X-band mini weather radar network and other wireless sensor networks for environmental monitoring

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Co-Supervisor: Prof. Giovanni Emilio Perona

Outline

- Presentation on my Ph. D. program in “Alto Apprendistato”
- Presentation of research activities
  - X-Band mini weather radar network
  - Quantitative Precipitation Estimation (QPE)
  - Clutter analysis to control the radar stability
  - Early stages in FMCW radar design
  - Wireless Sensor Networks (WSNs)
    - DGPS for environmental monitoring
    - WSN as anti theft alar system for PV panels
    - WSN as smart grid for gas metering
- Publications list

Ph. D. Program in “Alto Apprendistato”

Ph. D. Program in “Alto Apprendistato”

- Since 2010 the Regione Piemonte has started the experimentation for the “**Alta Formazione in Apprendistato**” which include some Ph. D. programs.

- Aim of the experimentation is:
  - to offer to the Ph. D student the possibility to **work with high level technologies** offered by a company.
  - to attend **high level formation activities** offered from both Politecnico di Torino and also from other institution thanks to additional fund provided by Regione Piemonte.

- **I was selected to be employed at Envisens Technologies s.r.l.**
- **The main project was “Monitoraggio Radar Ambientale” (2012-2013)**

Envisens Technologies s.r.l. (EST)

- EST has been established in 2006 as a spin-off of Politecnico di Torino and inherit experience in academic and applied research of the Remote Sensing Group (RSG) leaded by Prof. Giovanni Perona at Politecnico di Torino.
- EST operates in innovative technological solution engineering in the framework of environmental and safety applications, with particular focus on sensors and simulations, including prototyping, paying attention to low cost solutions and multipurpose electronic realizations.
- Examples of EST products:
  - Firecast ®
  - GPS monitoring systems for glaciers and landslides
  - **MicroRadarNET®**
  - **Wireless Sensor Networks**

EnviSens Technologies

Spin Off del Politecnico di Torino

Special formation activities

The PhD program in "Alto Apprendistato" give to the students **more fund for further specialist formation activities** with respect to the high level formation already provided by Politecnico di Torino:

- **Spatial Multicriterial Analysis for Environmental Decision Making, SMCA 2012**, 10th – 21st September 2012, University of Trento (IT).

- **9th Inernational Worskhop on Precipitation in Urban Areas, Urban Rain 2012**, 6th – 9th December 2012, Hotel Randolins, St. Moritz (CH).

- **5th International Summer School on Radar/SAR,**12th – 19th July 2013, Fraunhofer FHR, Rolandseck, Bonn, (DEU).

- **International Summer School on Atmospheric and Oceanic Sciences on Weather Forecasting (ISSAOS 2013)**, 16th – 20th September 2013, CETEMPS, L'Aquila (IT).

… Other than the formal PhD Politecnico training activity (52 credits)

Research activities

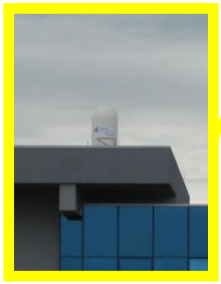
Research activities have been mainly focused on:

- **X-band mini weather radar** installations, network management and services and applications development.
- **Quantitative Precipitation Estimation (QPE)** using X-band mini weather radar.
- **X-band mini weather radar calibration and stability control using ground clutter echoes**.
- **Frequency Modulated Continuous Wave (FMCW)** radar study and early stages design.
- **Wireless Sensor Networks (WSNs)** design and realization (WSN for environmental monitoring, as anti-theft alarm system for PV plants, as smart gas metering…).

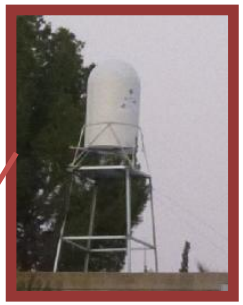
X-band mini weather radar network

The X-band mini weather radar network



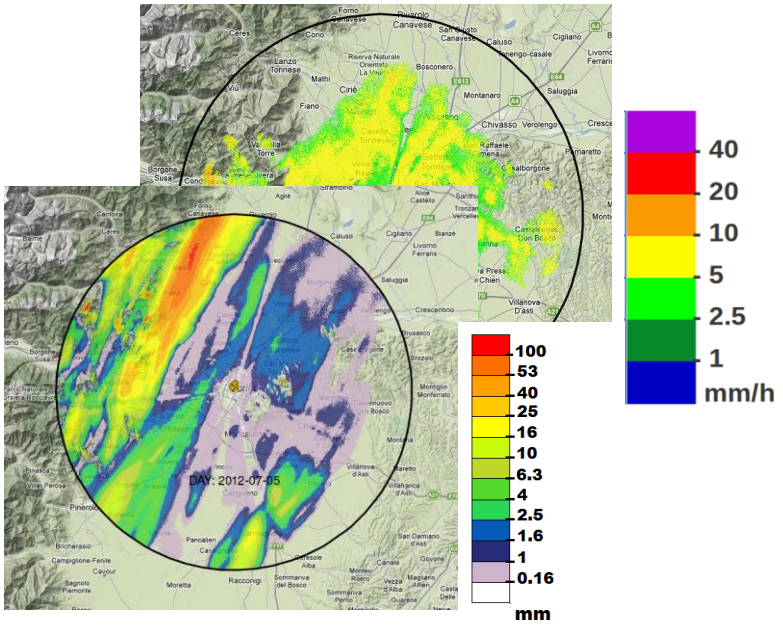





First operative installation in Turin, 2010

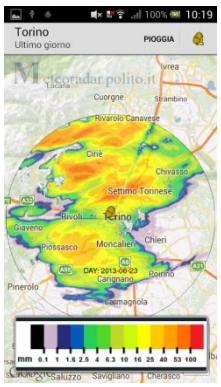
Developed applications and services

- Real time maps representation.
- Last hour cumulated rain.
- Last 6, 12 hours cumulated rain.
- Last day cumulated rain.
- Last 15 minutes rain evolution.
- Last 7 days cumulated rain.
- Mobile version of the site.

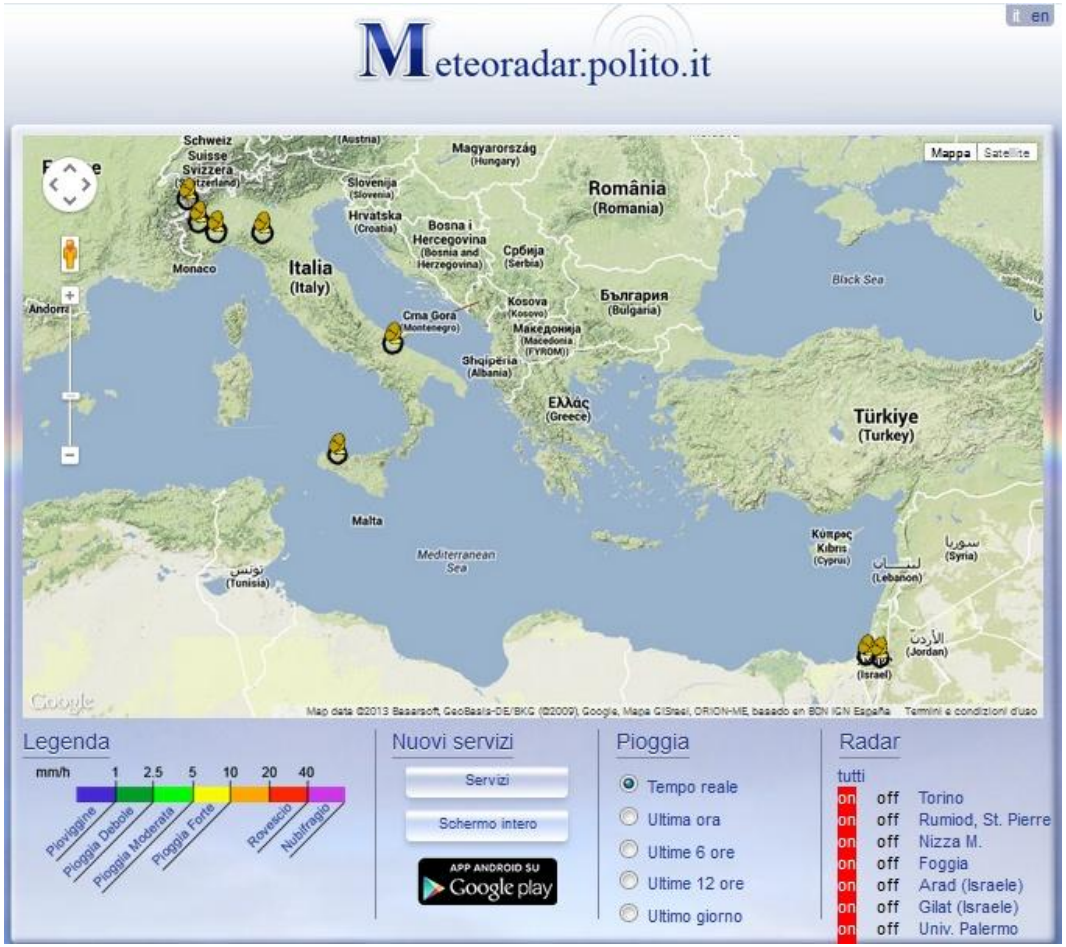


Android© App available for free

(**Meteoradar-IT**)



WEB SITE: http://meteoradar.polito.it



Applications and services available on the web site have been developed in the framework of the following projects:

- **Realizzazione di un progetto pilota per il monitoraggio delle precipitazioni con tecnologia radar ad alta risoluzione spaziale e temporale nel territorio della Provincia Regionale di Palermo** (2011).

- **Monitoraggio Radar Ambientale** (2012-2013).

