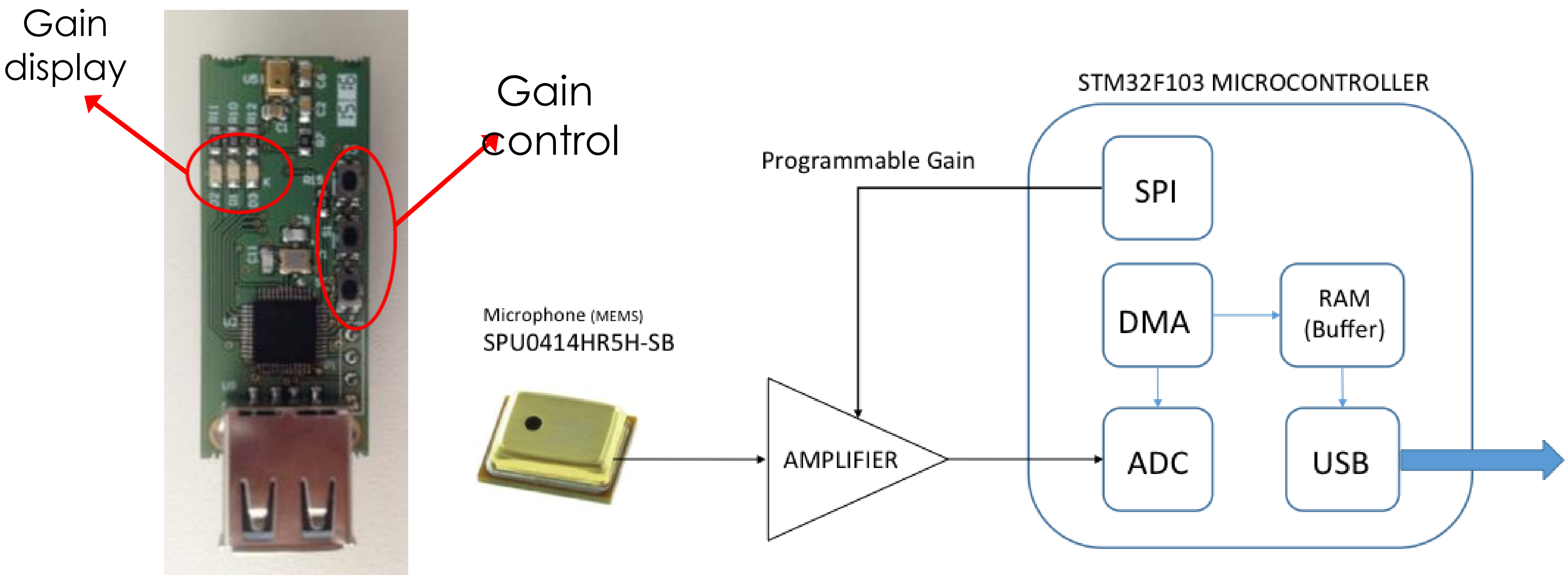
IMPLEMENTATION

Emission scheme: TCDMA protocol



IMPLEMENTATION

Receiver module



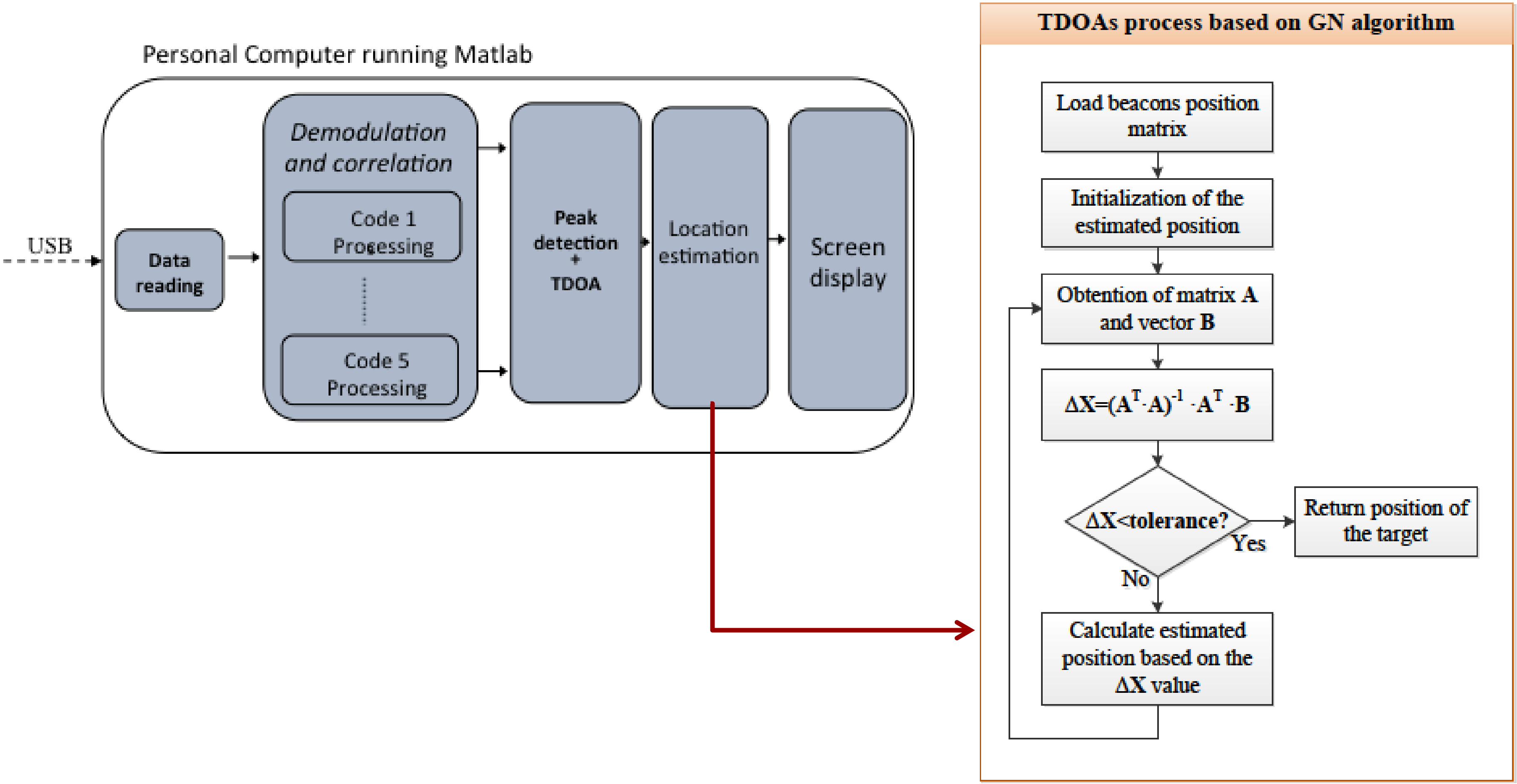
Includes a MEMS SPU0414HR5H-S microphone, a high bandwidth amplifier and an internally configurable high-pass filter.

Based on a STM32F103 uC, incoming signals are sampled at 100 Ks/s and stored in a buffer whose size (10 000 samples) ensures the acquisition of all emissions in a period.

USB powered and features high speed data transfer to a Host device (computer, smartphone,…)

IMPLEMENTATION

Emission scheme: TCDMA protocol
Signal processing



Personal Computer running Matlab

USB

Data reading

Demodulation and correlation

Code 1 Processing

Code 5 Processing

Peak detection + TDOA

Location estimation

Screen display

TDOAs process based on GN algorithm

Load beacons position matrix

Initialization of the estimated position

Obtention of matrix **A** and vector **B**

$\Delta X=(A^T\cdot A)^{-1}\cdot A^T\cdot B$

ΔX<tolerance?

