Radar Networking over the Tyrrhenian Sea

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1 Introduction

The climate change impact assessment and consequently severe weather conditions management can be articulated in three main activities: monitoring, mitigation and adaptation. These three issues are of great interest for the cross-border maritime area between Italy and France, i.e those regions bordering on the Ligurian Sea, the Channel of Corsica, and the upper portion of the Tyrrhenian sea that are characterized by similar weather and climate conditions. The need of a wide range cross-border cooperation, has lead to develop joint policies, integrated and shared in the field of environmental monitoring and protection in the territories of the cooperation regions. In such a context, therefore, it becomes essential to develop and implement more efficient monitoring instruments, and to develop risk reduction procedures. This is one of the main topic of the PROTERINA-2 project, which has the primary purpose of environment prevention, with particular interest in hydro-geological and forest fires risk management, both of them affecting the entire territory of the project (Liguria, Corsica, Sardinia and Tuscany). In particular the partners of the project undertake to identify the best strategies through the improvement of the monitoring network, and the implementation of a platform for sharing the informations (both data and models).

This work fits in the project activities related to hydro-geological risk management. One of the main input need by this task is the measurement and forecasting/nowcasting of heavy rainfall. Monitoring weather phenomena from radar has an essential role in nowcasting applications, as one of the most useful sources of quantitative precipitation estimation. Its short-term prediction is often needed in various meteorological and hydrological applications where accurate rainfall observations are essential, as for national service and civil protection forecasting, agriculture and urban activities. Very recently, Tuscany region (central Italy) is equipped with two X-band radars with a maximum range of 108 km, a beam width of 3° and a high spatial resolution (i.e. radial resolution up to 90m), located in Livorno and Cima di Monte (Elba island) sites. The first system is property of Livorno's port Authority, the second one of Consorzio LaMMA (Laboratory of Monitoring and Environmental Modeling for the sustainable development). Both systems are managed by LaMMA. In the next months a third X-band radar will be installed and made operational in the northern part of the Tyrrenian area (in Montemarcello site), to complete the Tuscany coast monitoring coverage. The complete shared network will be composed by this three short range radars, the Monte Rasu (north Sardinia) radar and Aleria (mead Corse) radar. The cross-border sharing of such relevant meteorological observation instruments and the integration of these data with existing tools and methodologies is intended to improve operational regional weather services in nowcasting activities and their impacts on the territory, as those related to LaMMA daily issues. This sharing is widely promoted within PROTERINA-Due project between the different partner regions. The integration of these data with other complementary and ancillary measurements is also needed to increase the reliability and accuracy of radar measurements in view of both a better meteorological phenomena understanding and quantitative precipitation estimation. The regional raingauge network and meteorological stations have been used to obtain useful information for a preliminary performances assessment. The radar system and its mosaicking is presented, as well as some preliminary products.

The first part of the work is concerning the implementation of the cross-border radar networking and mosaicking; the second one deals with the activities made by LaMMA for the management and development of the Tuscany radar network.

2 SHARED SYSTEM DESCRIPTION

The weather radar used in this work are those installed in Sardinia (Monte Rasu), Corse (Aleria), Elba Island (Cima di Monte) and Livorno. They mainly have regional spatial coverage, with a large overlap over the maritime area of interest. These systems have been designed and produced by different manufacturers and have very different technical characteristics, with particular reference to the operational frequency, system dimension and architecture, the measured data format. One of the objective of this work, was the sharing of data coming from the involved weather radars. A necessary and preliminary task has been the technical specifications analysis of each radar, to identify a common format for data exchange.

The Sardinia radar (Monte Rasu) is a doppler, single-polarization weather radar, operating in C-band. It belongs to the GPM 250-C series of systems, manufactured by Alenia, and has been installed in 1998. The radar system consists of a transmitter, a solid-state modulator and a klystron 250 kW power amplifier, a digital receiver, a 4.2 m diameter parabolic antenna located on the top of a 38 m tower and a dedicated radar data processor (RSP Radar Signal Processor). The Monte Rasu radar became operational in June 2005, after a long and difficult stage of development that has partially modified the original project configuration. The operational range of the radar is ordinarily oriented to the regional territory coverage, but in its maximum spatial coverage can reach the Tyrrhenian coasts of Tuscany. The following table shows the main technical characteristics of the considered weather radars.

Table 1: Technical characteristics of radar systems

TECHNICAL CHARACTERISTIC	MONTE RASU RADAR VALUE	ALERIA RADAR VALUE	LIVORNO ELBA RADAR VALUE
Geographical Coordinates (lat/lon) and height (over sea level)	40°25’ 15” N, 09°00’ 19” E, 1258 m	42°07’ 47.14"N, 09°29’ 47 E, 63.4 m	42°48' 00.9"N, 10° 23' 31.1"E, 440 m (Elba radar) 43° 33' 43.2" N, 10°1 8' 13.7" E, 77m (Livorno radar)
System Model	GPM 250-C	Thalès MTO 2000 S	WR10X
Frequency band	C-Band (5600-5650 MHz)	S-Band (2802 MHz)	X-Band (9410 MHz ± 30MHz)
Transmitter Power	250 kW (Klystron)	620 kW	10 kW (Magnetron)
Antenna diameter	4.2 m	6.5 m	0.7 m
Antenna 3dB beamwidth	0.95°	1.28°	< 3°
Antenna gain	45 dB	42.5 dB	35 dB
Receiver Sensitivity (dBm)	S/N=0 dB (-10dBz target) at 79 km	-115 dBm	10dBz target at 25 km
Pulse Repetition Frequency (PRF)	300/600/900/1200 Hz	290.02 Hz / 257.8 Hz/ 232.02 Hz	800 Hz
Pulse width	0.5/1.5/3 µs	2 µs	0.6 µs
Doppler spectrum	± 16 m/s ; ± 48 m/s (dual PRF)	from 60 m/s ato 60 m/s	No Doppler
Polarization	single (H)	Single (H)	single (H)
Range	500 km (max) - 125 km (max doppler)	200 km	108 km (max)
Antenna rotation speed	36 rpm (max)	18°/s (max)	20°/s
Clutter suppression	> 30 dB		Statistic filter