Quantitative Precipitation Estimation (QPE)

Quantitative Precipitation Estimation (QPE)

QPE is necessa
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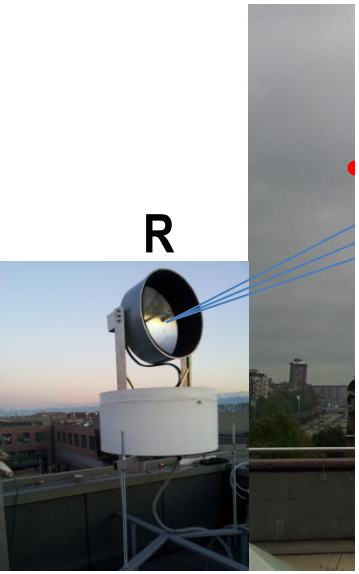
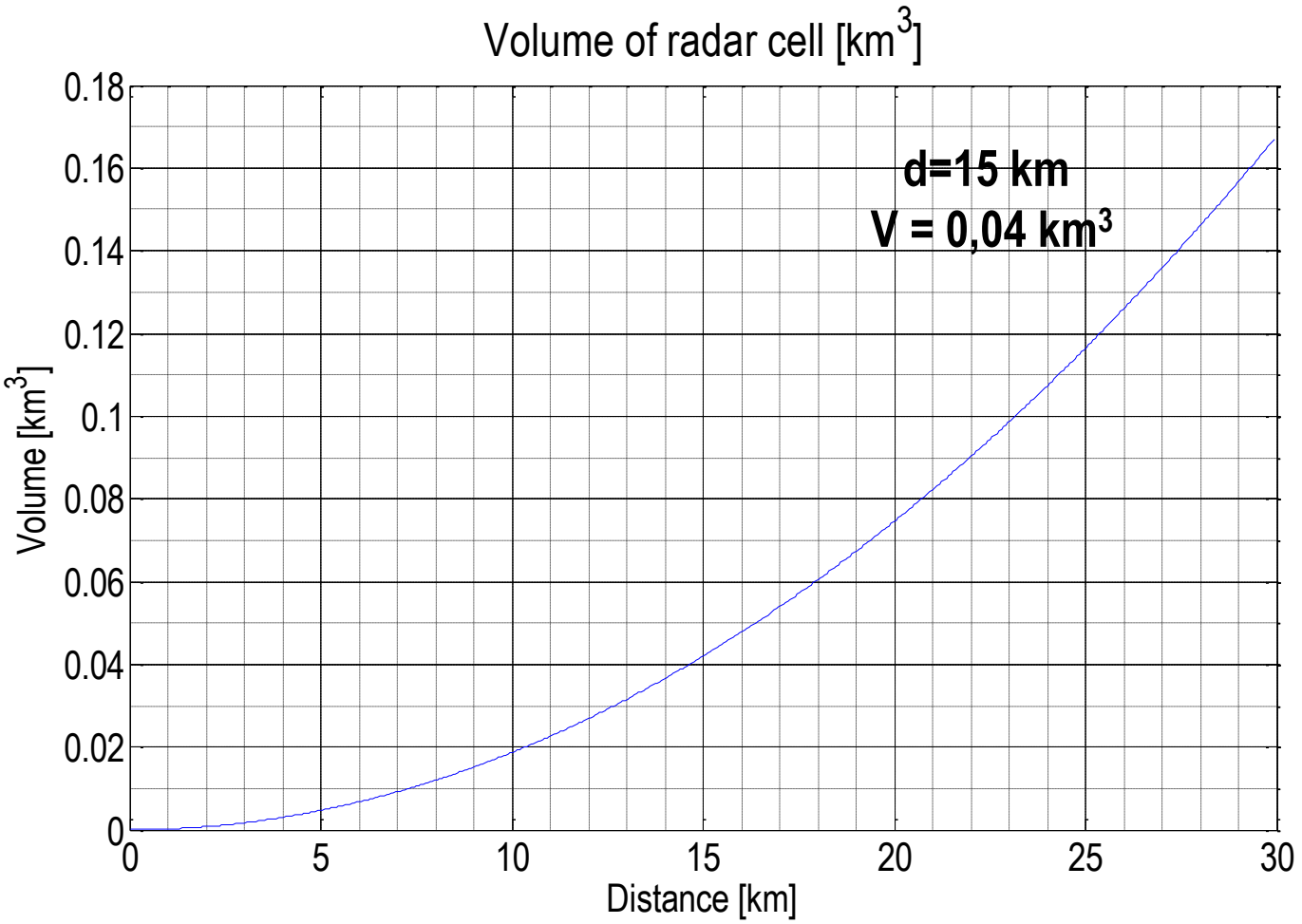
Common technic
Gauges compa





Radar equation and Z-R equation

- **Equation for weather radar**

$$P_r = \left(\frac{P_t \pi^3 G_0^2 \theta_{3dB} \phi_{3dB} c\tau}{\lambda^2 1024 \ln 2} \right) L^2 |K|^2 \frac{Z}{r^2} \longrightarrow P_r \cong K \frac{Z}{r^2}$$

- **Digital Number on the Cartesian radar maps** are represented as:

$$DN = (100 + P_{r,[dBm]} + 20 \cdot \log_{10} r_{[km]}) \cdot 2.55$$

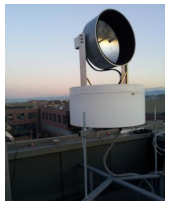
$$P_r \cong K \frac{Z}{r^2}$$

Z = Reflectivity due to the rain cell [$mm^6 mm^{-3}$].

$$Z_{[mm^6 m^{-3}]} = a \cdot R^b$$

R = Rainfall rate [mm/h].
a and ***b*** depends on the precipitation type, in our case ***a*= 316, *b*= 1.5** (**Marshall and Palmer Equation or Z-R equation**, 1948)

Radar and Rain Gauge



COMPARISON

R ⟷ **G**

- Radar maps available with a sample time of 1 min
- **Rain maps are cumulated over 1 hour time interval → R**

- Rain data available with sample time of 15 min
- **Estimated hourly cumulated rain → G**

- Selection of **Rain Gauges**:
  - Avoid clutter zone (Urban, mointaunous, hill)
  - Using free services provided by **Weather Underground network** (www.wunderground.com)
- **Radar** processing:
  - The value of rain is spatially averaged over a 1 km x 1 km (19 pixels by 19 pixels) area around the position of each rain gauge.
- Colocated R and G couples are divided into 2 datasets:
  - 1° for **CALibration** - 2° for **VALidation**

CALibration and VALidation procedure (CAL/VAL)

CALIBRATION

- Considering the (R,G) **CAL** couples, the **overall bias** is computed, following a procedure normally identified as **Bulk Adjustment:**

$$BA = \frac{\sum_{storms\_CAL} \sum_{places\_CAL} G}{\sum_{storms\_CAL} \sum_{places\_CAL} R}$$

VALIDATION

- Necessary to evaluate the effectiveness of this Bulk Adjustment procedure:

$$R_{BA} = R_{VAL} \cdot BA$$

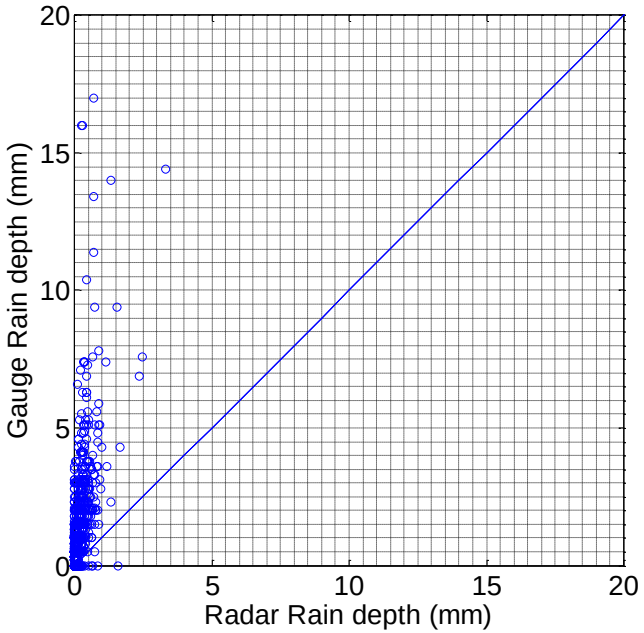
- Considering the couples (R_{BA}, G) of the VAL dataset some statistical indicator are computed:

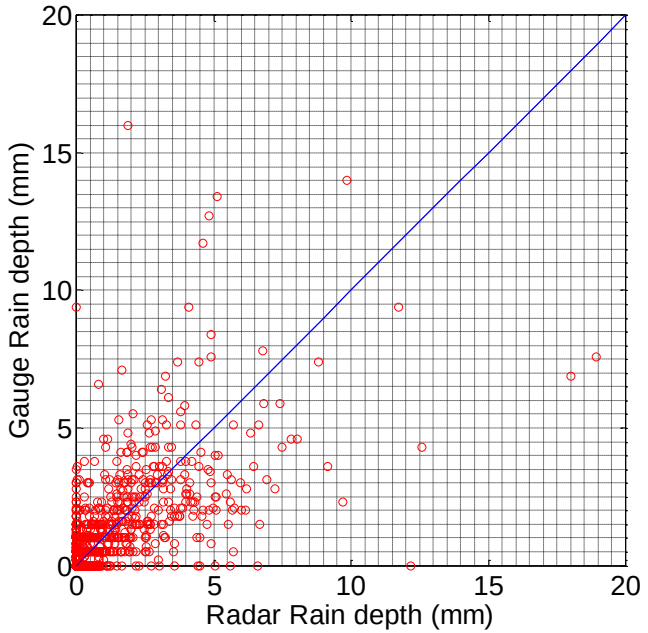
$$corr = \frac{\mathrm{cov}(R_{BA}, G)}{\sigma_{R_{BA}} \sigma_G} \qquad bias = \frac{\sum_{storms\_VAL} \sum_{places\_VAL} G}{\sum_{storms\_VAL} \sum_{places\_VAL} R_{BA}} \qquad rmsd = \sqrt{\frac{\sum_{gouges} \sum_{stroms} (G - R_{BA})^2}{N}}$$