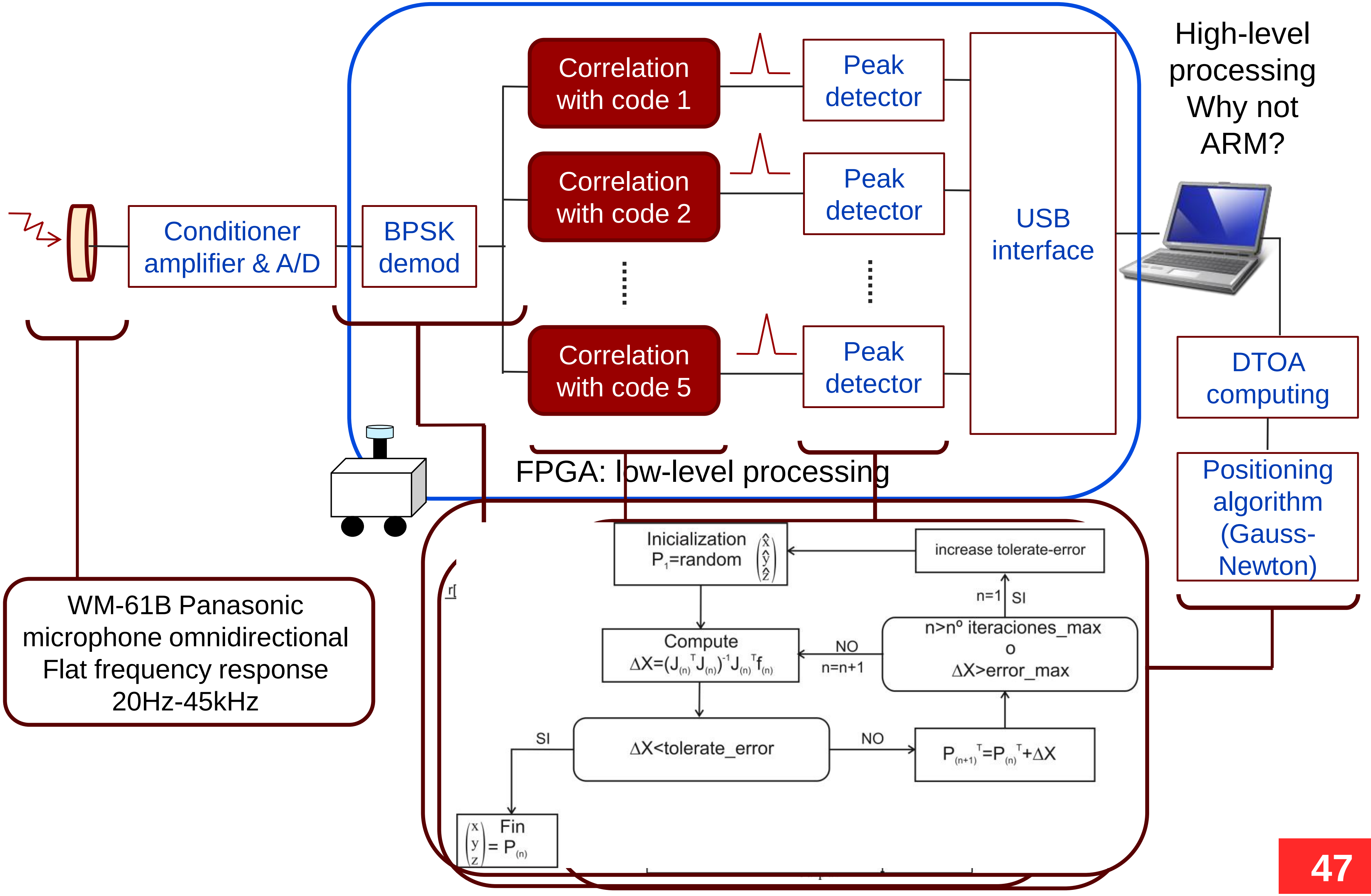
Yes

Return position of the target

No

Calculate estimated position based on the ΔX value

RECEIVER DESIGN



High-level processing
Why not ARM?

Conditioner amplifier & A/D

BPSK demod

Correlation with code 1

Correlation with code 2

Correlation with code 5

Peak detector

Peak detector

Peak detector

USB interface

FPGA: low-level processing

DTOA computing

Positioning algorithm (Gauss-Newton)

WM-61B Panasonic microphone omnidirectional
Flat frequency response
20Hz-45kHz

Inicialization
P_1=random $\begin{pmatrix}\hat{x}\\ \hat{y}\\ \hat{z}\end{pmatrix}$

increase tolerate-error

n=1 SI

n>nº iteraciones_max
o
ΔX>error_max

NO
n=n+1

Compute
$\Delta X=(J_{(n)}^{T}J_{(n)})^{-1}J_{(n)}^{T}f_{(n)}$

SI

ΔX<tolerate_error

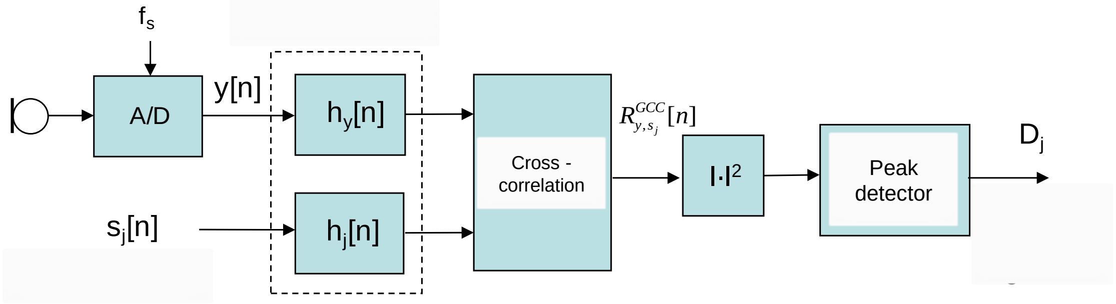
NO

$P_{(n+1)}^{T}=P_{(n)}^{T}+\Delta X$

Fin
$\begin{pmatrix}x\\ y\\ z\end{pmatrix}=P_{(n)}$

GENERALIZED CROSS CORRELATION

- Detection of the sequences assigned to each beacon using GCC-PHAT



Signal received from ***N*** beacons

$$y[n] = \sum_{j=1}^{N} s_j[n] * h_j[n] + \eta[n]$$

Modulated sequence assigned to beacon ***j***

Channel response from beacon ***j***

Noise

GCC-PHAT

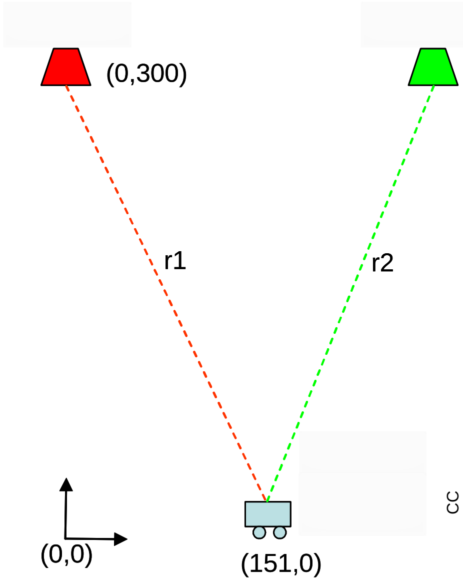
PHAT filter

$$\hat{R}^{GCC}_{y,s_j}[n] = \frac{1}{K}\sum_{k=0}^{K-1}\frac{1}{\left|\hat{\Phi}_{y,s_j}[k]\right|}\cdot\hat{\Phi}_{y,s_j}[k]\cdot e^{j\omega_k n}$$

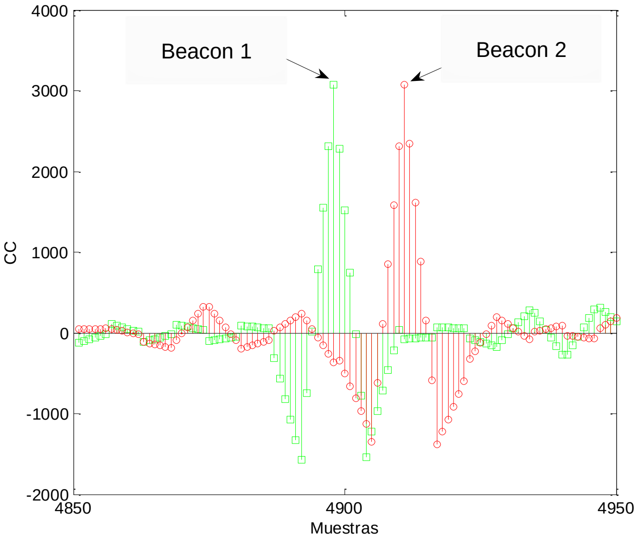
$$= \frac{1}{K}\sum_{k=0}^{K-1}\frac{1}{\left|\sum_{\substack{i=1\\ i\neq j}}^{N}\hat{\Phi}_{s_i,s_j}[k]\cdot e^{-j\omega_k D_i} + \hat{\Phi}_{s_j,s_j}[k]\cdot e^{-j\omega_k D_j}\right|}\cdot\left(\sum_{\substack{i=1\\ i\neq j}}^{N}\hat{\Phi}_{s_i,s_j}[k]\cdot e^{-j\omega_k D_i} + \hat{\Phi}_{s_j,s_j}[k]\cdot e^{-j\omega_k D_j}\right)\cdot e^{j\omega_k n}$$

