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MARG – MICROWAVE AREAL RAIN GAUGE
a Low Cost Solid State Microwave Areal Precipitation Measurement System

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1. INTRODUCTION

Knowledge of rainfall distribution and intensity and precipitation totals over land or over determined regions are necessary for meteorological, hydrological and agricultural purposes. The estimation of the rainfall over an area is a difficult task. The rainfall is discontinuous in space and in time because of having large natural variability unlike many other meteorological parameters. The widely used method for getting relatively accurate precipitation data over land is the combination of radar rainfall and rain gauge data. The typically used radar data is coming from long-range weather radars operating in C or S band but using such radar data we are facing several constraints:

- operational weather radars are large, complex and expensive measurement systems resulting that the cost of radar data is high limiting their accessibility and applications,
- application of weather radar equation needs too much assumptions which are can not be managed well at long ranges and in many weather situations and in different seasons, (because of the nature of radar measurements the reliable rainfall data from operational weather radars are limited in space, typically one half or one third of operational measurement ranges),
- latest advances in weather radars (dual-polarization, dual wavelength) provide more reliable rainfall data but it is valid for relatively short ranges only.

To overcome these constraints more and more MINI meteorological radar are deployed and application projects has been started exploiting them needs (FREMEA, FORALPS, HYDROMET, RAINGAIN, etc.)Typically they are based ship-borne or airborne radars but research laboratories and radar manufacturers are developing general purpose MINI weather radars on X band with Doppler and dual-polarization capability.

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Most of these MINI radars are magnetron based like HYDRIX, CASA IP1, METEOR 50DX, RANGER X, etc. Some specific MINI radar are also available for rainfall monitoring and measurements on X band bringing lower procurement and operational cost as they are based on ship borne radars. Such radars are the SELEX Rainscanner and DHI LAWR radar both without Doppler capability. Among the MINI radars there are some solid state solution also. The pulse compression X band EWR E700XD and C band Baron PULSAR are on the market now.

An other type of solid state MINI radar has been developed for research purposes by ICTR Delft. It is the X band FMCW IDRA with Doppler and dual polarization capability. Making a survey on the available tools for measurement of rainfall distribution over an area we have recognized that an important gap exists in instrumental market for having reliable rainfall intensity and precipitation amounts on the wide variety of rainfall intensity in all seasons at low and affordable costs because of

- rain gauges are able to provide date on single installation points only and very high number of such rain gauges is needed for reliable areal precipitation data causing high procurement and operation costs of such networks
- long range weather radars operating on C and S band and their networks are expensive and having high operational costs also but not supplying accurate precipitation data with high temporal and spatial resolution at longer ranges
- low priced X band MINI radars are giving unreliable data a.) in moderate and heavy precipitation because of the strong attenuation, b.) in stratiform rain because of very big vertical beam with caused by the typically used slotted waveguide antennas,
- Doppler dual polarized X band MINI radars are expensive and having high operation cost also.
- Nevertheless X band measurements can be blocked in heavy thunderstorm because of the attenuation.

Based on present radar technologies and keeping in mind the end user needs, we decided to built up a concept for an innovative measurement device so called Microwave Arial Rain Gauge – MARG for the meteorological instrument market to reach better measurement performances than existing low cost X band radars.

2. MARG SYSTEM CONCEPT

2.1 Selection of Wavelength

It is well known that the radar reflectivity is inversely proportional to the fourth power of the wavelength; as shorter the wavelength chosen radar will be more sensitive and smaller antenna and lower transmitter power will be required. Therefore, the use of the X band is so popular. But attenuation of the microwaves by solid or liquid particles in the atmosphere has a great importance. It is depending on the wavelength and diameter and dielectric constant of the particles. At short wavelength – X band – in heavy rainfall (50 mm/h) the attenuation is so high that the X band radars can only detect the first edges of rainy areas or the measurement can be totally blocked. Comparison between X band and C band attenuation when the intensity of the stormy areas are reaching 45- 55 dBZ is shown in **Figure 1.**