The Aleria radar is a single polarization (horizontal) doppler weather radar operating in S-band frequency. The radar model is MTO 2000 S produced by Thales. It has been installed in 2002 in a site located in Aleria. Due to the high dimension of the antenna (diameter of 6.5 m), the installation required a specific building dedicated to the radar. The antenna is located 63.4 m over the sea level. The radar system uses a coaxial magnetron oscillator and the peak power is 620 kW. The radar control system and the computer software been developed and are managed by Meteo France.

In order to improve the weather radar coverage two systems have been installed in the coastal areas of the Tuscany Region. The radars have been positioned in the Elba Island (site of Cima Del Monte) and in the Livorno port. Both radars are operating in X-band, model WR10X designed by ELDES with a magnetron transmitter a solid state modulator and a logarithmic receiver; despite the known disadvantages in terms of spatial coverage and signal attenuation compared to the conventional C-band and S-band radar, however, they offer some advantages:

- High spatial resolution (radial resolution up to 90 meters)
- High refresh rate (every minute)
- Size (90 x 130 cm), weight (100 kg) and power (5 W on average) are reduced: it can be installed almost anywhere
- Low cost of operation and maintenance
- Easy of use (high level of automation)
- Ideal instruments for monitoring basins and areas hardly covered by conventional radars (e.g., mountains)
- Placement opportunities on mobile platforms (trailers or vans).

The recently installed radar system are very useful for the monitoring of the portion of the Tyrrhenian Sea between Corsica and Tuscany, often characterized by intense meteorological phenomena. This area is also covered by the other two preexisting radars of Corse and Sardinia, giving spatial overlapping and redundancy opportunities, very useful in environmental monitoring applications oriented to civil protection activities.

The intercalibration and interoperability between different systems have been very important issues toward the fusion of all the different information in a unique monitoring instrument. Since the beginning of this work radars of Sardinia and Corse already where included in the respective national mosaics, both of them adopting not standard data format and not open source harmonization and processing softwares, mainly due to actions targeted to a national optimization made on previous heterogeneous realities. The OPERA [1] composite was presenting a sufficiently extended European coverage, also spanning the maritime area of interest; moreover the purpose of the OPERA program was the exchange of data and knowledge in radar meteorology, using open and standard formats, widely documented and already partly integrated into next-generation systems, due to the dissemination activities in the years. In conclusion, therefore, the owners of the radar have mutually decided to adopt OPERA radar composite as reference and, consequently, the OPERA formats for encoding and exchange of radar data. The shared informations are the polar reflectivity volumes generated in both BUFR 3.1 and HDF5 formats [1].

2.1 The Tyrrhenian weather radar mosaic

The purpose of putting in a common factor the radar systems operating in the various regions of the cross-border maritime space generated a variety of benefits. Certainly a substantial economic savings is related to the synergic use of technical resources provided and financed from different governments; in most of cases neighboring regions can increase the spatial coverage of their monitoring networks; the overlapping areas can be essential for the reduction of false alarms and to increase the probability of detection, as well as to ensure a more efficient and uninterrupted service in case of failure of one of the systems. Referring to Figure 1 the mentioned benefits are clear. The figure shows the ideals overlapping areas, taking into account the maximum range, and do not considering obstacles due to orography.