PERFORMANCE COMPARISON

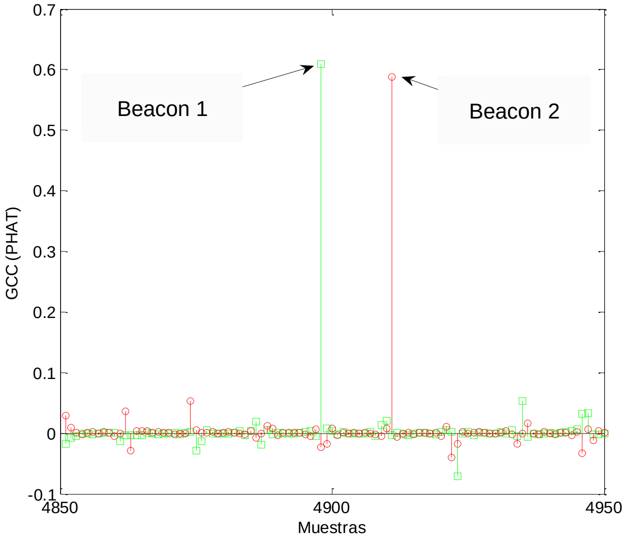
- Simulation of the simultaneous detection process for the case of two beacons: CC vs GCC-PHAT
  - High SNR is required for a good performance



Kasami 255 bits (m=1)



CC



GCC-PHAT

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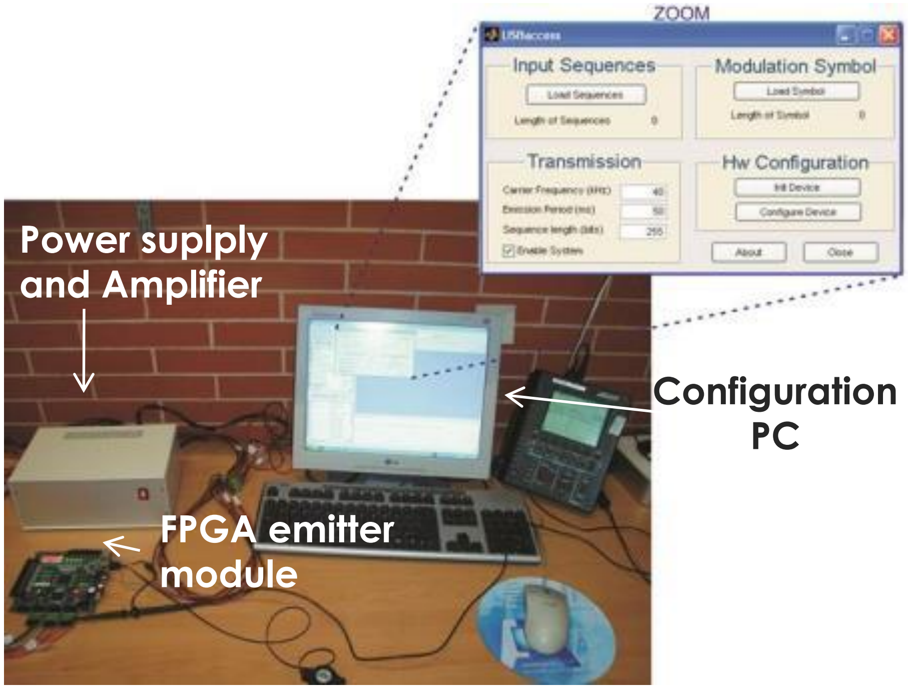
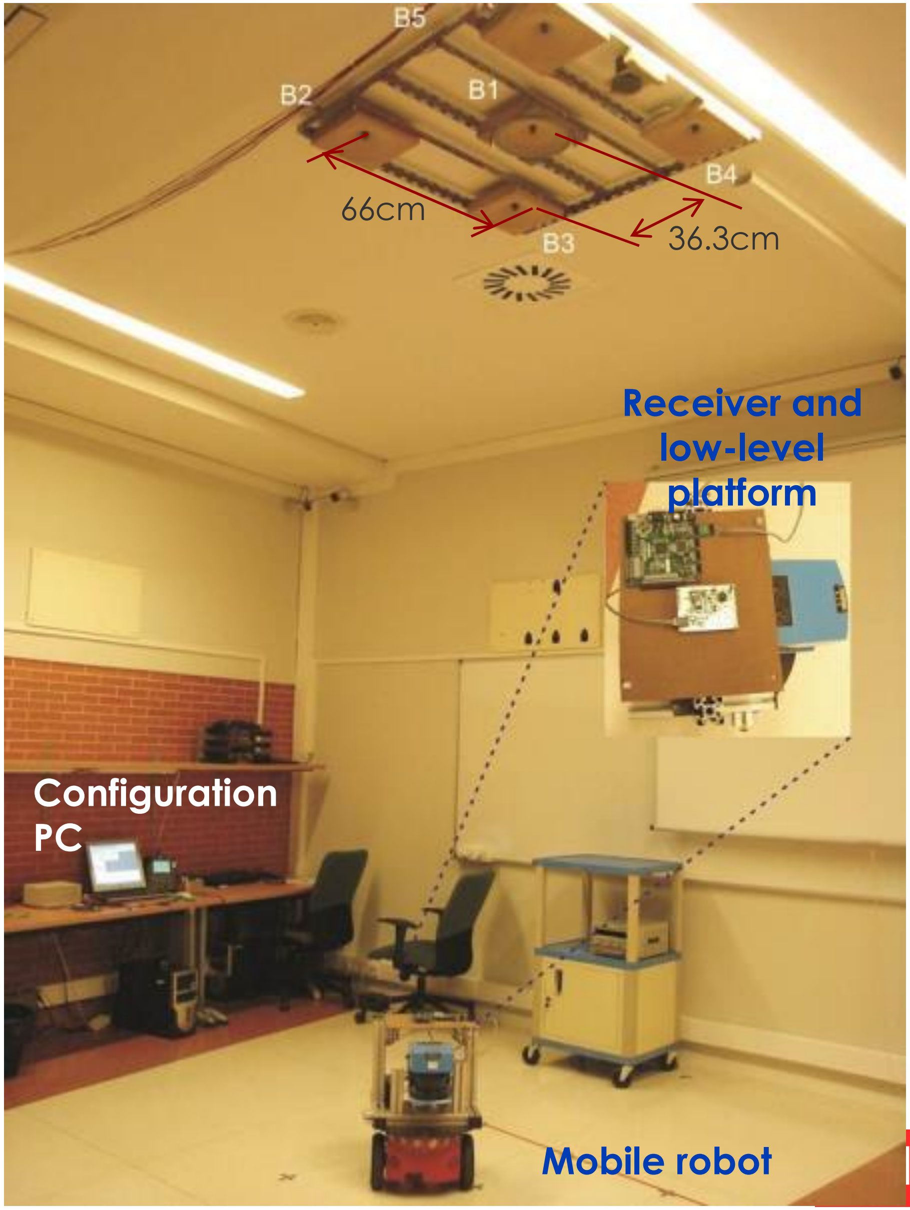
TEST ENVIRONMENT A

- Influence from the sequence type
- Different test positions have been evaluated in the real environment
  - Carrier frequency 41.6kHz
  - 1023-bit Kasami code
  - 1151-bit LS codes