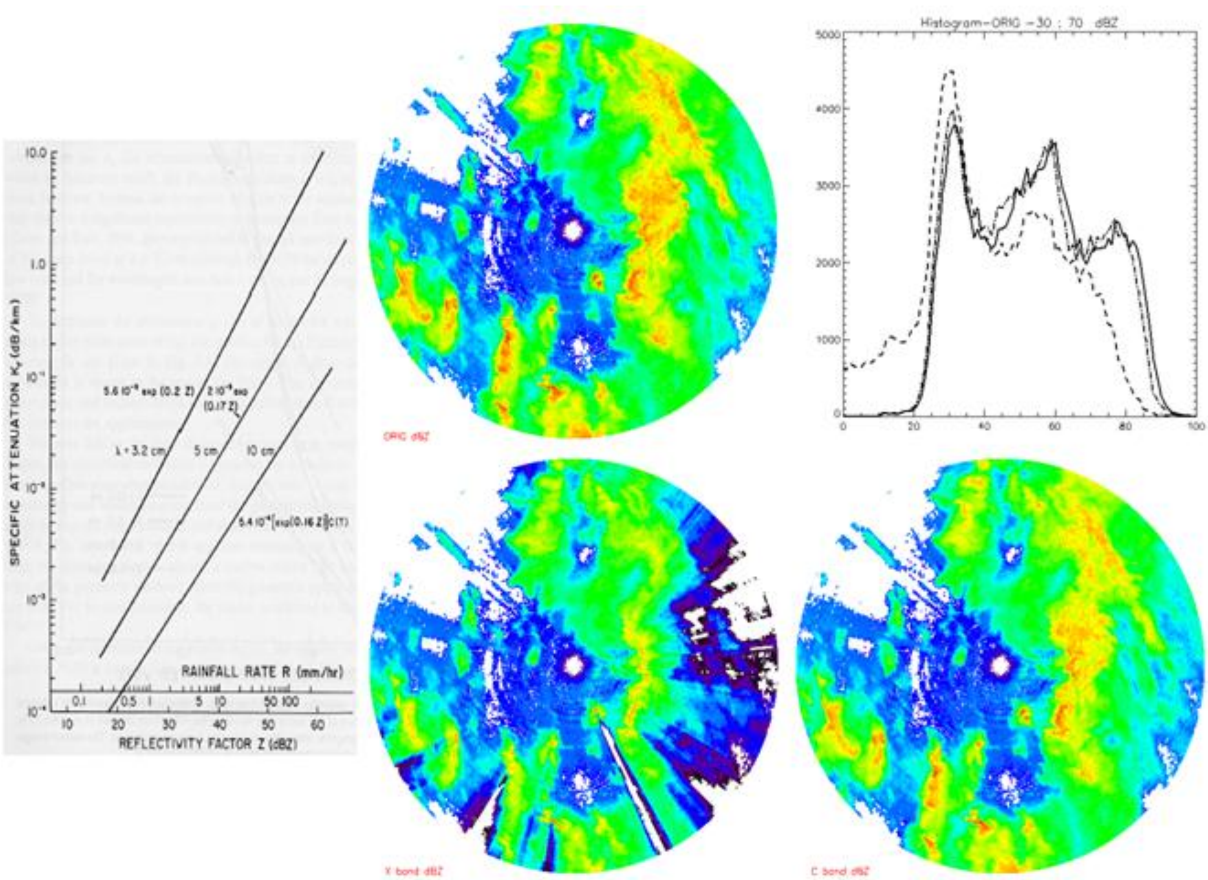

Figure 1. *The impact of the attenuation calculated for X band (middle below) and C band (right below) using a reference dBZ distribution (middle upper) with 50-55 dBZ cells. The histogram of dBZ is shown also (upper right) – solid line for reference, dashed for X band and dotted for C band. Max range is 30 km.*

Longer wavelength are recommended in estimations of rainfall rate using the common reflectivity - rainfall intensity conversion l. For the shorter wavelength there are some algoriths for attenuation correction but all of them have some important drawbacks. The dual polarization methods need more sophisticated and expensive radar systems, see HYDRIX., METEOR 50DX; the combination of reflectivity's in tomography methods using overlapping measurement ranges need more radars deployed on a given area, see CASA; the direct compensation of attenuation using the calculated total attenuation is very unstable and needs very precise calibration and regular statistical control. However, none of these methods works when signal extinction is reached (Figure 1.).