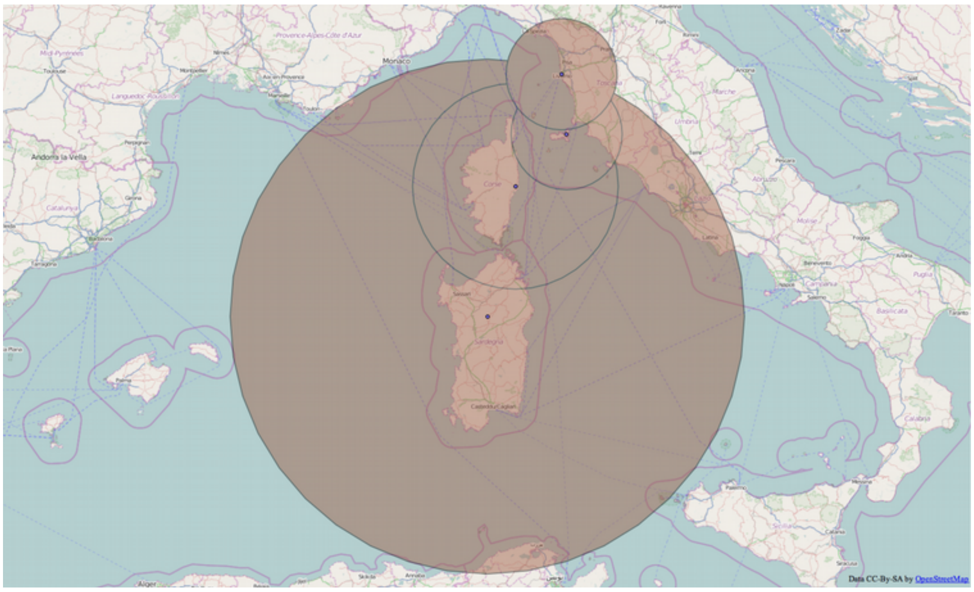


Figure 1: The nominal overlapping area between radar systems

The Tuscany monitoring network takes advantage of the Aleria and Monte Rasu radars by increasing the detection capabilities toward the westerly and south-westerly weather systems respectively, that are very often cause of flooding and landslides, when the flaw of warm air that passes over the sea and increase the moisture load, drives orographic triggering of convection in proximity of mountains. For the same concept Corse can increase the coverage area of its monitoring in the south direction. Furthermore, since the Aleria radar is installed at east near the sea, and Corse is crossed longitudinally by high mountains (even up to 2000 m), its visibility is exclusively eastward. Even if the French radar network is able to partially cover this lack and one of the next actions will probably be the installation of a further weather radar in the west coast, Monte Rasu radar gives the opportunity to monitor weather systems both westerly and southerly of Corse. Finally also Sardinia can improve the capability of detecting and monitoring northerly weather systems, where, the flow of cold coming air, often is opposed to the warm air on the Tyrrhenian sea originating cyclogenesis.

Once all the radar systems have been made interoperable using common formats some preliminary tests have been made to merge all the information in a unique mosaic.

The implemented ([2]) mosaicking software takes as input radar data in BUFR format and allows the processing and displaying of the composite. At the moment the software allows the mosaics of two radar Cartesian products: the VMI (Vertical Maximum Intensity) which is related to the values of maximum radar reflectivity measured on the vertical axis; and the SRI (Surface Rainfall Intensity), which provides an estimate of the precipitation intensity at the ground level, starting from the radar measurements. The mosaicking algorithm returns, for each pixel of the area of interest, the value detected by the nearest radar or, in case of radar observations overlapping, the maximum value detected. In Figure 2 examples of mosaicking software outputs, obtained from single radar images, for the event of September 12[nd]-13[rd] 2012, are shown.