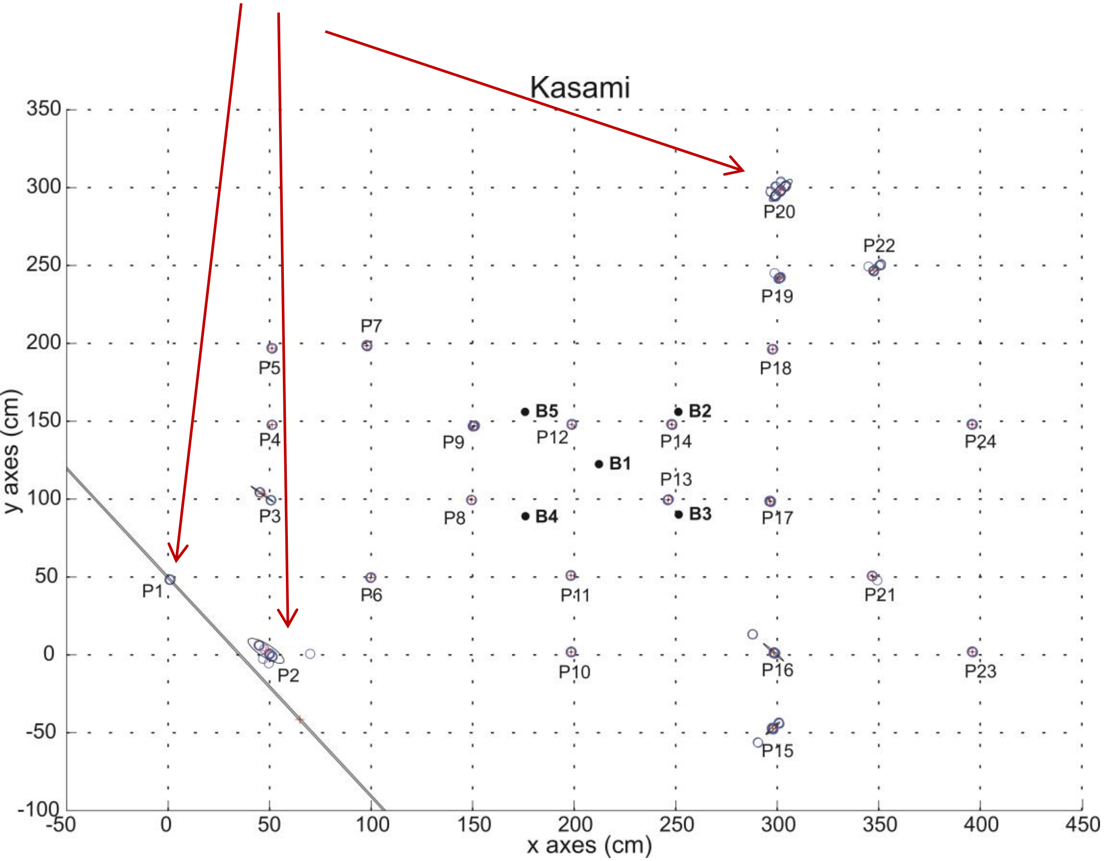


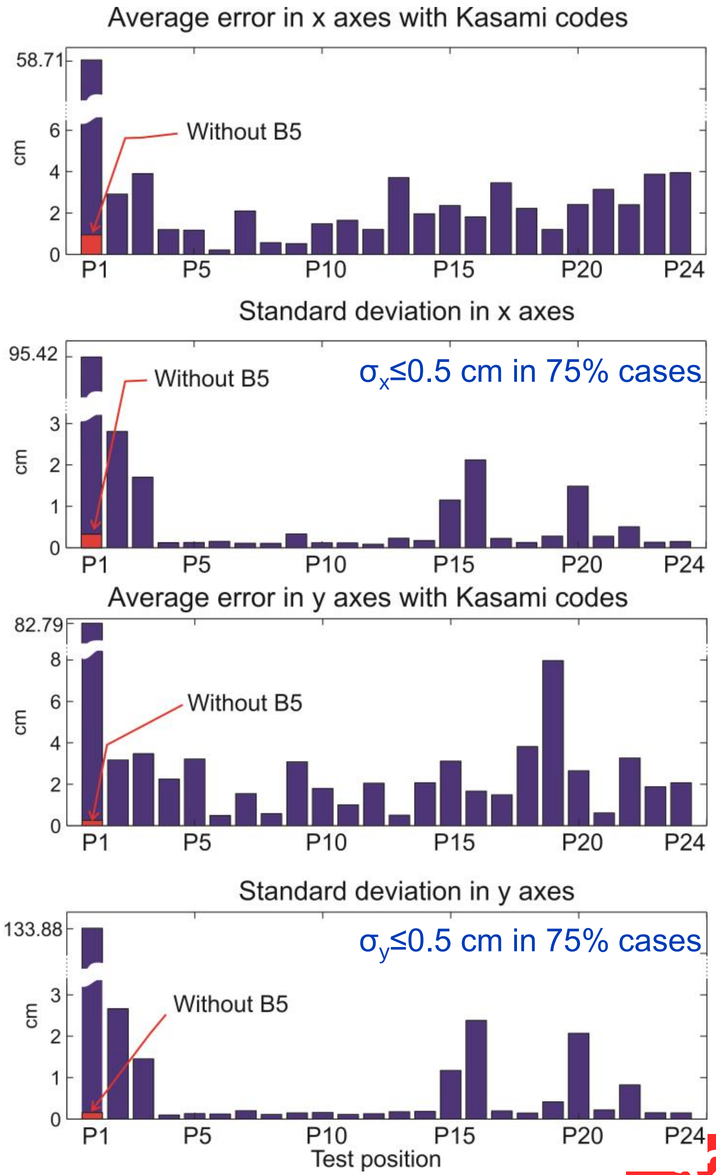


TEST ENVIRONMENT A

- 1023-bit Kasami codes

Interferences are mainly due to the multipath


Kasami


Average error in x axes with Kasami codes

Standard deviation in x axes

$\sigma_x \leq 0.5$ cm in 75% cases

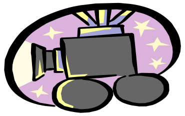
Average error in y axes with Kasami codes

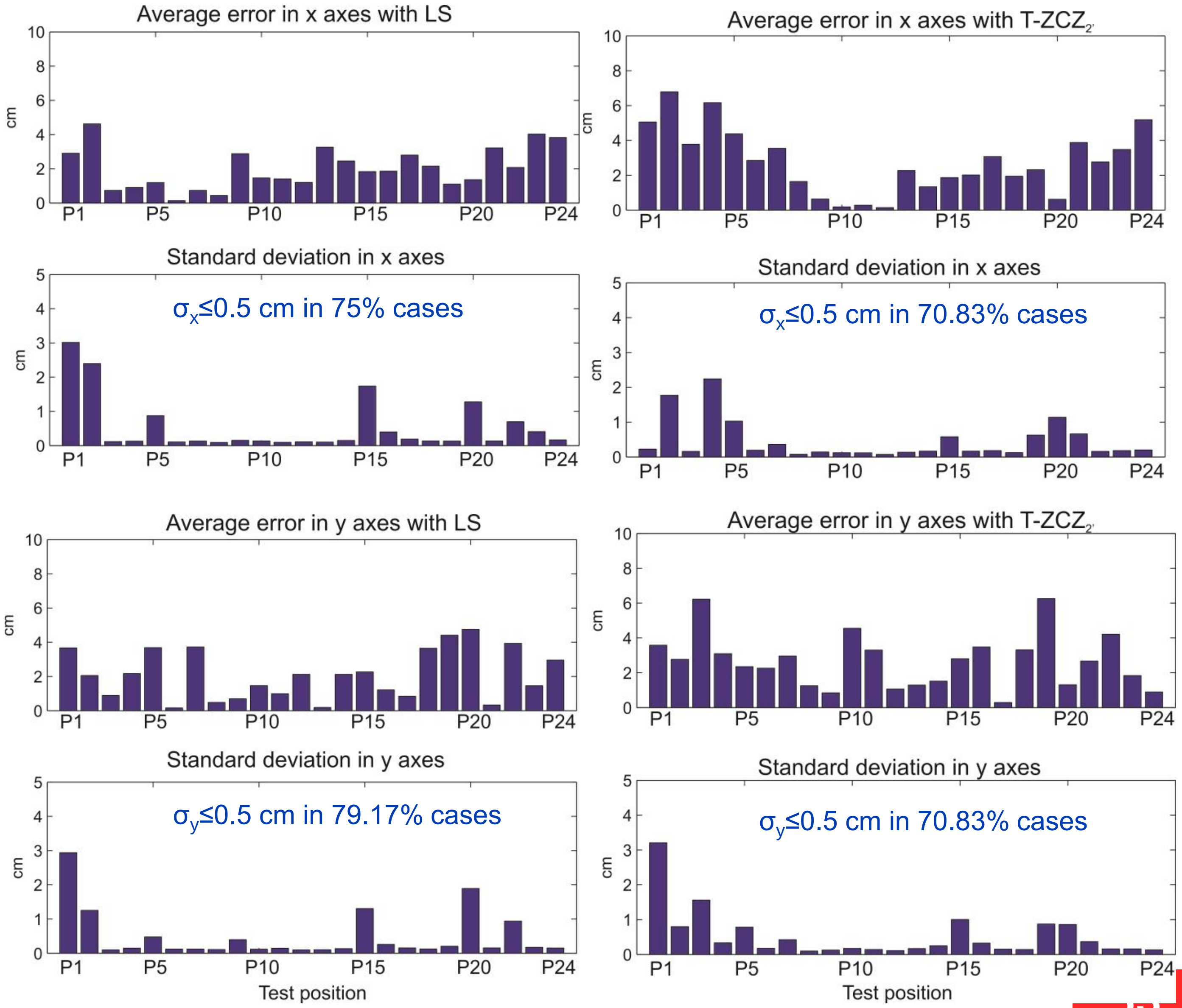
Standard deviation in y axes

$\sigma_y \leq 0.5$ cm in 75% cases

TEST ENVIRONMENT A

- 1151-bit LS and T-ZCZ codes
- LS codes and T-ZCZ are more robust to multipath and near-far effect than Kasami ones