„Modern weather radars are now able to apply a correction to a signal when it is suspected to have been attenuated behind a cloud. However, a black hole behind a red area on a weather radar display should always be considered as a zone that is potentially very active." – taken from instruction of pilots.

Keeping in mind our goal to develop a simple and cost effective solution which my be used in wide range of rainfall intensities the *C band have been choosed for the wavelength of MARG system.*

2.2 Selection of Antenna Type and Beamwith

The beam with and type of antenna selection is big issue for MINI radar concepts. To reach the minimum geometrical sizes and compactness we need for as small as possible antenna solution. Many of MINI radar such as SELEX Rainscanner or DHI LAWR have use the same slotted waveguide antenna the same as the parental ship borne radar have. The resulting beam forms of such antennas are not uniform in vertical and in horizontal. Typical vertical beam with is 22 degree which is suitable for detection of "ships" but such wide beam is not allowing to use of the weather radar equation even in short ranges. But the slotted waveguide antenna has a big advantages providing narrow horizontal beam with giving good resolution of the outputs of rainfall fields. Before choosing the antenna type and its geometrical properties we analyzed the impact of the horizontal and vertical smoothing of different antenna types and beam with. Although the narrow beamwith of slotted wave guides in horizontal gives sharper output images of radar reflectivity comparing to output of the usage parabolic antennas with wider beam with supposing the same antenna mass and loads the reliability of these data are not so good. Avoiding the unreliability and possible misinterpreting of weather radar equation the dual parabolic antenna solution has been chosen for MARG system. To make a compromise between the targeted space resolution and the overall cost of MARG system the dual parabolic antenna with size of 1.5 meters was selected for MARG resulting 3 degree beam width in horizontal and in vertical. See Figure 2.

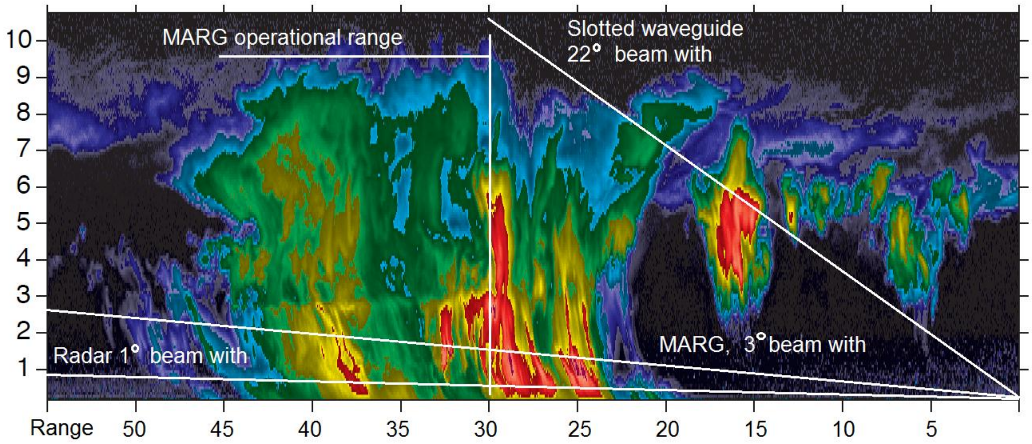

Figure 2. *Illustration of different beam with on a virtual RHI section. The background picture was taken from presentation I. Zawadzki (2008)*

2.3 Selection of FMCW Operation

FMCW technology is getting more common for small scale radar applications. The weakly backscattering meteorological objects are providing enough power for detection even when they are continuously illuminated by far less transmitted signal energy then conventional impulse radars. The power factor is about 1,000 that means we will need for some ten watts TX only instead of kilowatts. As a result solid state electronics can be applied in all modules and coaxial cables instead of wave guides causing the FMCW radars to be much cheaper than magnetron based pulsed radars. But they are needs more sophisticated signal processing as for getting range information it needs to use FM modulated transmitted signal and to do continuous spectral processing of the received signal, mainly dual FFT processing in real-time.