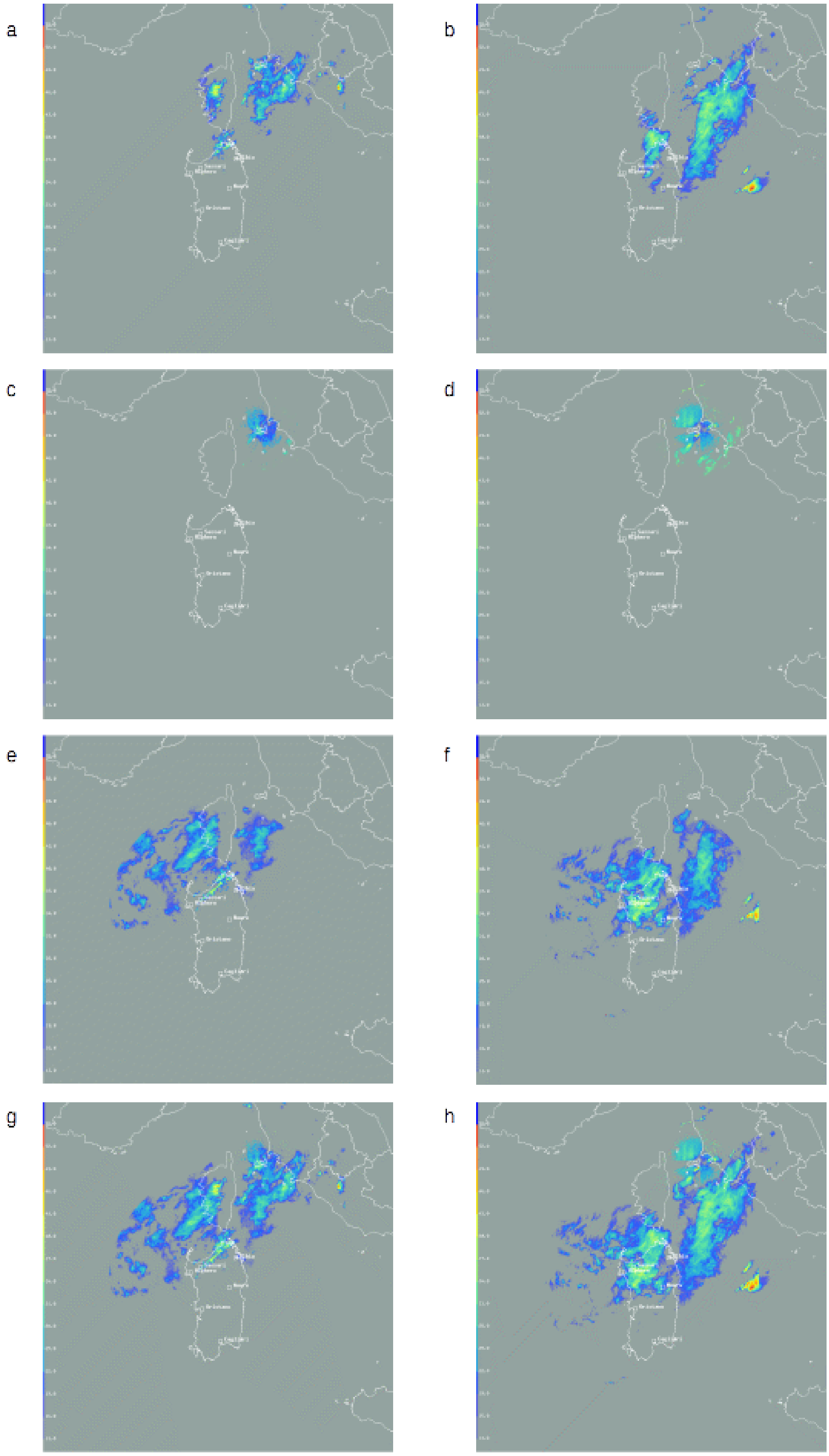


Figure 2: Example of mosaic output between single VMI radar images. Data are referred to 21:30 September 12nd 2012 (left images) and 00:30 September 13rd 2012 (right images). Single images are shown Aleria (a,b), Elba (c,d) Monte Rasu (e,f) and the final merged product (g,h).

The VMI mosaic for two different hours of the precipitating event is presented. As the figure shown the single radars are not able to completely represent the meteorological phenomena. The Aleria radar gives higher reflectivity values over the Corse mountains and more details about the reflectivity cells distribution over sea southern of Elba island. Monte Rasu radar expands the coverage over sea in the western part of the Corse island, and finally Elba radar improves the quality of the observation around its installation point although of course with a lower range.

Unfortunately at the time of this test the Livorno radar was not yet operational (it has been installed in December 2012 and final tests before the startup of the system have been made in February 2013); however, the results can be extrapolated also for this system.

3 THE TUSCANY RADAR NETWORK

The performances of the mosaic algorithm have shown some limitation mainly due to the absence of some intercomparison and intercalibration process. Moreover each radar system needs a spatial characterization of the quality of the measurements made. As manager of the Tuscany radar network the LaMMA Consortium has started a process for the assessment of the quality its radar systems, by performing a non conventional 3D geolocation of the observation to enable the exploitation of the higher resolution of X-band radars, and consequently analyzing the total visibility of the merged system (see Figure 3 Figure 5).

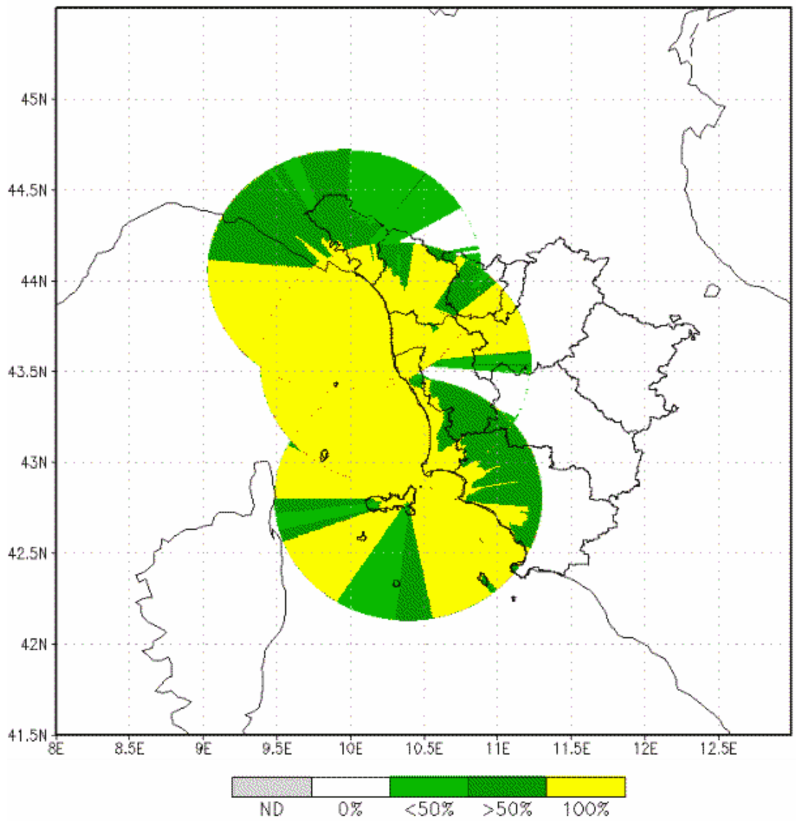


Figure 3: Merged visibility of the Tuscany radar network (Elba. Livorno and Montemarcello radars)

3.1 Methods for 3D radar geolocation

From a geospatial point of view, a radar network approach implicitly involves a common geographical reference system where different radars, each with its own elevation, resolution and range, can be analyzed in an interoperable way. For this reason a specific georeferentation process has been studying in depth, in order to make the data comparable even if coming from different radar sources. First of all, a relationship between polar (azimuth, radius, elevation) and Cartesian coordinate system has been formalized. As a consequence, each radar source scan can be visualized by a 3D shapefile format where a cloud of points is set up according to: max number of impulses in an azimuthal scan (800*18, where 800Hz is the PRF and 18s is the time necessary to complete a scan), elevation and range, as implementation of the Doviak and Zrnic equation [3] for a standard atmosphere:

$$h=\sqrt{r^2+(k_e a)^2+2rk_e a\sin(\theta)}-k_e a+H_0$$

where r is the distance from the radar, a is the Earth radius, θ is the antenna elevation, H_0 is the antenna height and $k_e a$ is the effective radius of the Earth as a function of the refractivity gradient.

