Exploiting X-band dual-polarization mini-radar network and hydro-meteorological forecast models in Moldova territory during the field campaign of HYDRORAD project

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1. Introduction

HYDRORAD is the name of the project, positively evaluated by European Commission under *Seventh Framework Programme* (FP7), which lasted two years and three months and ended on November 30, 2011.

The FP7 for research and technological development is the European Union's main instrument for funding research in Europe (see http://cordis.europa.eu/fp7/home_en.html).

The primary goal of HYDRORAD project (*Marzano et al. 2010*) is the development of an innovative integrated decision support tool for weather monitoring and hydro-meteorological applications. The integrated system tool is based on an optimized polarimetric X-band mini-radar (i.e. low power, small-size) network, a software-based radar product generator for data quality control, rainfall estimation, nowcasting and precipitation classification coupled with a hydrological and meteorological models able to ingest precipitation data and mini-radar products. The core of the decision support tool is the X-band polarimetric mini-radars which are low cost, easy to deploy and, thus ideal for the setup of radar network covering areas with complex terrain.

The whole integrated system had been tested on Moldova Operational Field (MOF) campaign took place during autumn 2011 in Moldova. During the MOF campaign, three upgraded WR-25XP radar systems and related products and forecast tools have been successfully tested and compared against a state-of-the-art radar (X-POL) and against in situ weather station measurements (video disdrometer, Doppler flow meter and rain gauges).

To meet our goal seven European Partners had joint an advanced complementary background and unique expertise in the fields of hydrometeorology and remote sensing technology, they are:

- HIMET (L'Aquila, Italy) a SME (Small and Medium-Sized Enterprises) that can exhibit a unique capability to implement operational meteorological modelling and remote sensing data processing;
- RST (Athens, Greece) a SME that has a long well-known experience in hydrological numerical modelling and water resources management;
- PROPLAN (Nicosia, Cyprus) a SME that can handle coordinated field instrumentation dealing with data analysis and radar algorithm development.
- ELDES (Florence, Italy), an international SME company fabricating X-band mini-radars and digital signal processors for weather radars;
- NOA (Athens, Greece), a well-known research Centre operating a state-of-the-art mobile weather observatory consisting of telemeter gauges, a 2-Dimensional video disdrometer and high-power / high-sensitivity Dual-Polarization and Doppler X-band radar
- SHMS (Chisinau, Moldova), the national hydrological institute in charge of the hydrometric and rain-gauge network and major river basin management in Moldova.
- MICC (Chisinau, Moldova), that has experience on logistic aspect regarding radar installation and on administrative aspect toward Moldovan Institutions

The HydroRad lead partner is HIMET which born as a spin-off enterpris**e** of the Centre of Excellence CETEMPS of the University of L'Aquila (http://cetemps.aquila.infn.it) and the Sapienza University of Rome (http://www.die.uniroma1.it/).

More information about HydroRad project are available at http://www.himet.it/hydrorad/.

The article is organized as follows: section 2, 3 and 4 describes the main components of integrated system tool and section 5 gives shortly information about MOF campaign. Finally a summary is given in section 6.

2. The X-band polarimetric mini-radar system

We recall that the primary goal of HYDRORAD is to develop a low cost, but robust, dual-polarization X-band radar to provide quantitative precipitation estimates with relatively high spatial and temporal resolution with limited range coverage equivalent to urban areas, small scale catchment basins or extended agricultural domains.

To achieve this goal the **customized design** specification and the realization of the main subsystem of the new mini-radar system (called WR-25XP) has been carried out during the project lifecycle. The interfaces of the WR-25XP were carefully analyzed with the need of HYDRORAD project, taking into account some critical parts and carrying out design, specification and fabrication of the main subsystems (antenna, radome, transreceiver, the control and signal processor and so on). Each component has been fully tested before final system assembly for the **production** and factory test.