σ_x≤0.5 cm in 75% cases

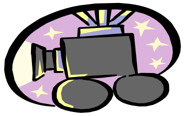
σ_x≤0.5 cm in 70.83% cases

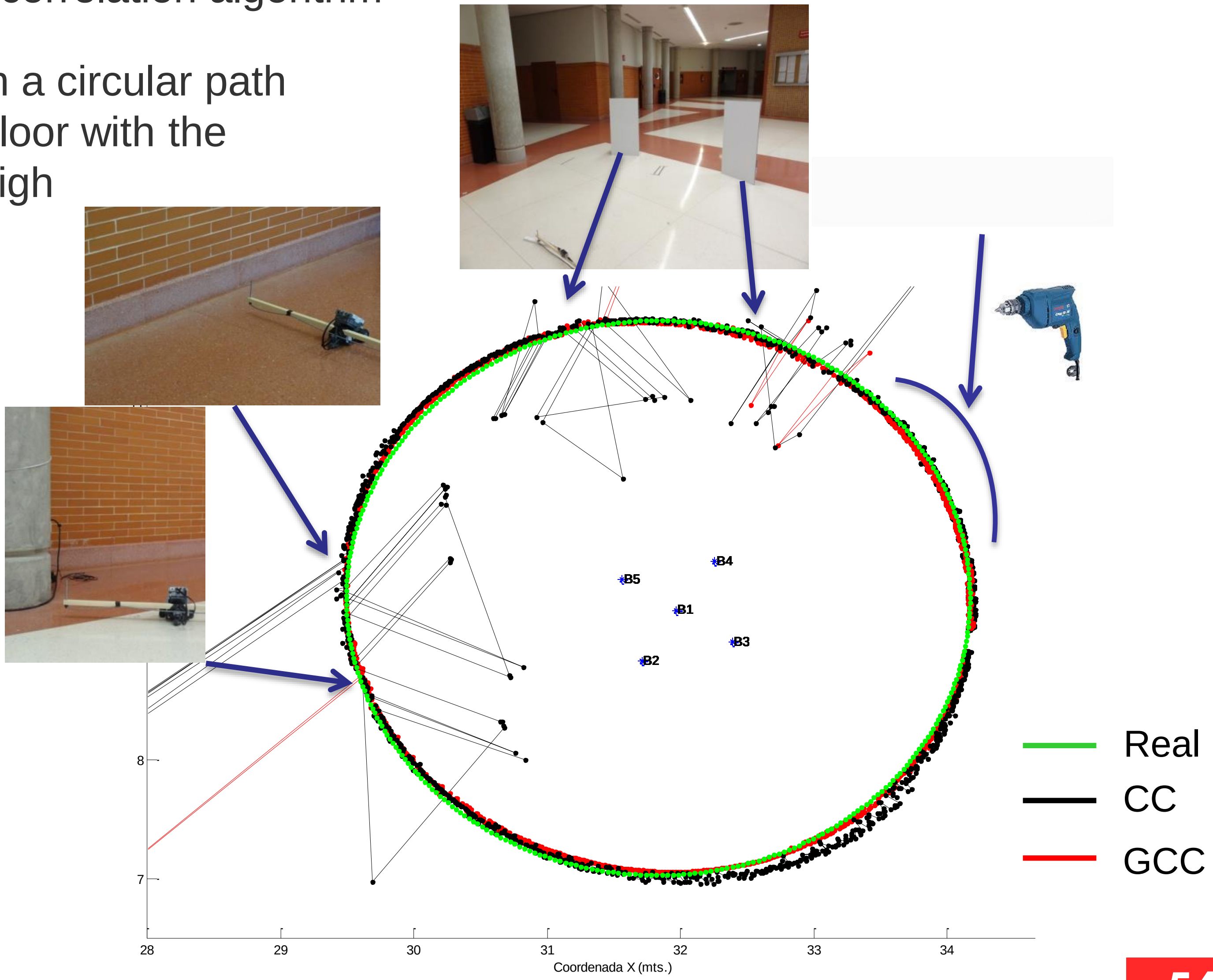
σ_y≤0.5 cm in 79.17% cases

σ_y≤0.5 cm in 70.83% cases

EXPERIMENTAL RESULTS

- Influence from the correlation algorithm
- Results obtained in a circular path (r=2.35 m) on the floor with the beacons at 3.5m high
  - Multipath
  - Noise





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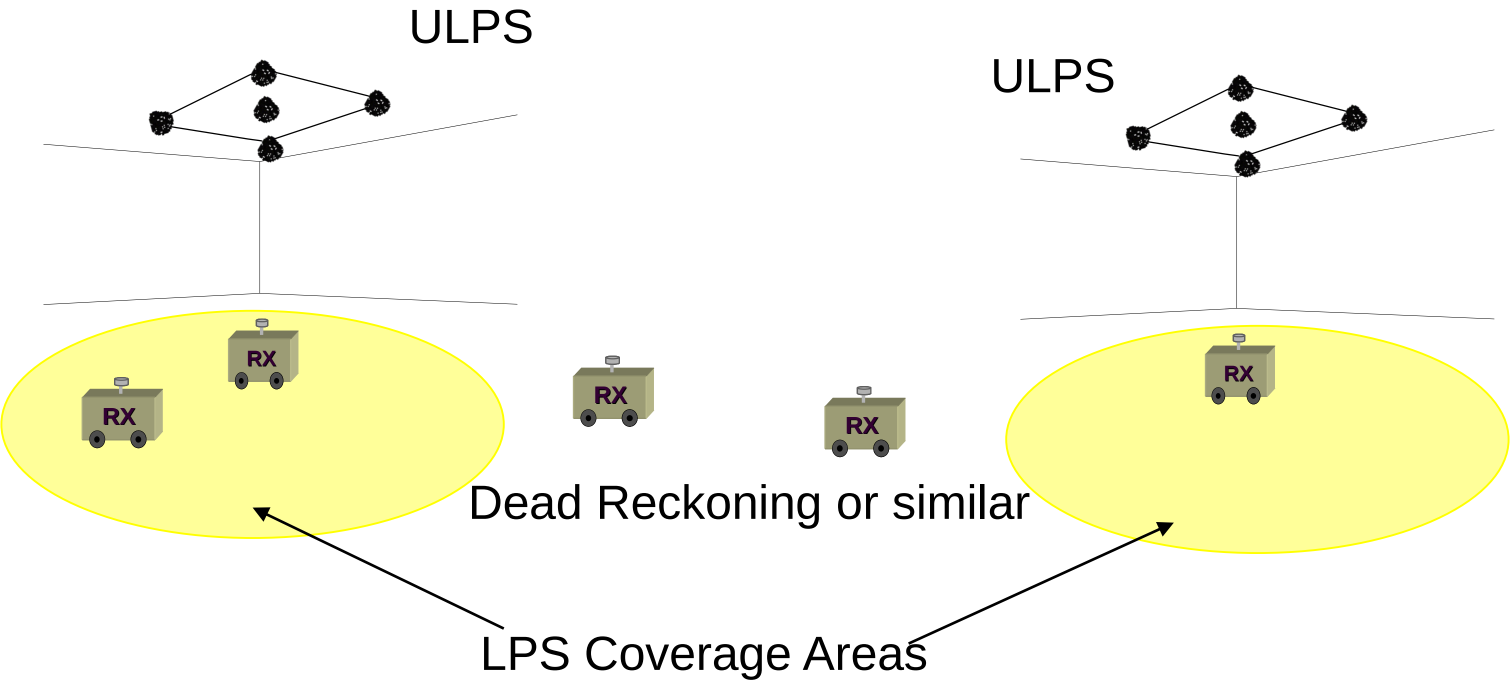
SENSORY FUSION FOR NAVIGATION