In FMCW radar the distance is a function of the frequency shift between transmitted and received signal. This so called beat frequency can be retrieved by comparing TX and RX signals. Additional frequency offsets are caused by Doppler shifts of moving targets. When measuring many targets like rain drops the retrieval of the beat frequency is a complex process, as there is not a

single frequency but a whole spectrum. The frequency spectrum can be calculated by means of the Fast Fourier Transformation (FFT).
To retrieve both distance and velocity information from the weather targets, a two stage or 2D-FFT implementation is necessary. The first stage of the FFT is applied on the echo samples from one frequency sweep, and the second stage on the range cell results of several consecutive sweep periods.

3. MARG TECHNICAL SPECIFICATION

3.1 Main technical specifications

The MARG sensor technical specification was derived from the user needs of the MARG consortium SME partners:

- Distances from 100 m up to 30 km and for all derived parameters
- Rainrate between 0.5 and 100 mm/h
- Reflectivity between 18 and 55 dBZ (using a standard Z-R relationship)
- Dynamic range distance and reflectivity) ~ 85 dB
- Range resolution 100 m
- Configurable FMCW parameters (sweep duration, frequency span, range resolution, number of range bins, number of sweeps for integration, unambiguous radial velocity)

Operating frequency: 5600 – 5650 MHz
Targeted output power: 20 W
Antenna gain: 36 dB
Halfpower-beamwidth: 3 degree
Bandwidth: 3 MHz for range gates of 50 m
Noise figure: estimated noise figure of 3-4 dB
Direct IF receiver with digital baseband conversion and IQ-demodulation
IF frequency: 60 – 70 MHz, but can be modified
IF conversion : Single stage RF to IF n with image rejection mixer
Image rejection : > 50 dB
Digital generation of IF signal, digital TX and RX IF
Single stage IF to RF conversion with single side band mixer
Software defined waveform generation, linear FMCW
Radar frontend control on integrated ARM CPU
System integrity monitoring, built-in test equipment.

3.2 Estimation of the MDS - Minimum Detectable Signal

The received average echo power at the radar receiver can be calculated according to the weather radar equation:

$$P_r = P_t \frac{\pi^3 |K_0|^2}{512 \cdot \ln 2} \cdot \frac{G^2 \theta_H \theta_V}{\Delta R \lambda^2 L_i} \cdot \frac{Z}{R^2 L_{(R)}^2},$$

where P_r and P_t denote the received and transmitted power, G^2 the two way antenna gain (assuming both antennas having the same gain), θ the horizontal and vertical beamwidth, ΔR the range resolution, λ the wave length, R the distance of the range cell, L internal and external (two way) losses, and Z the reflectivity.

With the parameters taken form the specifications of MARG the received power is calculated for desired rainfall intensity ranges are as:

-131 dBm for 18 dBZ in a single range gate in 30 km
- 42 dBm for 55 dBZ in all range gates from radar up to 30 km

Results for other reflectivities outside the desired operation range are
-142 dBm for 7 dBZ (drizzle, 0.1 mm/h) in a single range gate in 30 km
- 33 dBm for 64 dBZ (hailstorm) in all range gates from radar up to 30 k

In a pulsed radar system using a matched filter for the required bandwidth (1.5 MHz for 100 m resolution) the theoretical noise level is -109 dBm .
The minimum signal level is far below the noise level, but in FMCW radar as MARG there is a compression of the received signal due to the FFT processing in the receiver, which leads in a compression gain of 30 dB for a 1024 point FFT with respect to the noise level. Taking into account the compression gain of 30 dB the smallest echo signal is -101 dBm and with a safe margin over the noise level. There is an additional gain due to the second stage FFT processing, which further improves the signal to noise ratio.

4. MARG SYSTEM OVERVIEW

Within the frame of the MARG project we are intend to develop solid-state, electronics-based precipitation radar that uses *frequency modulated continuous wave (FMCW) operation*. To develop a cheap and reliable FMCW system, the approach will be to develop a system with very few enclosed modules, and to integrate most of the required radar functions within *the digital domain.* The MARG radar main modules are two parabolic antennas with rotational mechanics end electronics, radar frontend and network interface and control electronics.