Three WR-25XP radar systems were fully tested during the two months long of Moldova Operational Field (MOF) campaign (see section 5). One of the WR-25XP (located at Baltata site) is a tow-mobile radar, this unit makes possible to deploy the radar in different locations and thus optimize the radar coverage according to any possible future need. The other two radar systems (located at Straseni and Horesti sites) are fixed tower-based radar units. Pictures and main characteristics of both fixed and mobile WR-25XP units are shown in fig. 1. It worth mentioning that MOF study was performed to assess the strengths and weaknesses of the radar systems, newly developed within HYDRORAD project. After deployment and set-up activities the three radars were left in continuous operational mode to acquire volumetric scan with a 5-minute repetition. WR-25XP scanned in a 360° sector and for 0.5°, 1.5°, 2.5° and 3.5° elevation sweep. The two upper elevation sweeps were selected to avoid ground clutter and beam blockage in the some direction of horizontal scan. The pulse repetition frequency was 500 Hz with 250 m range resolution. Antenna rotation rate was 20 (°/s) and the time period for a full volume scan was about 3 minutes. The maximum range was set to 60 km for a conservative choice although maximum range is 120 km. Some WR-25XP radar maps acquired during MOF campaign are also shown in fig. 2.

The three radars system worked properly most of time during MOF campaign and the rainy events were well monitored from all three deployed radars although in a few times some problems due to some minor system bugs and logistics constraints was found and resolved. Polarimetric data assessment was carried out using the software-based radar product described in the next section.

WR-25XP Characteristics	
Manufacturer	ELDES
Frequency	9.41 GHz
Antenna Gain	35 dB
Antenna Type	Offset Cassegrain
Maximum Range	120 km
Bandwidth	3.0
Peak Power	25 Kw
Radome	YES
Dual Polarization	YES
Measurables	Z Z_{DR} V,Φ_{DP} ρ_{HV}

Fig. 1 Fixed WR-25XP radar (left) mobile unit (centre) and main operational characteristics (right)

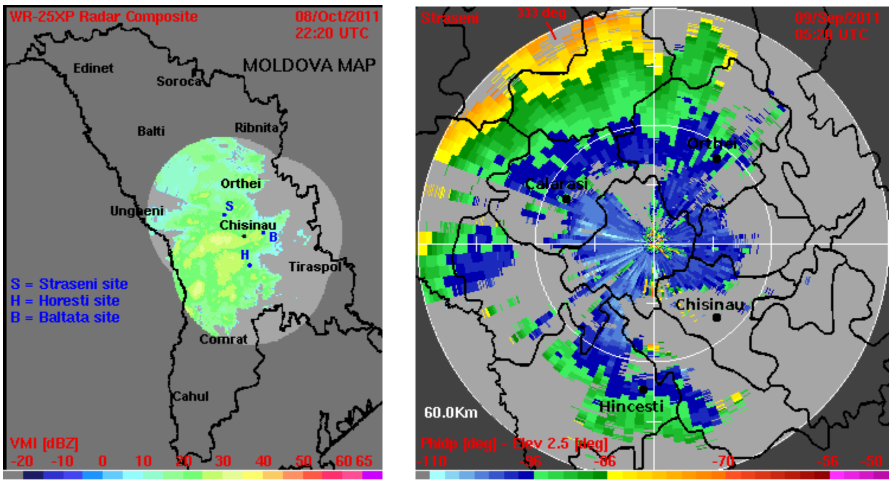


Fig. 2 A reflectivity map composite from the three radar sites (left) and a differential propagation phase shift map taken from Straseni site at 60 km range(right)

3. Software-based radar product generator

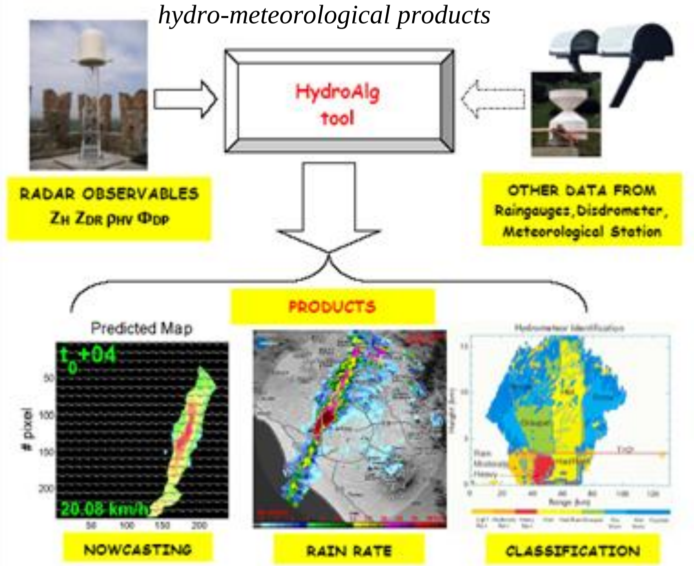
It is worth mentioning that the capability to invert the X band polarimetric radar measurements into useful hydro-meteorological products is crucial for the full exploitation of the mini radar system, developed within HYDRORAD and for any other radar system. Various operative aspects have to be examined to be able to extract quantitative information from radar data and to provide reliable products. In particular data quality verification, hydrometeor classification, water content, path-attenuation correction, vertical profile correction, rain-rate estimation and nowcasting deserved attention.