- Study the positioning and navigation of a mobile robot in an Extensive ULPS in degraded conditions
  - Some distance measurements are not available
- ULPS: Ultrasonic Local Positioning System
  - Composed of 4-5 ultrasonic emitters located at the ceiling and receivers on the mobile robots
  - Coverage area of about 30-40m^2
- Extensive ULPS:
  - Composed of several single ULPS
  - Coverage area of hundred/thousand m^2
- Mobile Robot
  - Integrate information from odometers and ULPS
  - Navigates on the floor (2D positioning)

WIDE ULPS OVERVIEW

- A globally referenced ULPS at the input/output points to a wide space
- Some locally referenced ULPS may exist inside the wide space
- Coverage areas can overlap



ULPS

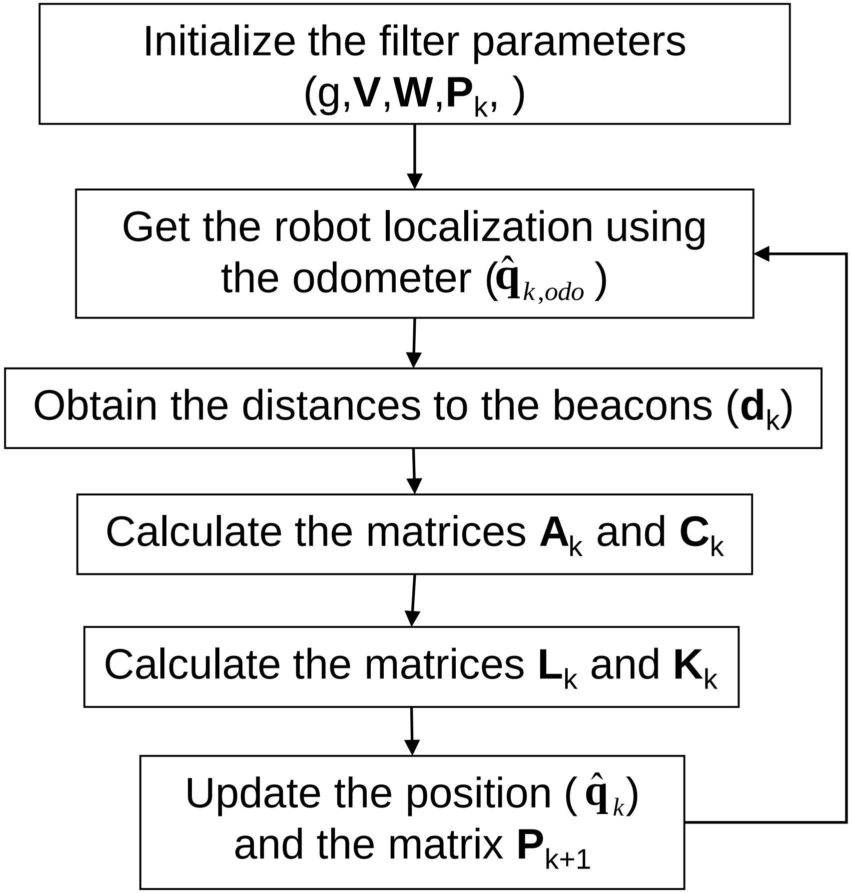
ULPS

Dead Reckoning or similar

LPS Coverage Areas

ULPS NAVIGATION

- Coverage areas do not overlap
  - Flowchart



Initialize the filter parameters (g,$\mathbf{V}$,$\mathbf{W}$,$\mathbf{P}_k$,)

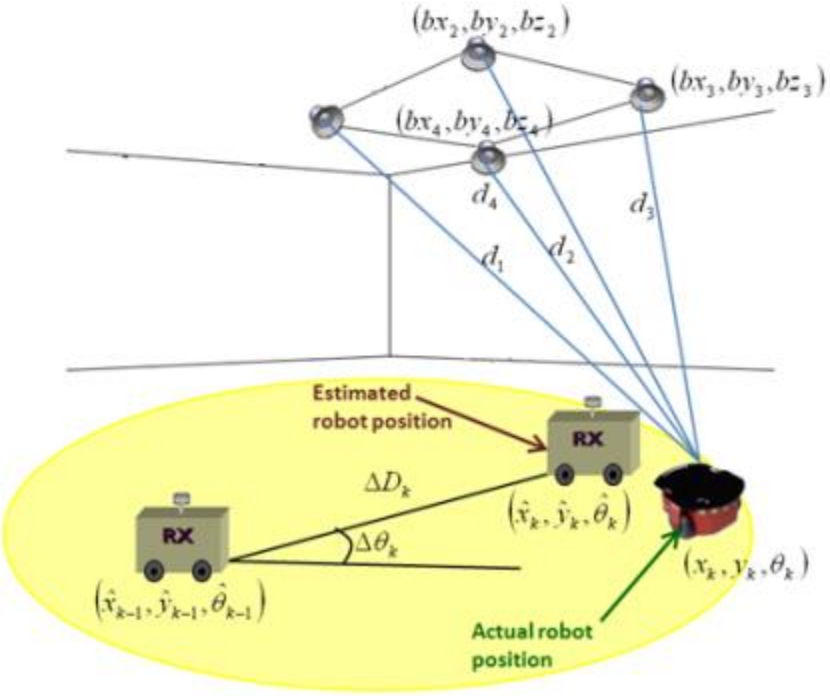
Get the robot localization using the odometer ($\hat{\mathbf{q}}_{k,odo}$)

Obtain the distances to the beacons ($\mathbf{d}_k$)

Calculate the matrices $\mathbf{A}_k$ and $\mathbf{C}_k$

Calculate the matrices $\mathbf{L}_k$ and $\mathbf{K}_k$

Update the position ($\hat{\mathbf{q}}_k$) and the matrix $\mathbf{P}_{k+1}$



H-∞ filter equations

Prediction stage:

$$\hat{\mathbf{q}}_{k,odo} = f\left(\hat{\mathbf{q}}_{k-1}, odometer\right)$$

Update stage:

$$\mathbf{L}_k = \left(\mathbf{I} - \gamma\cdot\mathbf{P}_k + \mathbf{C}^T\mathbf{V}^{-1}\mathbf{C}\cdot\mathbf{P}_k\right)^{-1}$$

$$\mathbf{K}_k = \mathbf{A}\cdot\mathbf{P}_k\mathbf{L}_k\mathbf{C}^T\mathbf{V}^{-1}$$

$$\hat{\mathbf{q}}_{k+1} = \hat{\mathbf{q}}_{k,odo} + \mathbf{K}_k\left(\Delta\mathbf{d}_k - \Delta\hat{\mathbf{d}}_k\right)$$

$$\mathbf{P}_{k+1} = \mathbf{A}\cdot\mathbf{P}_k\mathbf{L}_k\mathbf{A}^T + \mathbf{W}$$