- Computing 2 index from the contingency tables:
  - **POD** (probability of detection)
  - **MISS** (probability of missing observation)

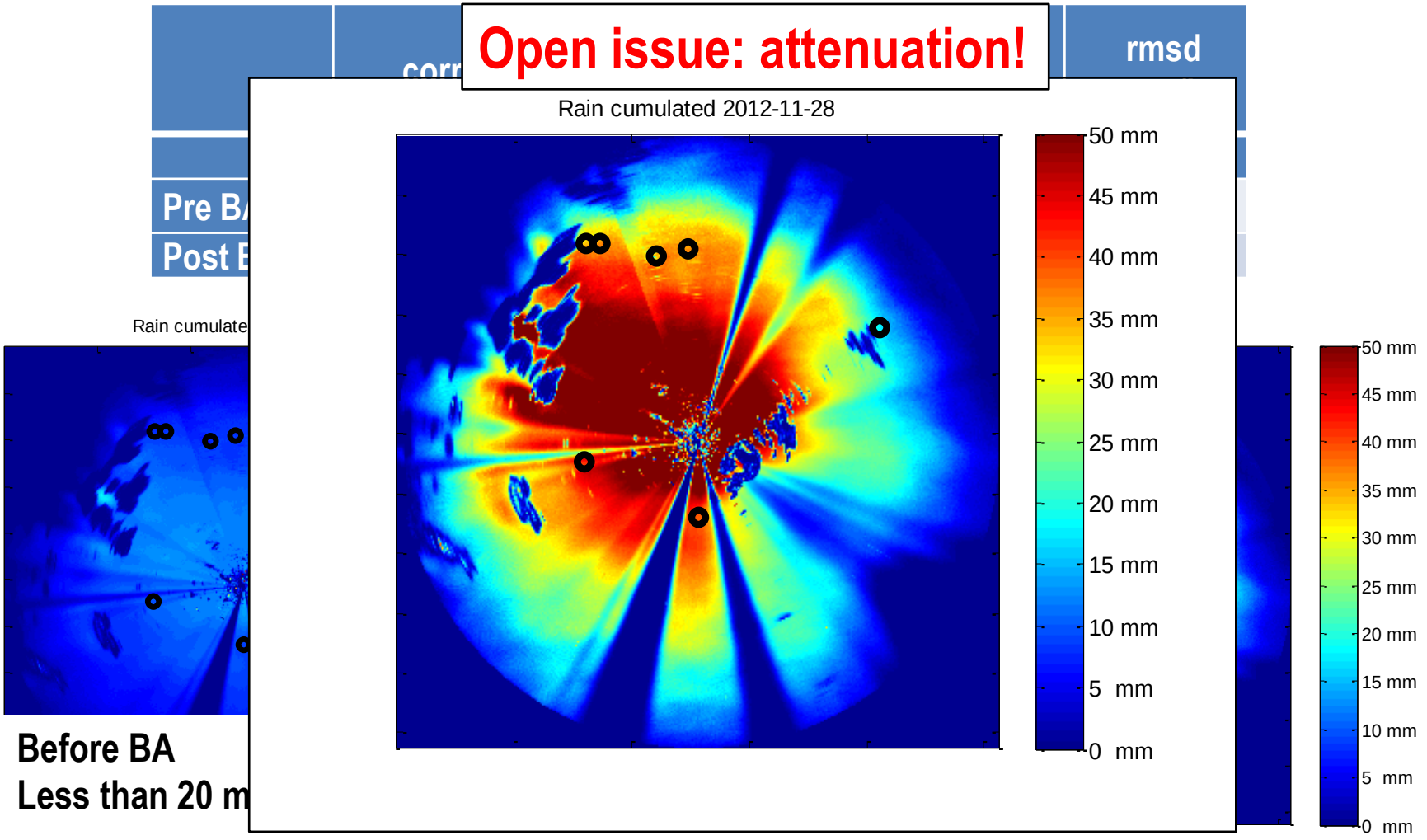
Results for radar of Turin

n° storms	n° couples	n° gauges Cal	n° gauges Val	data set date
13	1872	4	5	10-12 /2012





Results for radar of Turin



Clutter analysis to control the radar stability

Radar calibration and control using ground clutter echoes

- Each radar sub-systems may suffer for some degradations due to:
  - external factors (e.g. temperature fluctuations, humidity) .
  - equipment related issues (e.g. frequency drift of the magnetron, de-tuning of the receiver filter).
- To assure good performances in detection and measurement of rain, it is important to control the stability of the overall radar system components.

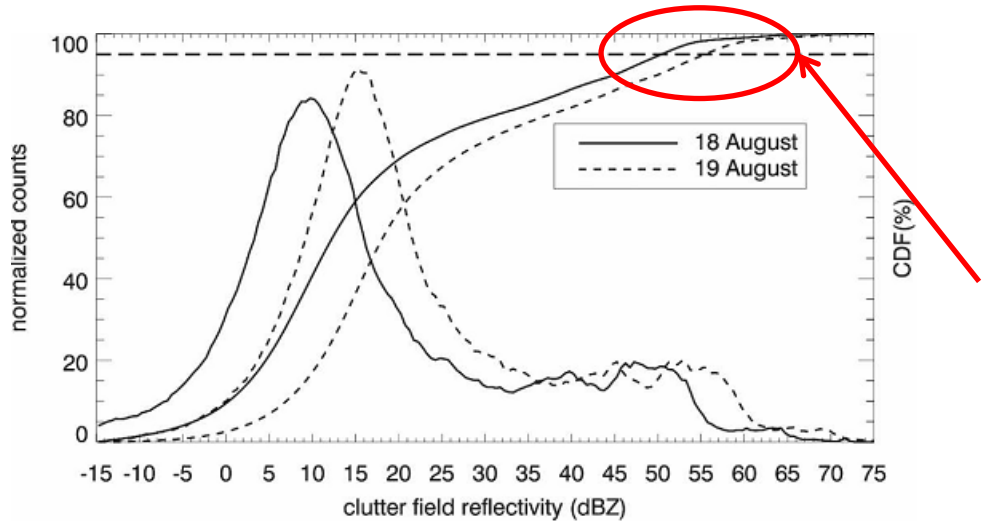
- **IDEA: use ground clutter echoes during clear sky days to check the radar calibration and control that any equipment failures occur.**

$$P_r \cong K\frac{Z}{r^2}$$

Z = Reflectivity due to the back scattering cross section of a portion of ground clutter, in case of no rain during clear sky days.

Relative Calibration Adjustment (RCA) algorithm

- The RCA (Relative Calibration Adjustment) by D.S. Silberstein et. al. in 2008, originally proposed for a S-band ground radar, uses the **Probability Distribution Function (PDF) of the clutter echoes and, consequently, the corresponding Cumulative Distribution Function (CDF).**
- **PDF and CDF should significantly change only if modifications on the radar systems occurred.**



Comparison of two daily PDFs/CDFs from August 2003. The horizontal dashed line represents the 95th percentile of the CDFs. Failure of the CDF curves to converge at the upper percentiles of the reflectivity is an indication of a calibration shift (D. S. Silberstein, 2008)

Use of Ground Clutter echoes for X-band radars

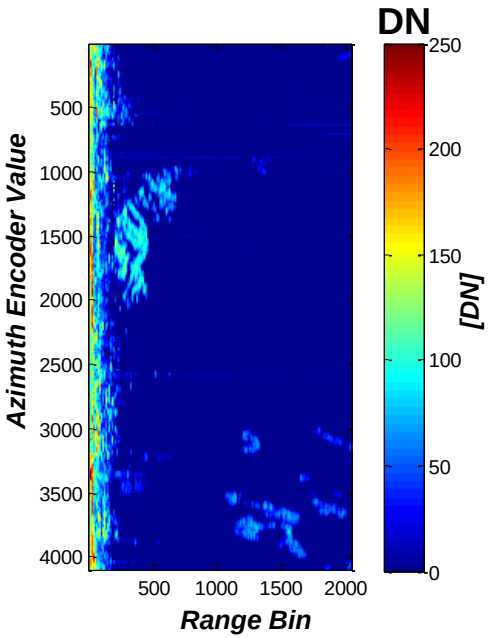
In order to use ground clutter echoes of X-band mini weather radar to control the radar stability, it is necessary to:

- Establish a **general criterion to detect an equipment failure or a radar "de-tuning" condition** in order to avoid wrong rain estimation with X-band weather radars.
- **Identify homogeneous clutter areas** in order to establish which is the most suitable clutter type (e.g. hill clutter, mountain clutter, urban clutter) to be used to control the stability of a X-band mini weather radar.
- **Measure the X-band weather radar losses** in case of "de-tuning" conditions or equipment failure.