The coordinate system is related to a Spatial Reference System (SRS) imposing the radar coordinate in a specific SRS (generally WGS84 UTM ETRS89, i.e. encoded in EPSG: 32632 for the 32N zone where radar network is located) as a false origin. Then each reflectivity measurement can be associated to the nearest neighbor mask point and viewed in any GIS (Geographic Information System), 3DViewer software etc. so that radar data can be combined, processed and analyzed through spatial/topological operators, as each geospatial dataset. For instance this system makes available comparison between reflectivity of different radar sources or between information of other kind of geodata as in particular DTM (Digital Terrain Model) dataset, very important in the voxel visibility evaluation. Finally this interoperable infrastructure will allow to implement each new radar information that will be made available. Figure (XXX) shows an example of 3D combined reflectivity data for Elba and Livorno radars for a case study of precipitating event occurred on 14/01/2013, 18:45 UTC.

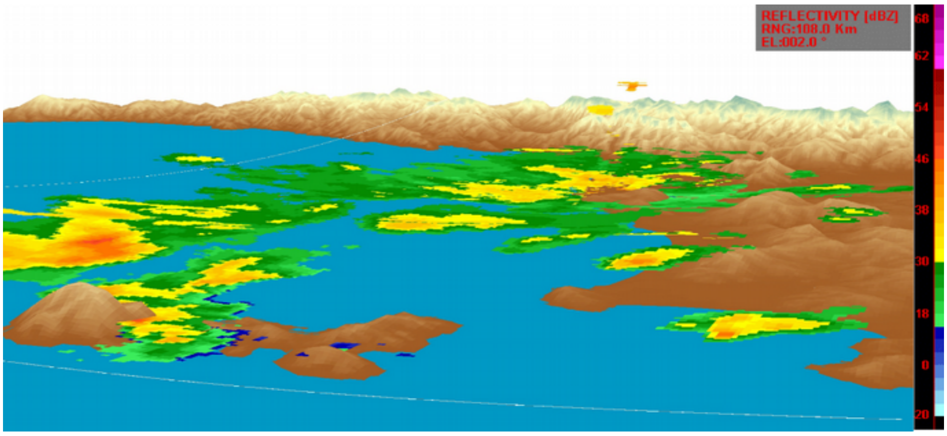


Figure 4: Example of 3D combined reflectivity data for Elba and Livorno radars for a precipitating event occurred on 14/01/2013, 18:45 UTC.

The combination of homogeneous information coming from different layers in the atmosphere allows to better characterize the spatial distribution of the precipitating clouds. The partial overlapping of the two radar footprints instead allows to deeply investigate the cells from different heights and stages of formation.
Some criticism are related to take care to each specific geospatial and temporal accuracy during comparison between different datasets. In that context, as a future development, we are going to study in depth the tuning of precisely geodetical parameters in the transmission equation.

3.2 Visibility by exploiting a DTM

As shown in [4] the ray propagation simulation in a standard atmosphere and the consequent intersection with a suitable Digital Terrain Model can be used for the assessment of the true visibility of each radar system. This type of approach has been applied to Elba and Livorno radars to extract a visibility index for each volumetric cell of the 3D radar scan. The radar beam has been divided in six portions and for each of them the occultation has been computed through the intersection with mountains by means of the high resolution 3D geolocation. The result of this approach gives six class of visibility (in the intervals 0%,16%,33%,50%,66%,83%,100%) to be assigned to each voxel. As an example in Figure 5 the merged visibility of the radars scans considering an elevation of 0.5° is depicted. It is clear the higher details level of this image in comparison with Figure 3. In fact this type of product has been designed and developed for the labeling of each single radar measurement during the azimuthal scan, so the maximum number of possible radius has been used. It follows that at the time of acquisition each single measurement can be processed taking into account also this quality factor.

4 CLUTTER REMOVAL ALGORITHM

One of the main problems of observing precipitation with weather radars is that they tend to be contaminated by non-precipitation echoes. These latter need to be identified and then removed before rainfall estimation. This is of considerable importance for operational applications such as, for example, precipitation nowcasting and flash flood warning. A number of techniques have been reported in literature to remove clutter signals in radar data. Some of these more advanced techniques make use of neural network and fuzzy logic classifiers using local statistical parameters (mean, median, standard deviation), and texture features (homogeneity) [5],[6]. We applied the Steiner and Smith technique [7] to remove sea clutter for the lower elevation scans, which are the more affected by non-meteorological echoes. This procedure takes advantage of some additional textures features such as SPIN, thresholds on the vertical reflectivity, vertical gradients, maximum elevation scans at which reflectivity are observed (ECHOtop), making use of a three-dimensional reflectivity structure, such as the vertical extent of radar echoes, their spatial variability, and vertical gradient of intensity, using a decision tree.