EXPERIMENTAL ENVIRONMENT

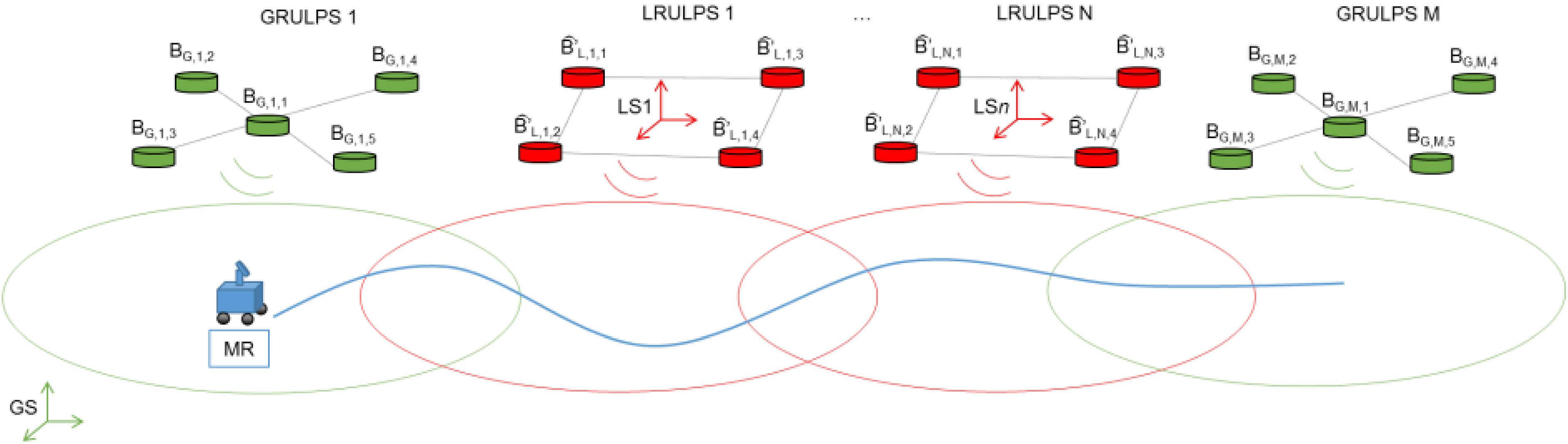
- 1023-bit Kasami codes

EXPERIMENTAL NAVIGATION RESULTS

- Coverage areas do not overlap: only navigation

SIMULTANEOUS CALIBRATION AND NAVIGATION

- Using the structure proposed previously, the objective is the calibration of the non-known LRULPS beacons while the mobile robot is navigating

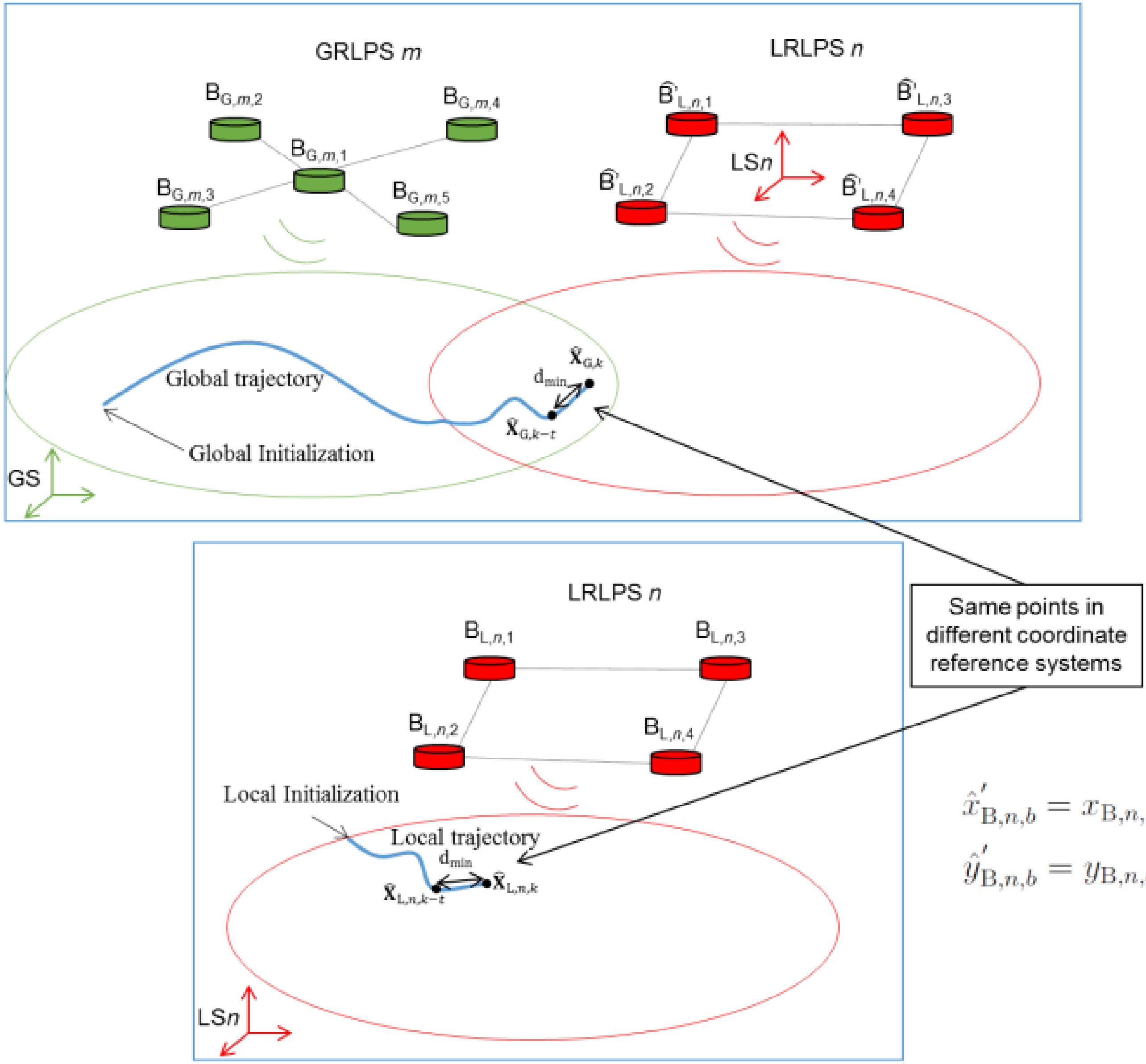


Beacons state vector

$$\hat{\mathrm{B}}'_{\mathrm{L},n,b,s} = \left[\hat{x}'_{\mathrm{B},n,b,s} \quad \hat{y}'_{\mathrm{B},n,b,s}\right]^T$$

SIMULTANEOUS CALIBRATION AND NAVIGATION

- Deterministic method



Same points in different coordinate reference systems

$$\mathbf{T_A} = \begin{bmatrix} x_{L,\text{initial}} & -y_{L,\text{initial}} & 1 & 0 \\ y_{L,\text{initial}} & x_{L,\text{initial}} & 0 & 1 \\ x_{L,\text{final}} & -y_{L,\text{final}} & 1 & 0 \\ y_{L,\text{final}} & x_{L,\text{final}} & 0 & 1 \end{bmatrix}$$

$$\mathbf{T_B} = \begin{bmatrix} x_{G,\text{initial}} \\ y_{G,\text{initial}} \\ x_{G,\text{final}} \\ y_{G,\text{final}} \end{bmatrix}$$