Experiment Description

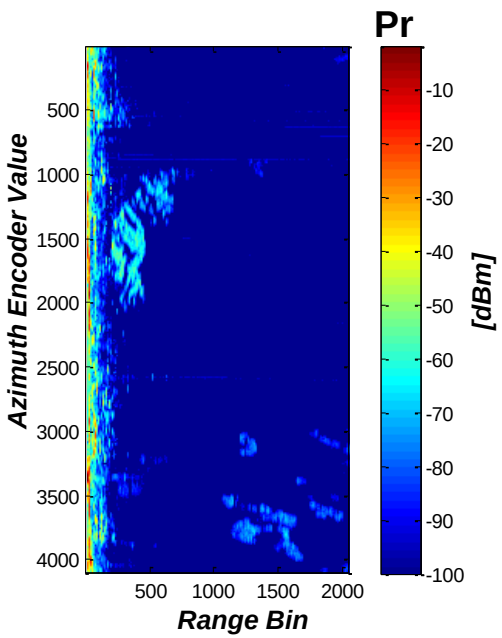
- The X-band radar receiver filter is controlled by a 8-bit register which control the filter central frequency.
- **To simulate a radar failure, the radar receiver filter has been intentionally detuned**.
- The radar central frequency, in tuned conditions (measured in laboratory) corresponds to a register value of 210.
- 11 different datasets of polar clutter maps have been acquired considering register code number between 160 to 255 with a step of 10.
- For each register value the acquisition period lasted 2 hours and 15 minutes, and correponds to 135 maps (1 map each minute).
- **The acquisitions have been performed in clear sky conditions in order to detect only clutter echoes and do not acquire echoes coming from meteorological targets**.
- **A statistical analysis have been performed on the maps.**
- Some statistical indicators have been computed
  - **16th percentile, 84th percentile, 90th percentile, Mean, Median**

Clutter maps processing



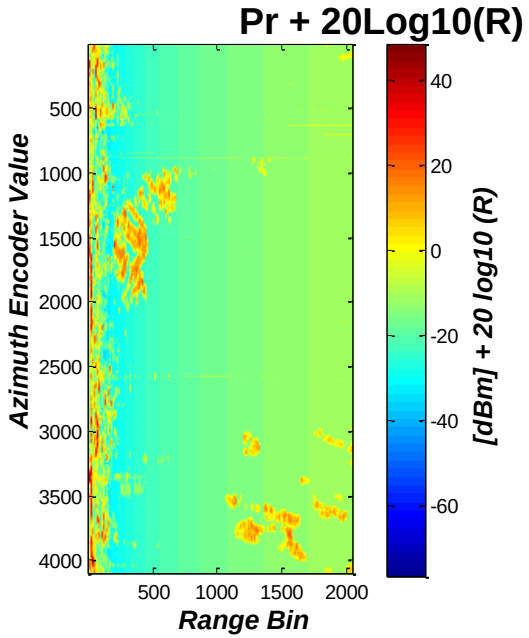
The radar acquired original cartesian map is in Digital Number (DN), values from 0 to 255.

$$DN = \left(100 + P_r^{[dBm]}\right) \cdot 2.55$$



DN are transformed into received power exploting the receiver law. Received power can be expressed considering the radar equation for meteorological target:

$$P_r = k \cdot \frac{Z}{R^2}$$



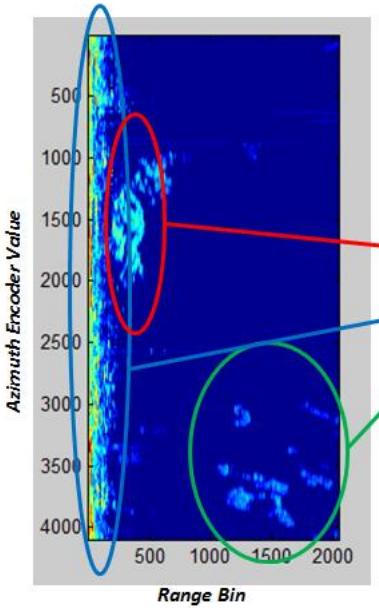
The backscattered power contribution (in dBm) coming from each ground clutter pixel is then compensated for space attenuation due to distance (R).

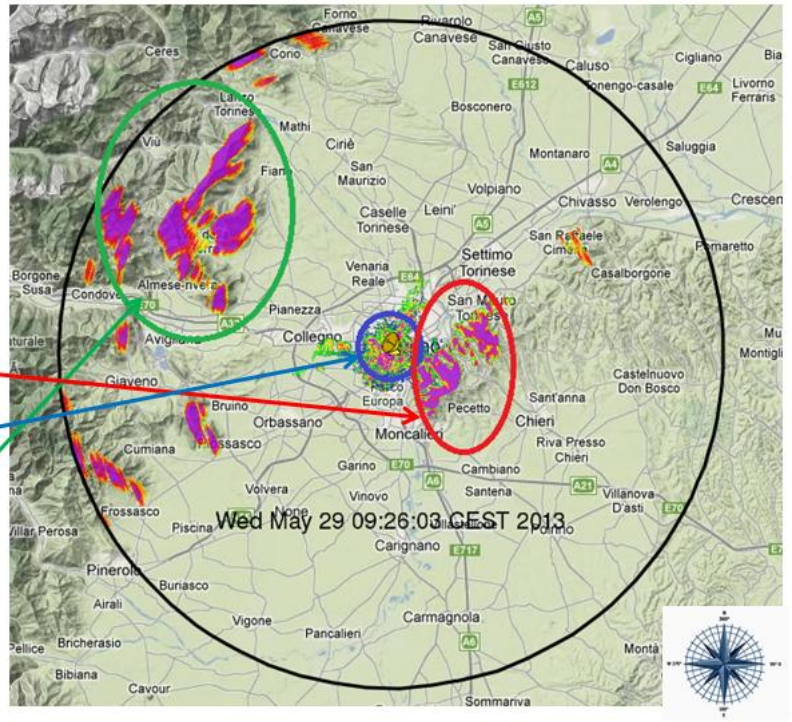
$$P_r + 20 \cdot \log_{10} R$$

Clutter maps

- 3 different areas can be observed considering a single clutter map acquired by the radar in Turin. Each area has a homogeneous type of ground clutter:

- **"Urban Clutter" (blue)**
- **"Hill clutter" (red)**
- **"Mountainous clutter" (green)**

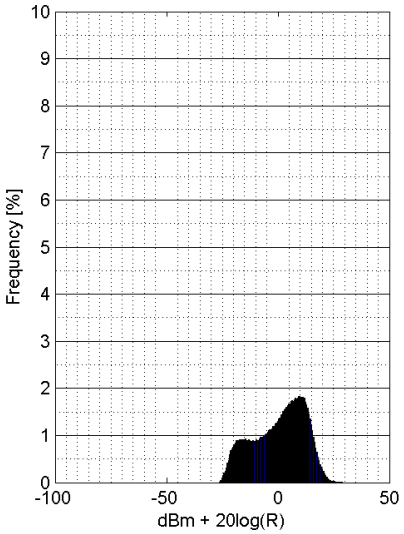




Clutter maps

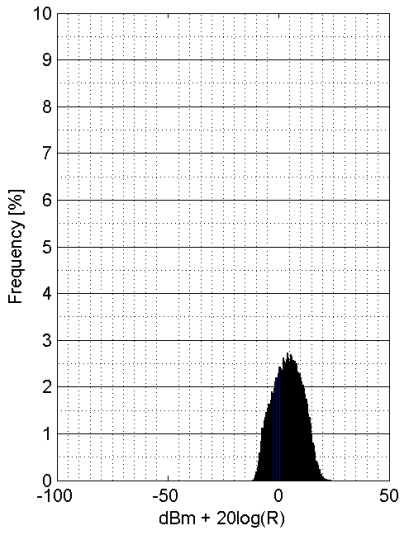
- The echoes power distribution from the 3 different clutter areas has been computed
- As example, the following PDFs have been computed for the filter code value equal to 210, the tuning condition.

Hill clutter



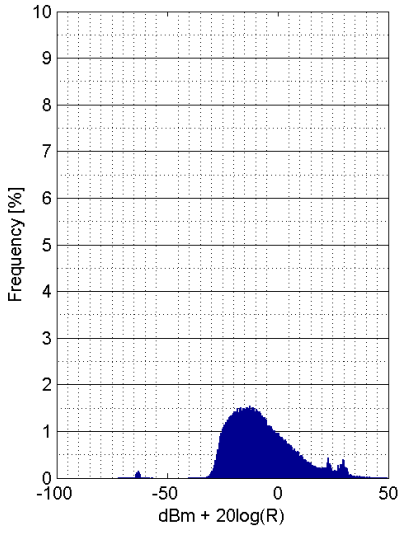
"Two modal"
2 different clutter sub-areas

Mountain clutter



"Normal distribution"
More uniform reflection geometry

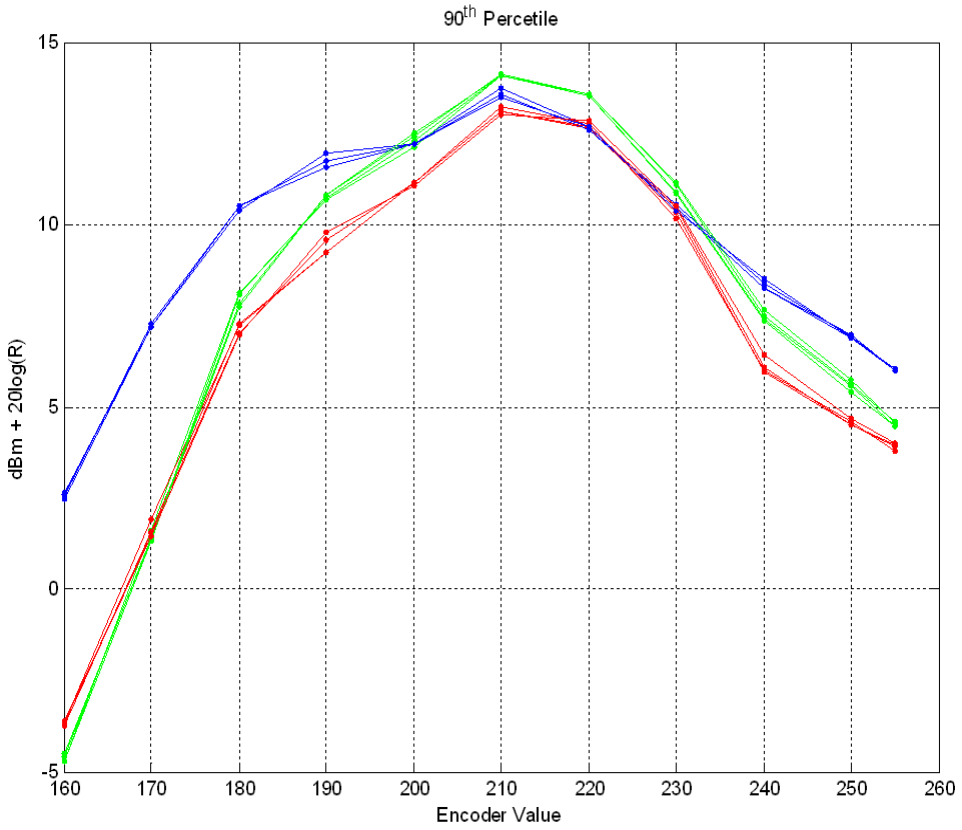
Urban clutter



"Rayleigh"
Absence, in average, of dominant scatterers

Detect a possible equipment failure

- Among all the statistical indicators, **90th percentile** is the best indicator to detect a possible radar equipment failure or modification, or a filter de-tuning condition.