The entire X-band radar algorithm developed is called HydroAlg tool (see fig. 3), specific results that have been achieved during this project are:

a) the development of a **quality check methodology** applied to flag radar observables as good or bad. Data quality has been estimated through polarimetric self-consistency (*Straka et al. 2000*) while ground-clutter, anomalous propagation and second-trip echoes has been removed by exploiting the textural spatial correlation of atmospheric targets with respect to reflectivity and propagation artifacts (*Marzano et al. 2007*).

b) the development of a technique for **water content estimation**, based on a parametric algorithm, trained by radar backscattering simulations and constrained to the hydrometeor classification product. The inversion of WR-25XP radar data into water content estimates can be performed using, for each detected hydrometeor class, a specific power-law regression previously outlined.

Fig. 3 HydroAlg tool convert radar observable into hydro-meteorological products



c) the development of a technique for **hydrometeor classification** aimed at partitioning a radar volume in terms of microphysical hydrometeor types. The algorithm provides hydrometeor class index for each radar range bin using a Bayesian decision rule starting from radar observables and temperature information (*Marzano et al. 2008*). The hydrometeor classification technique is trained with a radar backscattering-model simulation, based on the T matrix code where liquid, ice and mixed phase hydrometeors are simulated.

d) the development of a technique for the **correction of two-way path attenuation** which is a critical issues for X-band radar; the approach followed is original and is based on the use of relations between attenuation parameters Ahh, Adp, and backscattering phase shifts and radar observables Zhh, Zdr and Kdp. The approach followed is original with respect to past techniques since the below mentioned relations are found using radar backscattering simulations at X band, trained by microphysical 2D-video disdrometer (2DVD) measured size spectra, and their use allow to avoid time-consuming minimization approaches (*Anagnostou et al. 2006*).

e) the development of a technique for **VPR (vertical profile reflectivity) correction**, based on the melting layer identification, VPR normalization, extrapolation and corrections. The method used to correct for the BB (bright band) and mixed phase precipitation effect is called VPR correction algorithm which uses the polarimetric information (i.e., Rhv and Zhh) to identify the properties of the melting layer (*Anagnostou et al. 2009*).

f) the development of a technique for **rain rate estimation**, based on a new rainfall microphysics-based algorithm. The herein proposed rainfall algorithm is based on a new rainfall microphysics algorithm, developed from T-matrix simulations at X band using a method based on the Rayleigh limit with the addition of a rational polynomial dependence on median volume due to Mie scattering effects. A point to note is that our algorithm is based on the consideration that Gamma distribution model (or a similar model such as lognormal distribution) can adequately describe many of the natural variations in the shape of raindrop size distribution (*Anagnostou et al. 2010*) and (*Kalogiros et al. 2006*).

g) the development of a **short-term nowcasting techniques**, called SPARE, able to identify and forecast convective cells. The basic principle of Spectral Pyramidal Advection Radar Estimator (SPARE) is to perform spatial correlation on filtered radar images in the spectral domain and, by means of the estimated displacement vectors, to define how different rainy structures moves. The procedures take a temporal sequence of available radar maps and propagate the last available one in the future *(Montopoli et al.2010).*

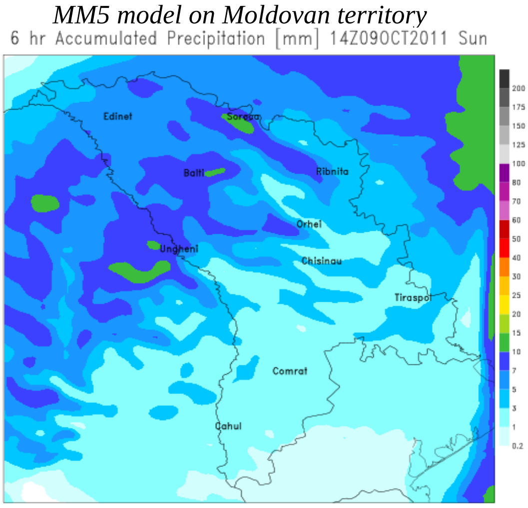
HydroAlg tool has been performed during MOF campaign using WR-25XP data, XPOL radar data and available reference data such as rangauges and disdrometer measurement. From the analysis of both dual-polarized amplitude and phase return, well described in *Kalogiros et al. 2012*, we can assess that the WR-25XP polarimetric mini-radars have the expected performances in terms of capturing the vertical and horizontal distribution of moderate and convective precipitation with features that are consistent with the ones derived from the high-power and high-resolution XPOL radar, taken as a benchmark.