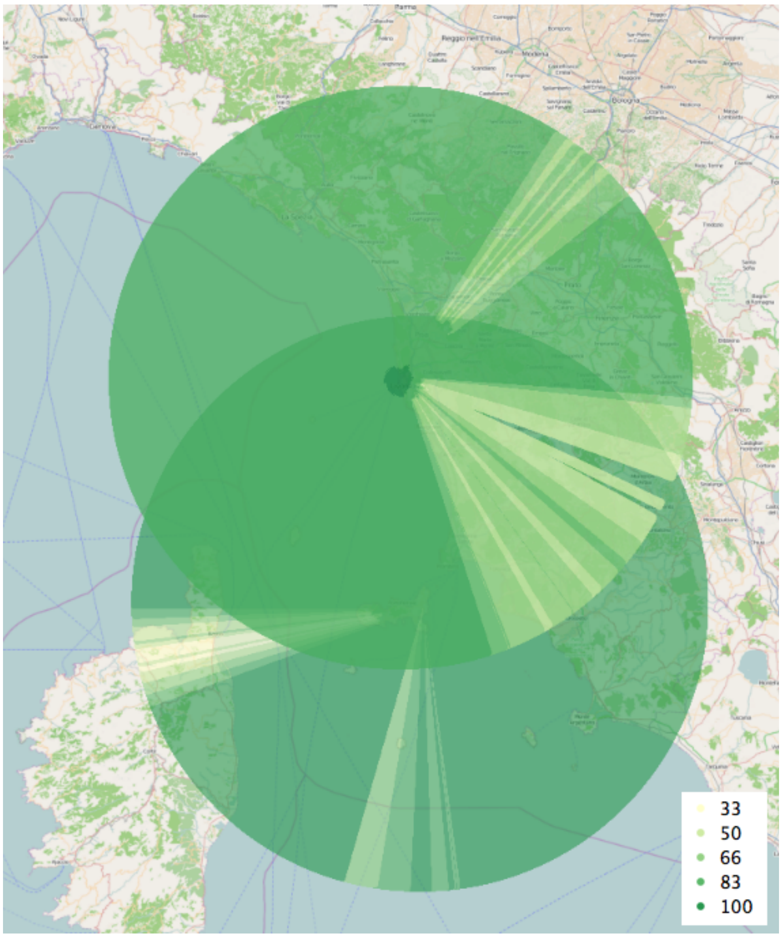


Figure 5: Merged high resolution visibility

For ground clutter, a statistical declutter filter was applied; its operating principle is based on the different distribution of samples occurring between the radar echo due to clutter and the radar echo due to the weather signal. Three main parameters are necessary to realize this kind of filter:

- the reflectivity stdDev value only related to the clutter typical of the installation site;
- the percentage of incidence of the clutter in the PPI in clear air, typical of the installation site;
- the reflectivity StdDev value typical of the weather signal.

The case studies of May, 3rd 2014, 08:30UTC for Elba radar is shown in Figure 6 (a-f), in which sea and ground clutter strongly affected radar signals, giving false precipitation alarms.
As shown in Figure 6 b), the raw reflectivity data scan at the lower elevation (0.5°) presents a lot of noise and a clear evidence of ground and sea clutter contamination that does not allow to correctly interpret the radar signal in terms of precipitation occurrence. Using a land-sea mask (Figure 6 a), the two declutter filters have been applied to remove echoes that are caused by orography and marine areas. The results are shown in (Figure 6 c-d), respectively. Both the algorithms have correctly filtered false echoes due to the presence of mountain reliefs in the south-eastern part of Tuscany and widespread sea clutter all around the radar site. In this latter case the declutter filter has retained the major precipitation fields occurring in that area, as the successive scans at 1.0° and 1.5° (see Figure 6 e-f) show, with persisting rainfall patterns stratified also in the higher atmospheric layers. The combination of the two algorithms is nearing completion and it will enable the implementation of such algorithms in an operational chain.