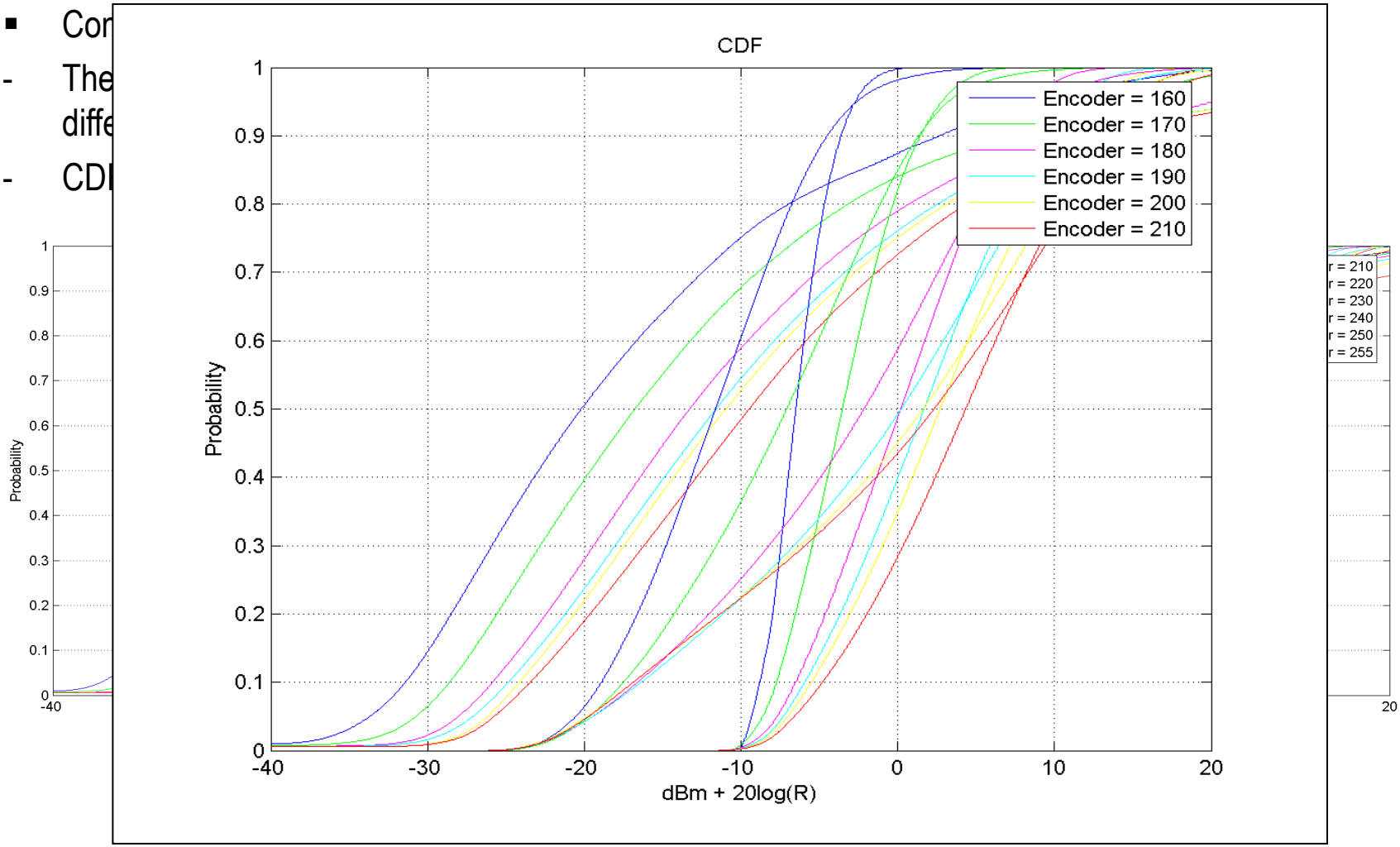


Variation of the clutter power 90th percentile indicator in function of the receiver filter code value for three different data subsets.

-"Urban Clutter" (blue)
-"Hill clutter" (red)
-"Mountainous clutter" (green)

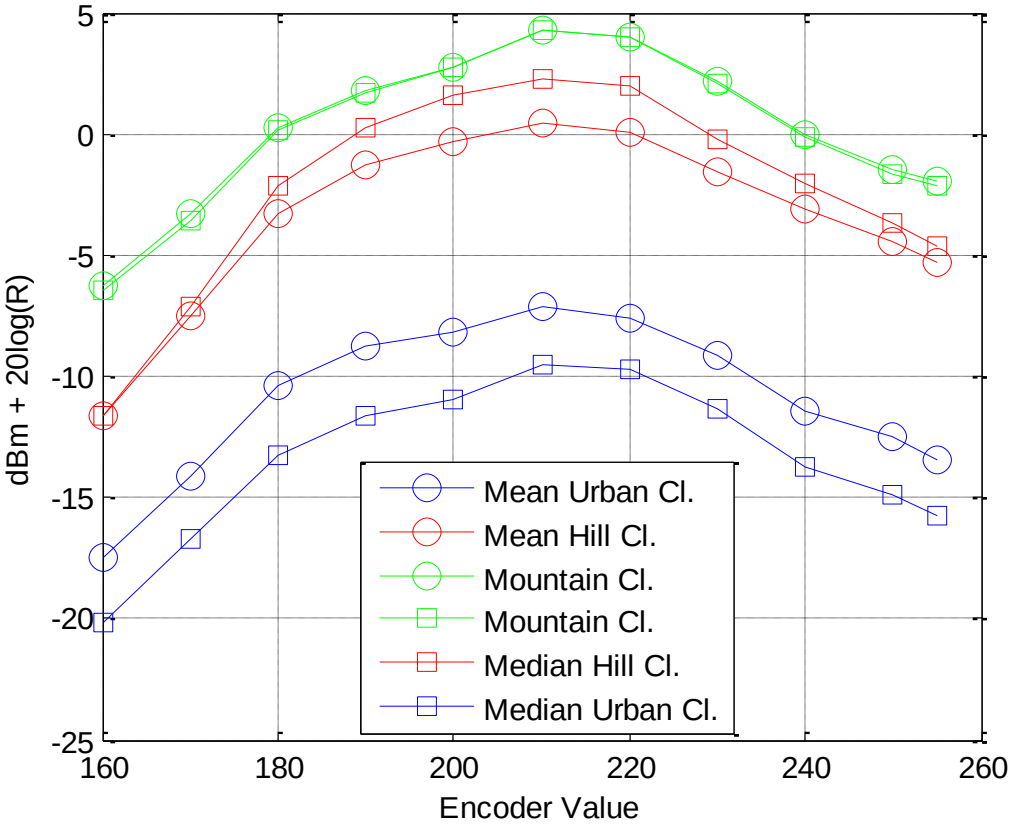
Cumulative Distribution Functions (CDFs)

- Cor
- The
  diffe
- CDI



Measure the losses

The **mean** and the **median** indicators, are more sensitive to clutter types.

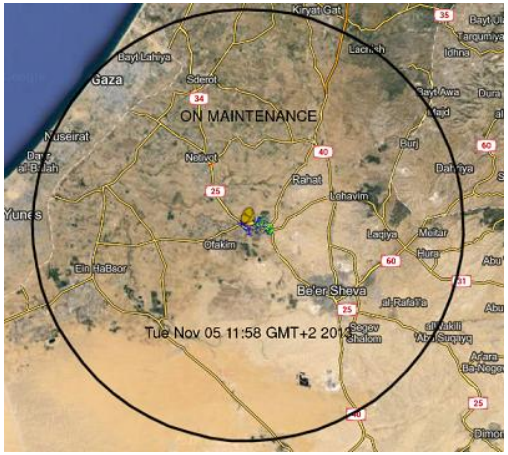


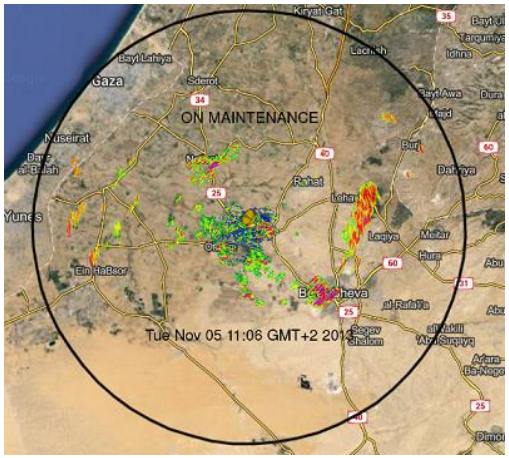
Taking into account the mean value when radar is tuned (encoder value 210) it is possible to observe:
-5 dB difference between mean power coming from Mountainous Clutter and Hill Clutter
-about 12 dB from Mountainous and Urban clutter

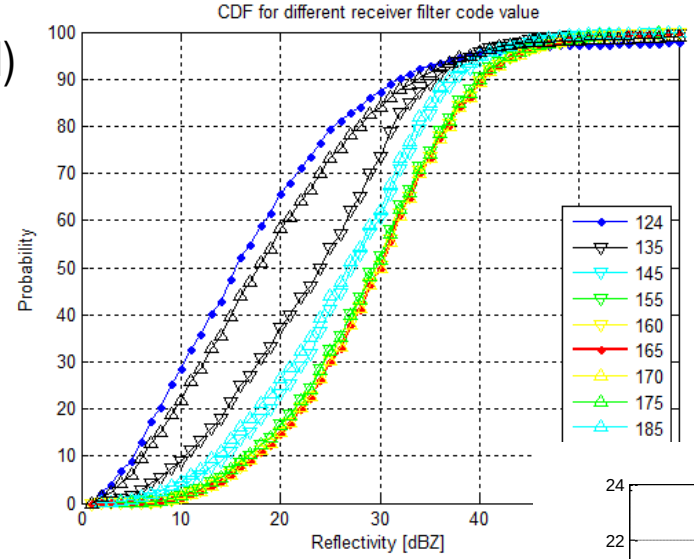
The same difference can be detected in detuning condition!