4 Meteorological and Hydrological forecast tool

An integrated tool for short-to-medium-range forecasting using coupled hydrological models, meteorological model and mini-radar data networks has been developed and tested during the MOF campaign.

The numerical **weather forecasting modeling** system has been implemented and tuned for Moldovan territory to medium range predictions able to ingest X-band radar high-resolution products and to interface with the hydrological model. The operational weather forecast has been performed using the Mesoscale Model 5 (MM5), a Limited Area Model (LAM), developed by Pennsylvania State University and National Center for Atmospheric Research (PSU/NCAR). The main purpose of integrating X band radar data in meteorological modeling is to assess the improvements that can be obtained in flood risk and flood emergency management using WR-25XP network estimate rain. We implemented a new alternative and simpler technique respect to the 3DVAR and NUDGING: the operational MM5 version includes some microphysical parameters derived from WR-25XP radar observations. Radar data has been ingested within the model forecast assessment and the microphysical module optimization. See in fig. 4 a map of 6 hours accumulated rain forecast by MM5 model on the whole Moldovan territory.

Fig. 4 Accumulated rain forecasted from MM5 model on Moldovan territory



The **hydrological model** implemented on Moldova region is based on semi-distributed parametric schemes such the HEC-HMS (Hydrologic Engineering Center - Hydrologic Modeling System) and HEC-RAS (Hydrologic Engineering Center - River Analysis System) hydraulic modelling chain. Both models was set up using historical data from Bic basin in Moldova about geology, land surface characteristic (terrain, soil, vegetation) and atmospheric forcing (radar, model and in situ data). A main goal of river management is the prevention of damage from flooding. This can be carried out by means of integration of the hydrologic model of the basin with the (i) mini-radar network rain estimated and (ii) numerical weather prediction model forecasted rainfall data as well as meteorological data from the area aimed to predict the timing and magnitude of flooding, which consequently can be a key tool in flood management. The main purpose of integrating mini radar data in hydrologic modeling is to assess the improvements that can be obtained in flood risk and flood emergency management using WR-25XP network rain able of reducing the uncertainty relative to sparse network of rain gauges.

The developed Hydro-meteorological system was tested during Moldova Operational Field (MOF). As shown in fig. 5 (left) the general result from the presented rainfall time series is the moderate underestimation (20%) and weaker temporal variability of basin average rainfall by the MM5 forecasts relative to gauges, which is not an unexpected outcome when it comes to quantitative precipitation forecasting of frontal systems. On the other hand the quantitative precipitation estimation by the mini-radar network observations exhibits close agreement with the gauge basin average rainfall having an underestimation of the order to about 8%. The flow predictions based on the various rainfall inputs is shown in fig. 5 (right). A point to note is that the low basin average rainfall bias is magnified through runoff simulations. The MM5 bias exhibits the most significant error propagation respect to miniradar network. This enhancement in underestimation is due to the dry initial basin conditions that resulted in a non-linear propagation of the basin response error from rainfall.

Overall results show that mini-radars networks can produce high quality and accurate rain fields for hydrological purpose in difficult to cover complex terrain areas.