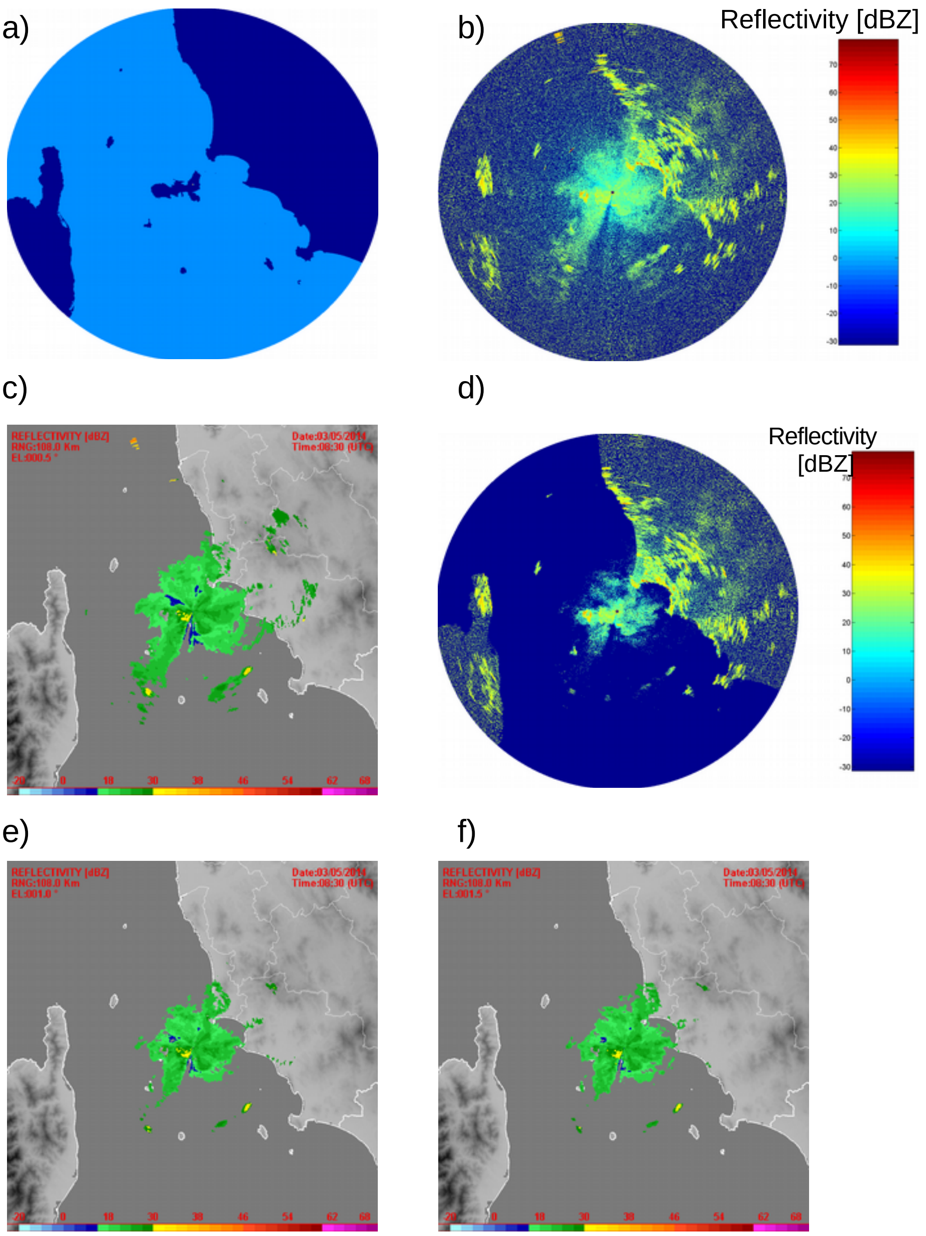


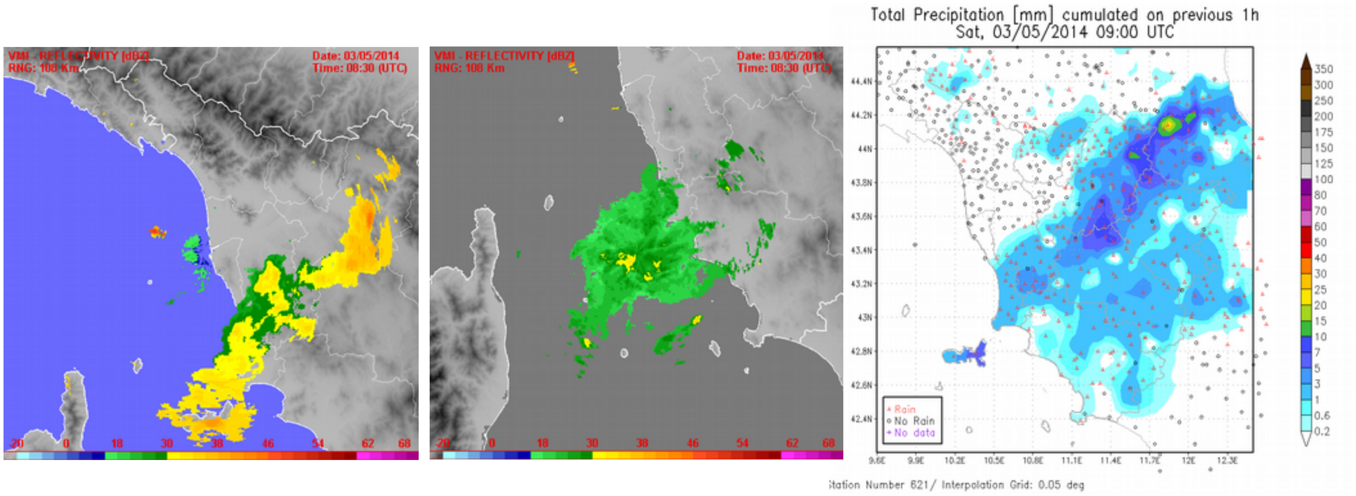
Figure 6:A case study of ground and sea clutter for May, 3rd 2014, 08:30UTC for Elba radar. a) Sea-land mask, b) Raw reflectivity data scanned at 0.5° elevation, c) Corrected reflectivity data for ground clutter at 0.5° tilt, d) Corrected reflectivity data for sea clutter at 0.5° tilt, e)-f) Corrected reflectivity data for ground clutter at 1.0° and 1.5°tilt.