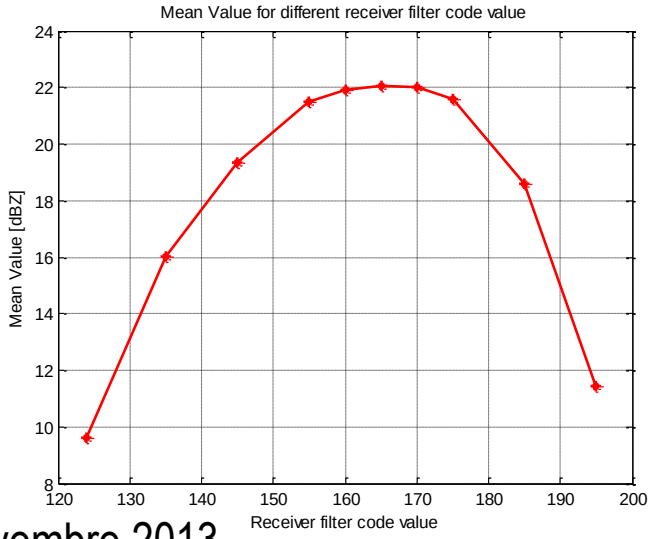
An example of remote re-tuning of radar

Radar installed in Gilat (Israel)









Installed in October 2012

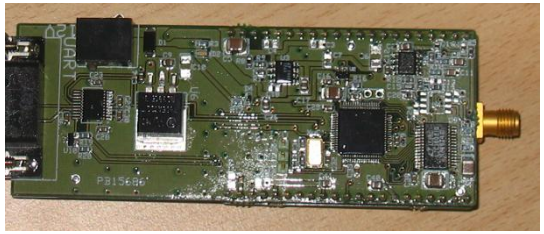
Remotely retuned on 5th Novembre 2013

FMCW radar

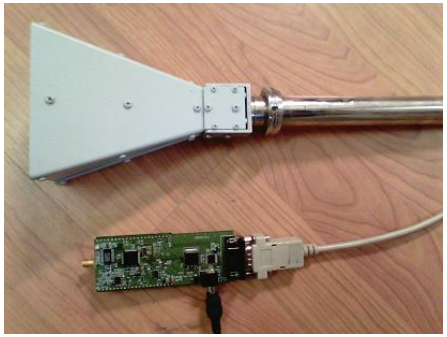
FMCW radar: early stages design and simulations

- One of the next goal of EST s.r.l. is to realize a **Frequency Modulated Continuous Wave** (**FMCW**) radar working at 10 GHz.
- The project is in its earlier stages of design
- The radar should be used as altimeter and in the future also as weather radar.
- In order to understand the FMCW radar capabilities:
  - A fully software simulator has been developed using Matlab©.
  - Some measurements have been performed using a cheap DEMO FMCW radar acquired by EST s.r.l.
- **The schematics of FMCW radar are finished, the components have been ordered** and it will be realized in the nex few months.