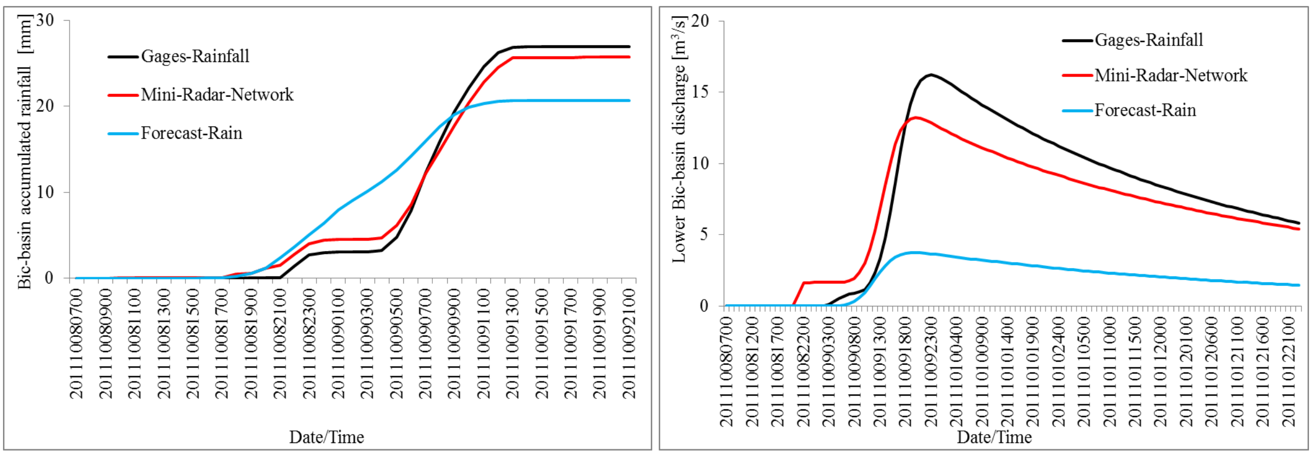


Fig.5 Time series of Bic basin rainfall accumulations (left panel) based on gauge measurements, the WR-25XP mini-radar network estimates and the MM5 forecasted rainfall and Bic basin streamflow simulations from the hydrologic model forced with the various rainfall sources data

5. Moldova Operational Field (MOF) campaign.

In order to test the integrated system a two month long experimental campaign took place during autumn 2011 in Moldova. The target for the campaign area was centered on the Bic river basin that is located in the center of the State of Moldova and running through the capital city Chisinau. Bic is a large river basin representing an area that frequently floods affecting a large population in Moldova (located at and around the capital city). The experimental basin has 2130,6 km2 surface area and the altitude range of this from 100 to 300 m above sea level. It worth mentioning that the Bic river basin is an important resource in central Moldova for which the central government is looking for a better management system.

The three WR-25XP mini radars (two fixed and one mobile) were deployed around the river Bic basin between 20-30 km apart from each other, while the X-POL radar was deployed in the middle of this triangle as a reference instrument which is at the outskirts of the capital city of Chisinau (see fig. 6). In addition to the radar sites, within the basin, were been deployed the in situ hydrological and meteorological stations. Specifically, six pair of rain gauges, one disdrometer, one doppler flow meter, a stream gauge and the water quality sensor.

Unfortunately, the experimental period did not associate with many rainy days or significant rainfall events, autumn 2011 was unusually (according to local climatic records) dry in Romania-Moldova region. For quantitative analysis we selected two distinct rains events among those collected. The first was a convective type rain with small isolated strong rain cells that persisted for 24 hours between September 8 and 9. The second was a stratiform rain type with widespread moderate rain with longer duration (36 h) that took place on the 8th-9th of October. Both events were well monitored from all deployed radars and meteorological instruments.