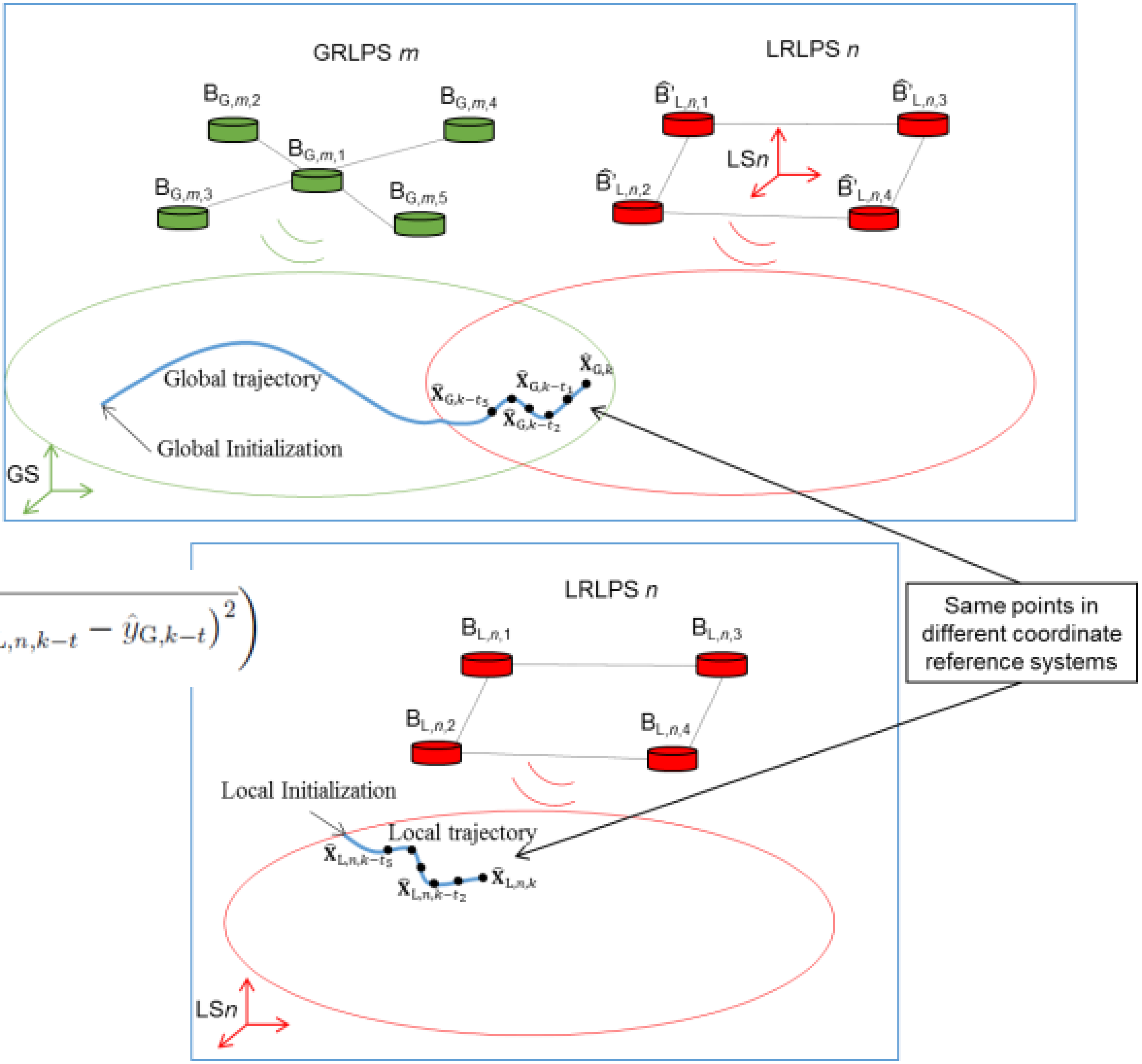
$$\mathbf{T}_{\mathbf{C},n} = \mathbf{T_A}^{-1} \cdot \mathbf{T_B} = \begin{bmatrix} \mathrm{T}_{C,n,1} \\ \mathrm{T}_{C,n,2} \\ \mathrm{T}_{C,n,3} \\ \mathrm{T}_{C,n,4} \end{bmatrix}$$

$$\hat{x}'_{B,n,b} = x_{B,n,b} \cdot \mathrm{T}_{C,n,1} - y_{B,n,b} \cdot \mathrm{T}_{C,n,2} + \mathrm{T}_{C,n,3}$$
$$\hat{y}'_{B,n,b} = y_{B,n,b} \cdot \mathrm{T}_{C,n,1} + x_{B,n,b} \cdot \mathrm{T}_{C,n,2} + \mathrm{T}_{C,n,4}$$

SIMULTANEOUS CALIBRATION AND NAVIGATION

- Numerical method

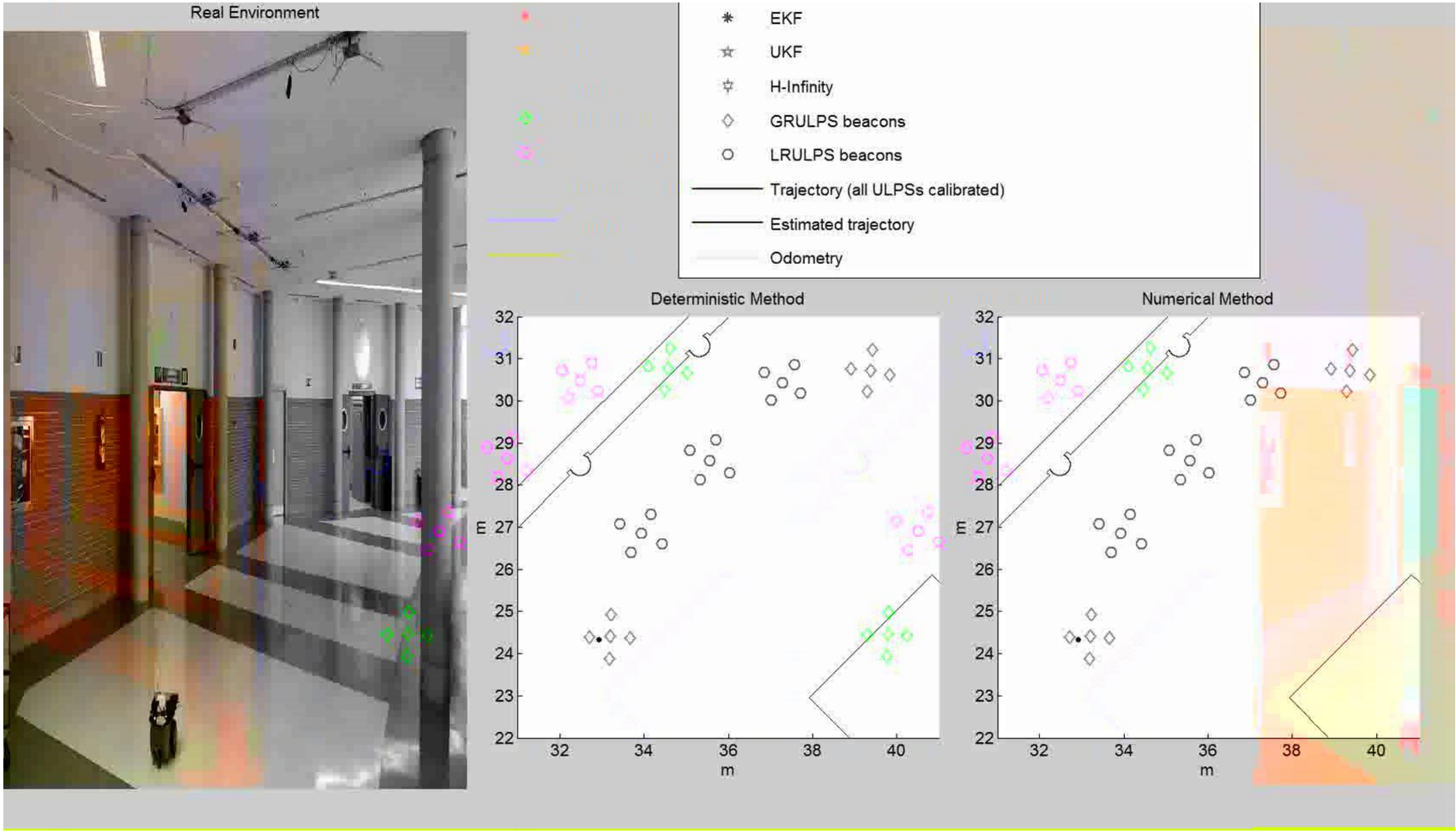
$$\mathrm{ME} = \frac{1}{T}\cdot\sum_{t=0}^{T}\left(\sqrt{\left(\hat{x}'_{\mathrm{L},n,k-t}-\hat{x}_{\mathrm{G},k-t}\right)^2+\left(\hat{y}'_{\mathrm{L},n,k-t}-\hat{y}_{\mathrm{G},k-t}\right)^2}\right)$$



Same points in different coordinate reference systems

EXPERIMENTAL SCAN RESULTS

- Coverage areas overlap
  - Beacon calibration, comparison of different integration filters



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CONCLUSIONS

- ALPSs are an alternative to positioning systems used from the 1990’s.
- First prototypes used to be with narrow band transducers. And, after, broadband systems were introduced.
- Important issues: coverage-beacons’ distribution, positioning algorithms (espherical or hyperbolic), coding, multimode access, channel and propagation effects (MAI, ISI, Doppler, near-far, …)
- Extensive ULPS to cover a large area in a building. Beacons’ calibration, as well as navigation algorithms must be considered.
- In order to merge the odometer and the ULPS information, when it is available, different kinds of filters can be implemented (H_∞, EKF, UKF, PF, …)
- Experimental results

Departamento de Electrónica

Universidad de Alcalá

Acoustic Local Positioning Systems

Jesús Ureña Ureña (UAH)
Álvaro Hernández Alonso (UAH)
Fernando J. Álvarez Franco (UEX)

Enero 2018

GEINTRA Research Group

Electronic Engineering Applied to Intelligent Spaces and Transport Group
geintra
www.geintra-uah.org
jesus.urena@uah.es

University of Extremadura
fafranco@unex.es