FMCW radar: early stages design and simulations

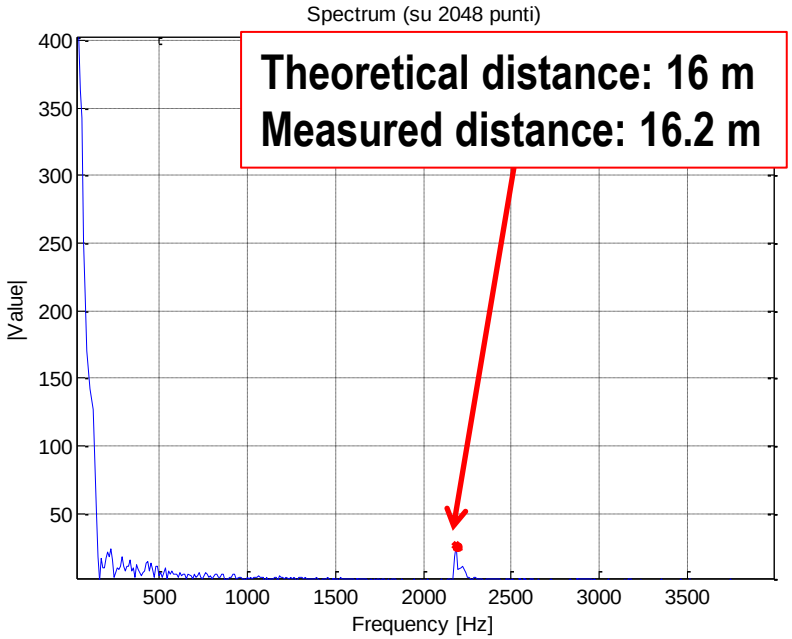


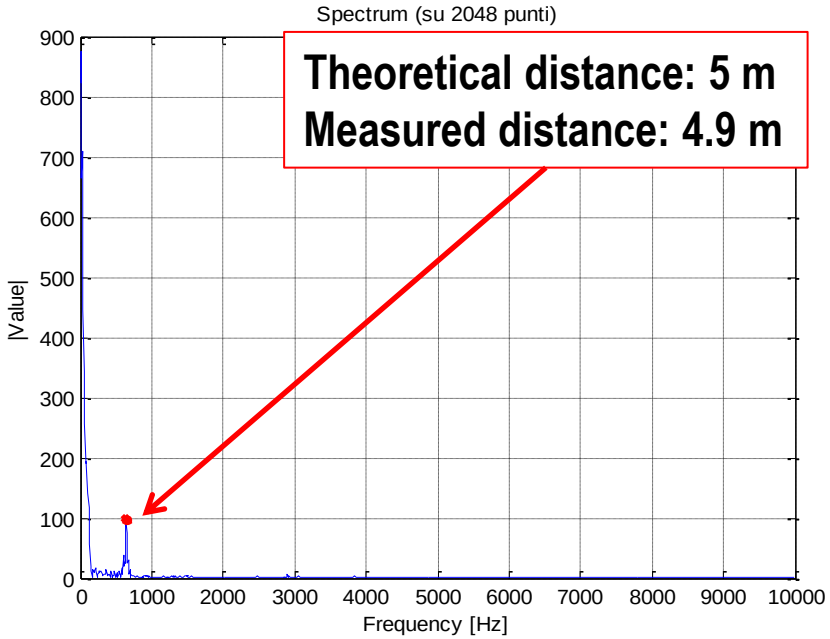
DEMO FMCW radar used for tests



$$\Delta f = \frac{BW}{T} 2\frac{d}{c}$$

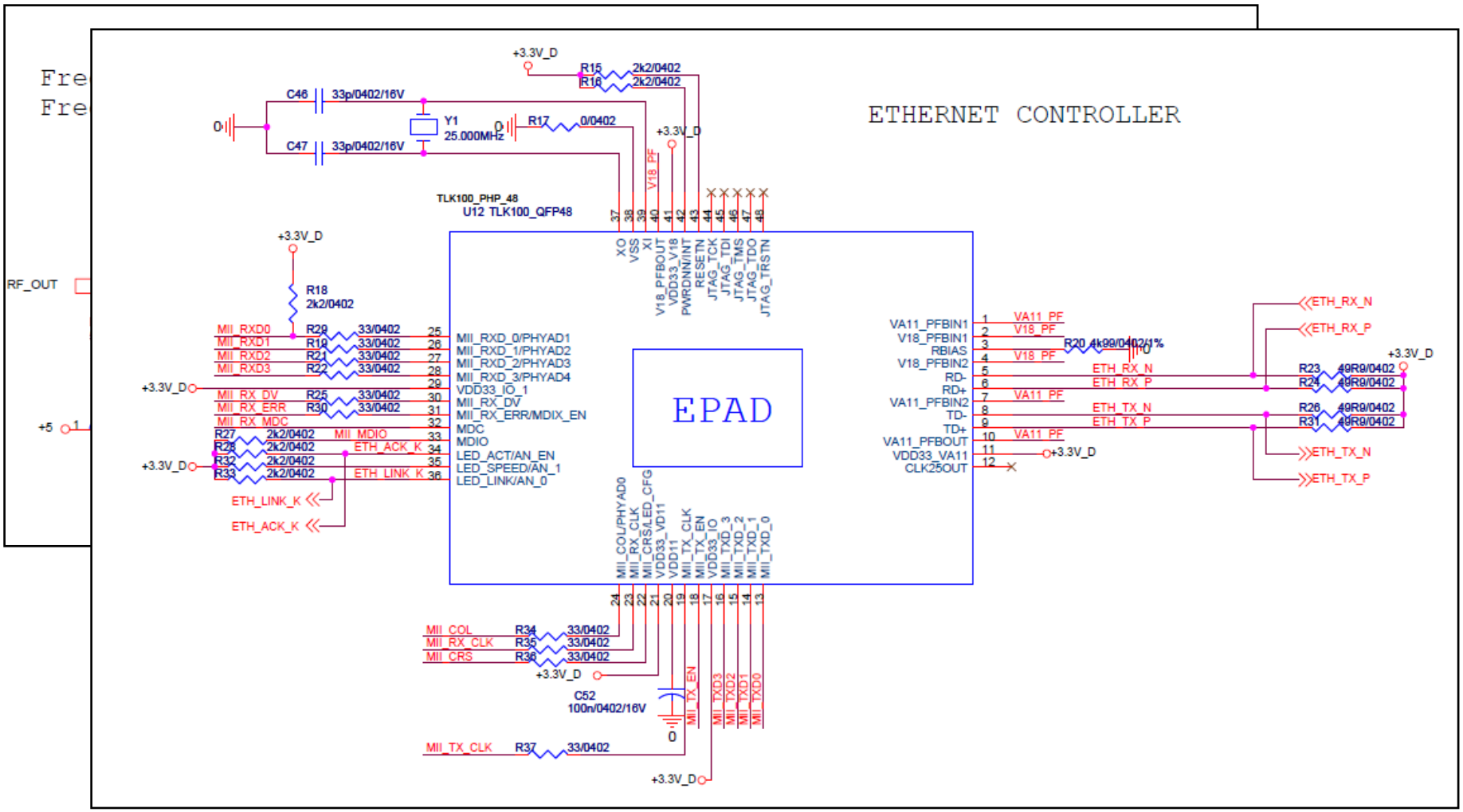
BW= 10 MHz
T= 1 ms





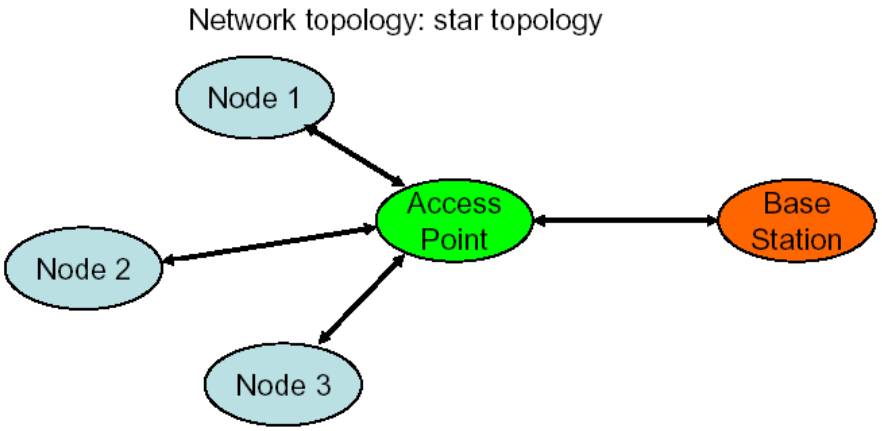
Example of results of MATLAB© simulations

FMCW radar: early stages design and simulations



Wireless Sensor Networks (WSNs)

WSN for environmental monitoring: DGPS

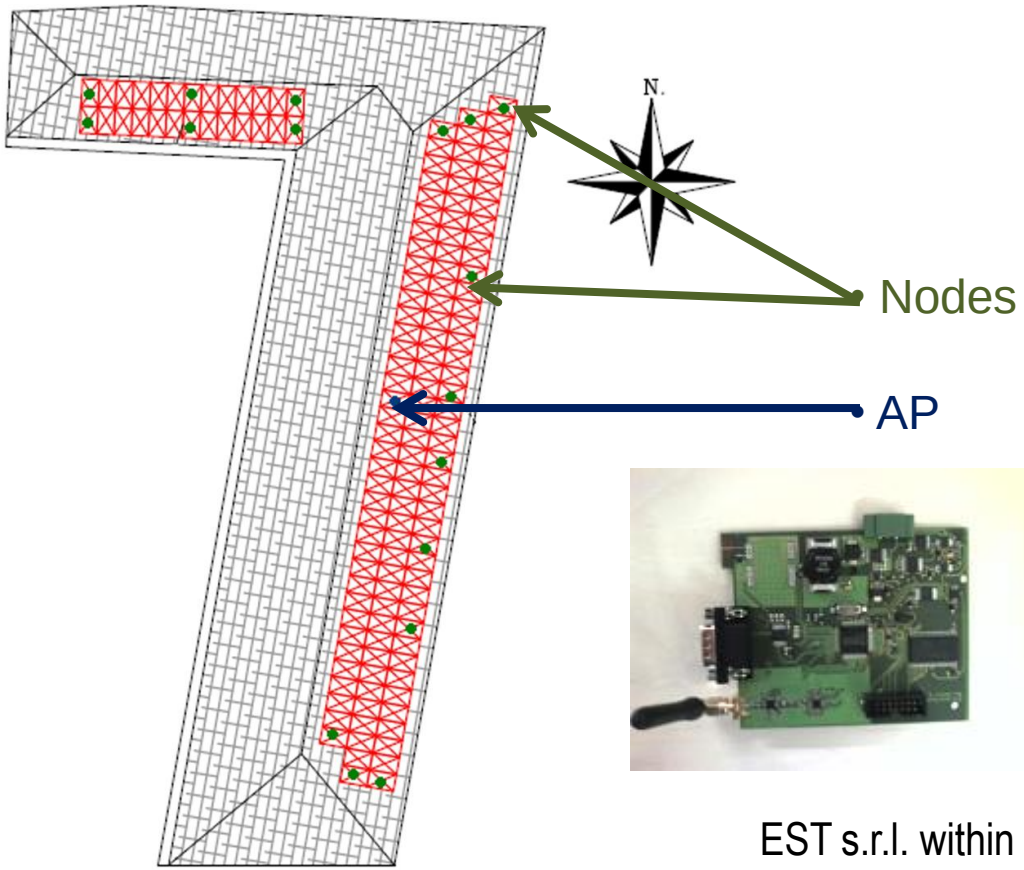


- Same hardware for both **GPS Node** and **Access Point** to reduct costs.
- Open source library.
- Real Time Operative System (FreeRTOS®).
- An ad-hoc hand shake protocol to manage the communication.
- Low power consuption to keep the node operative in hard environmental conditions.

Project between EST s.r.l. and CINFAI (2012-2013)

WSN as anti-theft alarm system for PV plant

The alarm is detected though an accelerometer sensor capable to detect a minimum displacement of the panel from its steady position.



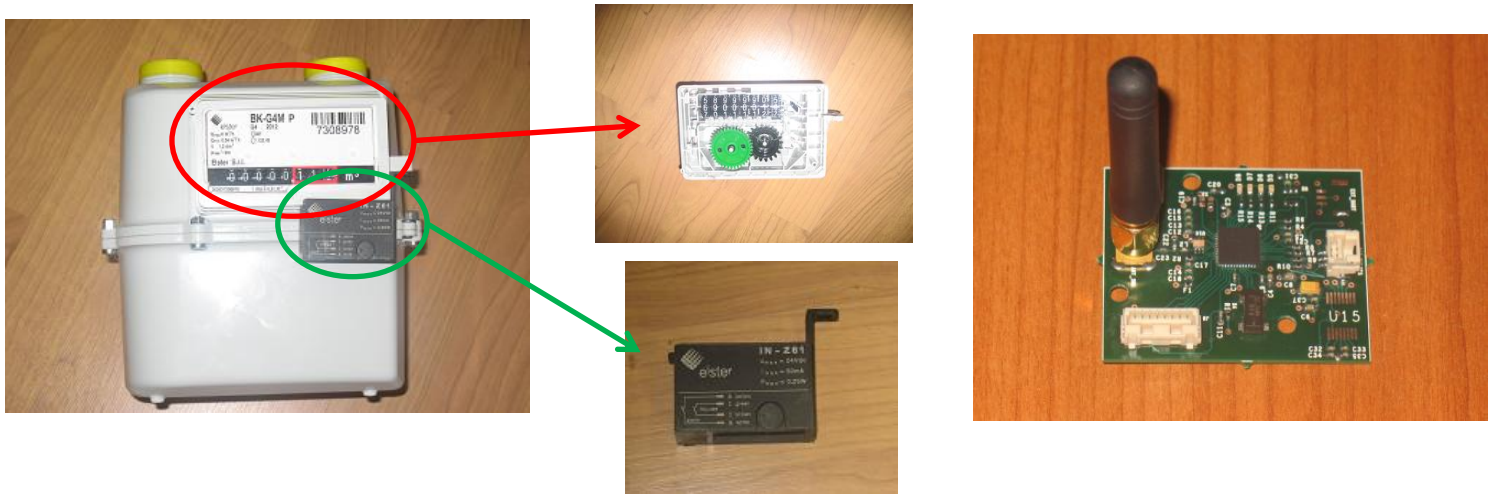
(Plant of prototypal WSN installation, kindly from ANKENERGIA s.r.l.)