5 THE RADAR PERFORMANCES EVALUATION

A preliminary evaluation of the radar performances was made analyzing several case studies in order to investigate radar behavior under different precipitation regimes (i.e., convective or stratiform) and seasonality. This evaluation was performed in terms of how both the systems have correctly followed the dynamics of the precipitating events, both spatially and temporally. The regional Tuscany raingauges network has provided a reliable tool to test these issues, in addition to satellite imagery and the expert supervision of LaMMA's meteorologists. Two examples of precipitating events will be shown below, one being stratiform rainfall alternating to convective activity, the other orographic precipitation, to highlight how the radar systems perform in so different meteorological conditions.

- **Case study of May 3rd 2014**

This case was characterized by stratiform precipitation alternating with convective showers of moderate intensity associated to an east flow. This cloud system has affected the central-meridional part of Tuscany region for the most part of the day. A very good correspondence between the VMI reflectivity radar signal (Figure 7 a-b) and the precipitation of moderate intensity as recorded by rain gauges (Figure 7 c) was found for both radars. Precipitating event occurred on Elba Island was correctly detected and followed, confirming that the synergy and integration of multiple informative layers at different atmospheric levels lead to a correct characterization of the occurring phenomena.

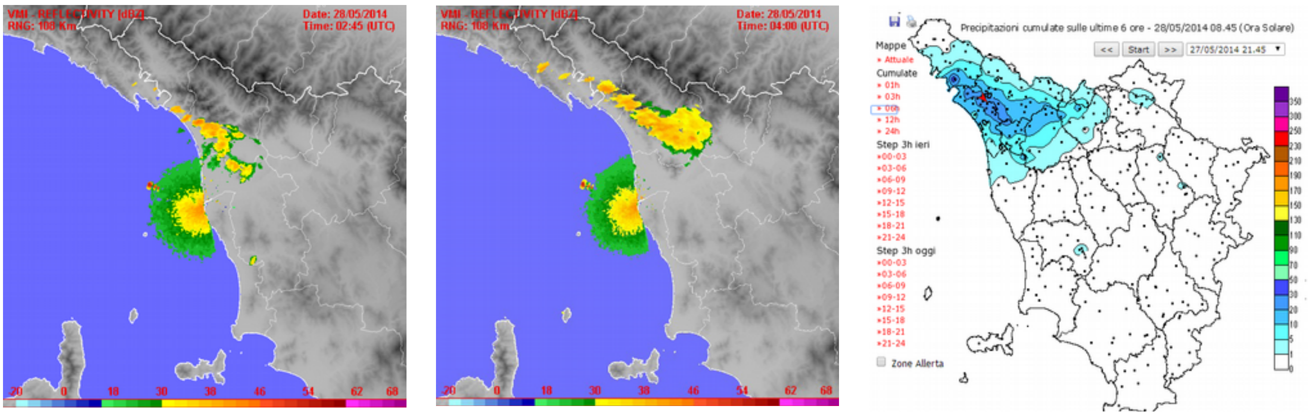


a) b) c)

Figure 7: VMI reflectivity for 3rd May 2014, 0830UTC, for a) Livorno and b) Elba radars; c) Total precipitation cumulated for the 3rd May 2014, from 0800 to 0900UTC over the Tuscany Region.

- **Case study of May 28th 2014**

On the night of May 28th 2014, precipitation of moderate-strong intensity have affected the North-western Tuscany, being more abundant in the Apuan Alps. Rainfall, mainly triggered by orography, has shown also a moderate convective activity around 4000-5000 m. Livorno's radar has correctly identified and followed those areas that have intense precipitation (behind and on the western slopes of the Apuan Alps – Figure 8 b), including a small convective cell on the Pisa hills (Figure 8 a), as shown by the cumulated rainfall measured by the rain gauges in the study area (See Figure 8 c). Some areas leeward of the Apuan reliefs and the more higher Apennine ones remained blind to radar, due to higher orography which blocks radar signal.



a) b) c)

Figure 8: Livorno radar VMI reflectivity for 28th May 2014 for a) 02:45UTC and b) 04:00UTC; c) Total precipitation cumulated for the same day, from 02:45 to 08:45UTC over the Tuscany Region.

6 CONCLUSIONS

The regional radar network, has to be considered a necessary and integral part in improving the operational Tuscan weather services in nowcasting activities and their impacts on the territory, as those related to LaMMA daily issues. The integration of these data with other complementary and ancillary measurements is also needed to increase the reliability and accuracy of radar measurements. In this work the first step towards the implementation of such a monitoring system is presented by highlighting the obtained results such as the installation of two modern X-band radar systems (Livorno and Elba) shared between Tyrrhenian cross-border regions, a preliminary mosaic products for the partners institutional activities, and a series of scientific analysis towards the intercalibration and integration with conventional weather radars (Aleria and Monte Rasu). In the next few months, as a task of the Proterina-Due project, a third X-band radar will be installed in Montemarcello

(Liguria) and inserted in this network, improving the spatial coverage and the performances of the weather system monitoring capabilities.
The future steps of this scientific and technical activities will be the implementation and integration in an operational chain of the shown algorithms, which have been presented as single components of a general architecture oriented to the development of a now-casting tool taking advantage of heterogeneous instruments.

Acknowledgement

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