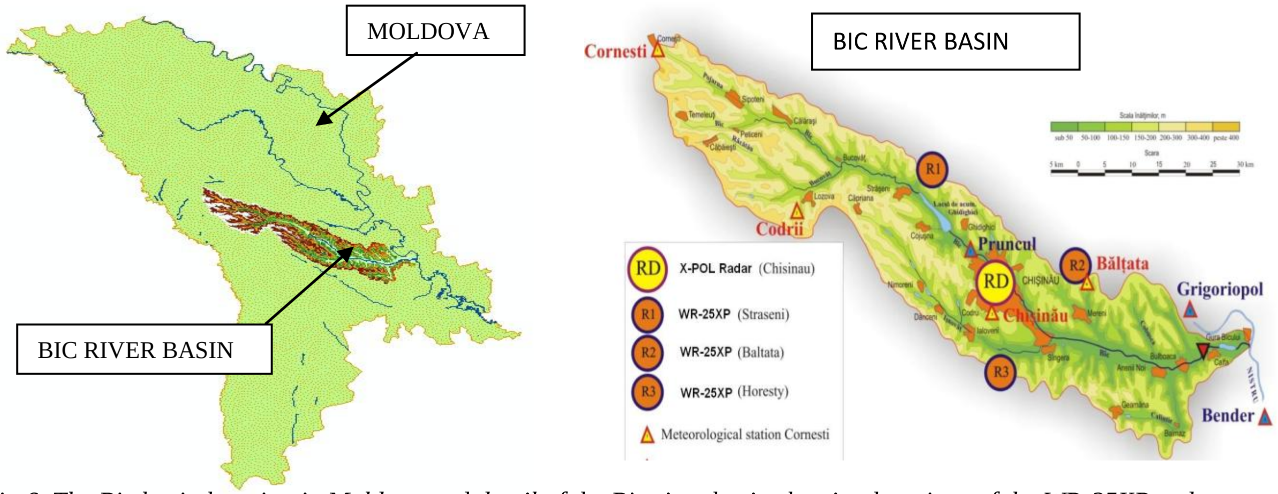


Fig.6 The Bic basin location in Moldova and detail of the Bic river basin showing locations of the WR-25XP radar systems (R1, R2 and R3) and location of X-POL radar (RD).

6. Conclusion and Outlook

Weather and hydrologic hazards constitute two of the most critical environmental issues world-wide. Meteorological hazards like wind storms and convective outbreaks leading to torrential rain and flooding affect all of World. In that context weather radar observations have proven to be very useful in providing information on the spatial distribution of rainfall and floods, which is required by both the meteorological and hydrological communities. However, radar rainfall estimations are subjected to many limitations and uncertainties (Anagnostou et al. 1999). The use of dual-polarization technique in X-band has provided a solution to mitigate some limitation and explore the benefit of their low costs, easiness to transport and mount, and the high spatial and temporal resolution (e.g. Matrosov et al. 2005).

New developments on X-band dual-polarization technology in recent years have revived the interest of scientific and operational communities in these systems so new enterprises are focussing on the advancement of mini-radar network technology, based on high-frequency (mainly X-band) and low-power/low-cost weather radar systems for weather monitoring and hydro-meteorological forecasting.

Within the above context the general aim of the HYDRORAD project was the development of an innovative integrated system, consisting of networks of small-size/low power dual-polarization X-band radars and an original and advanced system of radar retrieval algorithms and software-based tools for hydro-meteorological monitoring and nowcasting. Introducing X-band radar-based products generated by the developed algorithms into meteorological and hydrological models constitutes a new challenge with precedents or guideline. Such a tool is not currently readily available in the weather radar industry.

The core of the decision support tool is the X-band polarimetric mini-radars WR-25XP. Our first results show that mini-radars can give reliable estimates of rainfall, networks of mini-radars can cover broader areas in complex terrain where large expensive systems cannot achieve this. On the other hand the integrated system tool here developed seems to be the best low-cost solution to the problem of hydro-meteorological forecasting and monitoring for weather surveillance especially for hazard prevention and civil protection purposes.

The whole integrated system, outlined in fig. 7, was tested on Moldova Operational Field (MOF) campaign took place during autumn 2011 in Moldova. During the MOF campaign, three WR-25XP radar systems and related products generator and forecast tools have been successfully tested and compared against a state-of-the-art radar (X-POL) and against in situ weather station measurements such as one video disdrometer, one Doppler flow meter and several rain gauges properly located around the Bic basin.

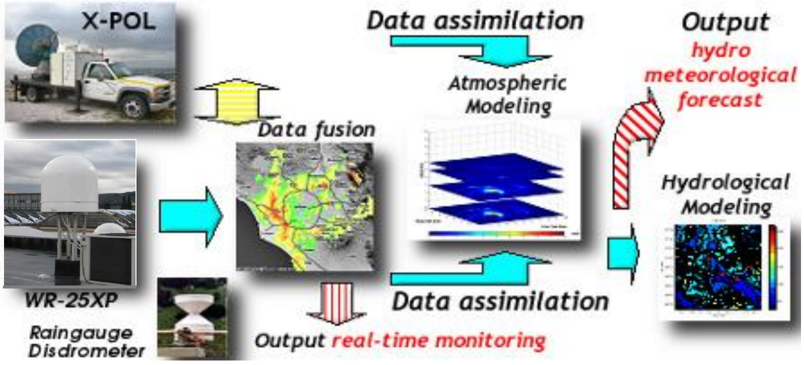


Fig. 7 Scheme of the integrated tool for short and medium weather forecast and monitoring.

It would be advisable to extend the herein project with additional field observations that we will be focusing as part of our continuing effort to improve our radar system and hydro-meteorological integration framework. Data collected from future experiments will support the further development of our algorithms and the verification of the accuracy and consistency of the newly developed mini polarimetric radar systems and related network.

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