EST s.r.l. within a research project with **ANKENERGIA s.r.l.** and **CINFAI** (2011-2012)

WSN for smart gas metering

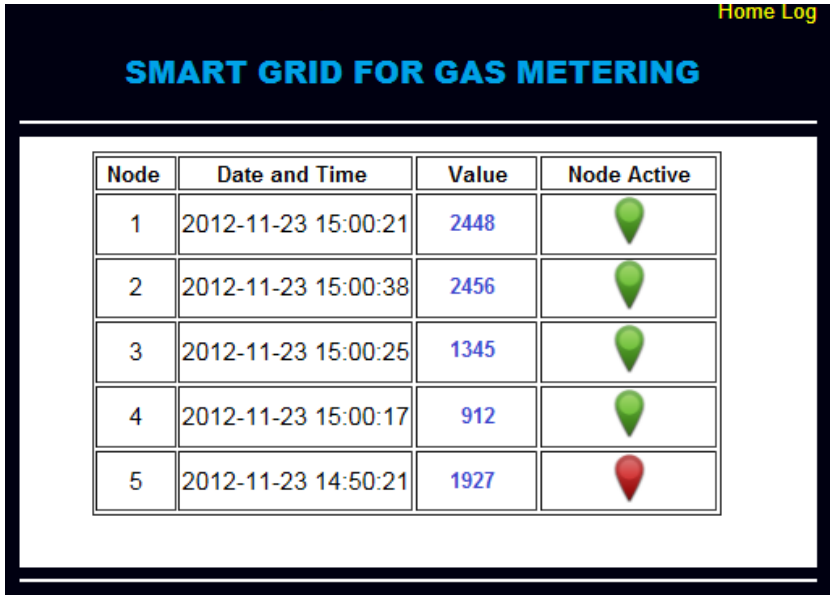
- Within the goals "20/20/20" (Horizon 2020) the Smart Grids will have a key role in the transformation of the current functionality of the energy distribution system.

- EST s.r.l. within a research project with **Piceno GAS s.r.l. and CINFAI** (2012) realized **a new prototypal smart grid for gas metering** able to give to gas operators a simple and cheap tool to keep under control the costumers gas consumption using commercial equipments.



WSN for smart gas metering

- **The Master Node** is developed to collect the data coming from each Sensor Node (the network has a star topology) through RF link at 868 MHz as operational frequency
- **The Master Node** is connected to the embedded PC through RS-232 link.
- **The Embedded PC** is equipped with a LAMP framework to store data coming from the Sensor Nodes and to present data on a web page accessible to authorized users.



Test on 14 days equivalent to 7 operational years, with a network of 5 Sensor Nodes, show a percentage of correctly received packets of 92 %.

Publications

The research activities during the Ph. D. period are documented in:

- 1 book chapter
- 5 journal articles
- 12 Conference contributions:
  - 10 proceedings (1 invited paper)
  - 2 abstract
- 1 patent pending as inventor

Publications

Book Chapter

- Gabella M., Notarpietro R., **Bertoldo S.**, Prato A., Lucianaz C., Rorato O., Allegretti M., Perona G. (2012) *A Network of Portable, Low-Cost, X-Band Radars.* In: Doppler Radar Observations - Weather Radar, Wind Profiler, Ionospheric Radar, and Other Advanced Applications. Dr. Joan Bech and Dr Jorge Luis Chau (InTech), pp. 175-202. ISBN 9789535104964

Journal articles

- O. Rorato, **S. Bertoldo**, C. Lucianaz, M. Allegretti, S. Bertoldo, R. Notarpietro (2013) *An Ad-Hoc Low Cost Wireless Sensor Network for Smart Gas Metering.* In: WIRELESS SENSOR NETWORK, vol. 5 n. 3, pp. 61-66. - ISSN 1945-3086
- **Bertoldo S.**, Rorato O., Lucianaz C., Allegretti M. (2012) *A Wireless Sensor Network Ad-Hoc Designed as Anti-Theft Alarm System for Photovoltaic Panels*. In: WIRELESS SENSOR NETWORK, vol. 4 n. 4, pp. 107-112. - ISSN 1945-3086
- M. Allegretti, **S. Bertoldo**, A. Prato, C. Lucianaz, O. Rorato, R. Notarpietro, M. Gabella (2012) *X-Band Mini Radar for Observing and Monitoring Rainfall Events*. In: ATMOSPHERIC AND CLIMATE SCIENCE, vol. 2 n. 3, pp. 290-297. - ISSN 2160-0414
- **Bertoldo S.**, Lucianaz C., Rorato O., Allegretti M., Prato A., Perona G. (2012) *An operative X-band mini-radar network to monitor rainfall events with high time and space resolution.* In: ENGINEERING TECHNOLOGY AND APPLIED SCIENCE RESEARCH, vol. 2 n. 4, pp. 246-250. - ISSN 1792-8036
- Rorato O., Lucianaz C., Vittaz E., **Bertoldo S**., Allegretti M. (2012) *A wireless sensor network board for environmental monitoring using GNSS and analog triaxial accelerometer. In: International Journal of Embedded Systems and Applications*. In INTERNATIONAL JOURNAL OF EMBEDDED SYSTEMS AND APPLICATIONS, vol. 2 n. 4, pp. 35-43. - ISSN 1839-5171

Patent pending

- Allegretti M., Amici A., **Bertoldo S.**, Giorgi A., Norcini Pala G., Pacetti A., Rorato O.,*Rete di sensori wireless per la misura da remoto di consumi di gas da interfacciarsi con i tradizionali contatori in dotazione alle utenze*. Patent pending N. TO2013U000009, 23rd January 2013

Publications

Conference contibutions -1-

- **Bertoldo S**., Notarpietro R., Branca M., Dassano G., Lucianaz C., Rorato O., Allegretti M. (2013) *Characterization of the receiver filter of a X-band weather radar to improve the performance of an application to control the radar stability*. In: International Conference on Electromagnetics in Advanced Applications (ICEAA '13), Torino (Italy), 9-13 September 2013. pp. 935-938
- Notarpietro R., Branca M., Morin E., Lokshin A., Gabella M., De Vita P., Basso B., Bonfil D., **Bertoldo S**., Shah S., Lucianaz C., Rorato O., Allegretti M. (2013) *Towards sustainable agricultural management using high resolution X-band radar precipitation estimates*. In: International Conference on Electromagnetics in Advanced Applications (ICEAA '13), Torino (Italy), 9-13 September 2013. pp. 915-918
- Shah S., Notarpietro R., **Bertoldo S.,** Branca M., Lucianaz C., Rorato O., Allegretti M., (2013) *Automatic Storm(s) Identification in High Resolution, Short Range, X-Band Radar Images*. In: International Conference on Electromagnetics in Advanced Applications (ICEAA '13), Torino, 9-13 September 2013. pp. 945-948
- Allegretti M., **Bertoldo S.,** Lucianaz C., Rorato O., Branca M., Shah S., Notarpietro R., Perona G. (2013) *Monitoring precipitation on mountain streams to optimize the hydroelectric power production*. In: 2nd International Conference Energy and Meteorology, Tolosa (FRA), 25-28 June 2013 (Only abstract in the proceedings).
- **Bertoldo S.**, Bracco L., Notarpietro R., Gabella M., Lucianaz C., Rorato O., Allegretti M., Perona G. *Clutter analysis to monitor the stability of a portable X-band mini weather radar* UrbanRain12, In: Urban Rain 2012 - 9th International Workshop on Precipitation in Urban Areas, Hotel Randolins, St. Moritz, Switzerland, 6 - 9 December 2012. pp. 171-176.
- Losso A., Corgnati L., **Bertoldo S**., Allegretti M., Notarpietro R., Perona G. (2012) *SIRIO: an integrated forest fire monitoring, detection and decision support system - performance and results of the installation in Sanremo (Italy).* In: Forest Fire 2012, The New Forest, UK, 22-24 May 2012. pp. 79-90

Publications

Conference contibutions -2-

- **Bertoldo S**., Corgnati L., Losso A., Perona G. (2012) *Safety in forest fire fighting action: a new radiometric model to evaluate the safety distance for firemen working with hand-operated systems.* In: Forest Fire 2012, The New Forest, UK, 22-24 May 2012. pp. 3-12. (INVITED PAPER).
- Rorato O., Lucianaz C., **Bertoldo S**., Allegretti M., Perona G. (2012) *A multipurpose node for low cost wireless sensor network*. In: 2012 IEEE-APS Topical Conference on Antennas and Propagation in Wireless Communications (APWC), Cape Town, WP, South Africa, 2-7 September 2012. pp. 247-250
- **Bertoldo S**., Bracco L., Notarpietro R., Lucianaz C., Rorato O., Allegretti M., Perona G. (2012) *A standalone application to monitor the stability of a low cost maintenance free X-band mini weather radar, using ground clutter echoes.* In: International Conference on Electromagnetics in Advanced Applications (ICEAA '12), Cape Town, WP, South Africa, 2-7 September 2012. pp. 1040-1043
- Paolella S., Prato A., Turso S., Notarpietro R., **Bertoldo S**., Cucca M., Gabella M., Perona G., Ferrarese S., Richiardone R. (2011) *Identification, tracking, validation and forecast of local high resolution precipitation patterns observed through X-band micro radars.* In: ICEAA'11, Torino (ITA), September 12-16, 2011. pp. 1436-1439
- **Bertoldo S.**, Corgnati L., Perona G. (2011) *Un nuovo modello radiometrico per l'identificazione di hot spot di incendi boschivi e come strumento di valutazione delle performance dei sensori in ambienti ad orografia complessa*. In: 15a Conferenza Nazionale ASITA, Colorno, Parma (ITA), 15-18 Novembre 2011. pp. 325-334
- Lucianaz C., **Bertoldo S.**, Rorato O., Mamino M., Allegretti M., Perona G. (2011) *High temporal and spatial resolution X-band radar based system to monitor rainfall events and detect landslide risk in the Mediterranean area.* In: 13th Plinius Conference on Mediterranean Storms (EGU Topical Conference Series), Savona (ITA), September, 7-9, 2011

Thank you!

Questions?

RAIN EVENT DEMO

Radar: Parma

Date: 13th July 2013

Parmaonline
il quotidiano di Parma

Noceto, allagamenti per il temporale

sabato 13 luglio 2013 09:35

Pioggia intensa nel Parmense. Tante le chiamate ai vigili del fuoco per richieste d'intervento. Nella Bassa segnalate grandinate

GAZZETTA DI PARMA.it

Violento temporale: a Noceto allagamenti, decine di chiamate. E la grandine imbianca Boretto

13/07/2013 - 08:51