Radar Frontend contains three main modules: *a digital radar transceiver, a power transmitter, and a low-noise receiver.* The core module is the *digital programmable radar transceiver module.* This will generate the modulated radar signals in an *intermediate frequency* (IF). This IF output will be linked to a separate transmitter module (HPA), where the signal will be converted to the radio frequency (RF) domain, and amplified to reach the required level of power at the antenna output. The transmitter module will include monitoring, protection, and control circuits that can measure transmitted and reflected power levels, and adjust the amplifier gain. This module will also have a *digital interface* to control and monitor these processes. See Figure 3. for the proposed MARG structure. On the receiving side, there will be a receiver module connected to the antenna. This module will contain a *low-noise amplifier*, to allow detection of very low signals. Radio signals will be converted to an IF, before being sent to the digital transceiver. This module will also have a digital interface to control and monitor these processes.

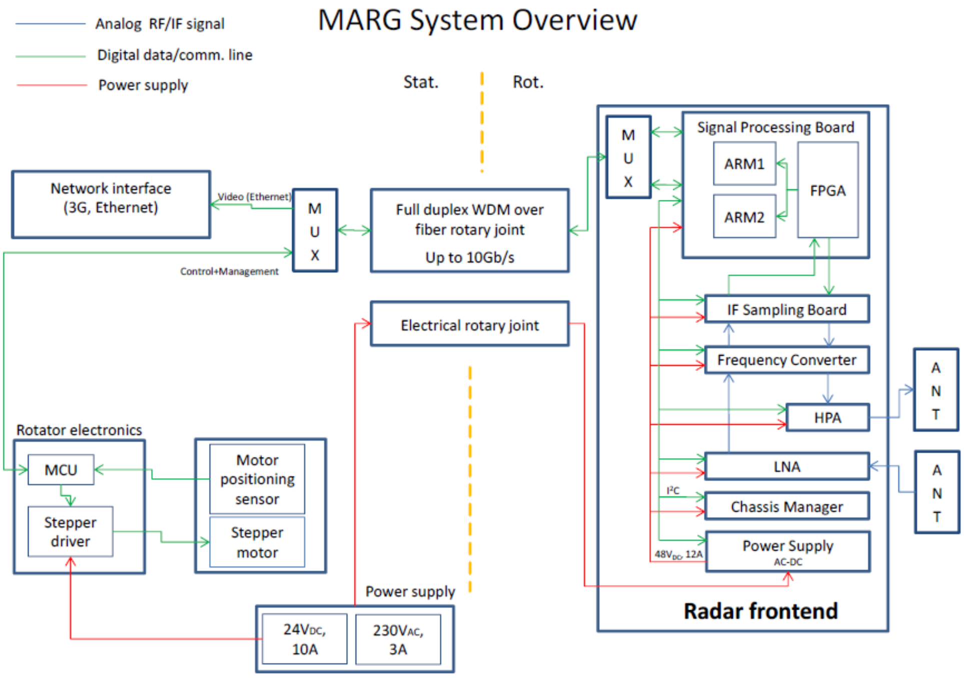

Figure 3. *MARG system overview (with authorization of MARG consortium)*

The digital transceiver will consist of an *analog IF to/from digital conversion linked to an FPGA*. The FPGA is a programmable device and will be used to implement various building blocks of digital radar functions, such as demodulation or synthesizing of modulation signals and analyze the signal and retrieve echo properties. An additional general-purpose processing unit (with memory and a standard network interface) will be included in the MARG system, which will allow for implementation of control and system interface software. The primary radar signal processing system will be based on a single digital IF-transceiver board, which will be capable of IF sampling, digital I/Q demodulation, and direct *generation of digitally modulated I/Q signals at IF*. This board will include analog-to-digital and digital-to-analog converters (ADC and DAC), and programmable DSP and microcontroller cores. Finally, it will be built with FPGAs.

To achieve sufficient isolation (> 50 dB) between the transmitter and receiver modules, and to avoid using complex and expensive microwave components, *two parabolic antennas* will be used to transmit and receive the FMCW signal. The RF front end will operate in the C-band at 5.6 GHz. At this frequency, the proposed *3˚ half power beam width* and *36 dB antenna gain* can be achieved using an antenna with a *diameter of minimum 1.2 meters.* The exact dimension will be a function of the shape of the reflector and the illumination pattern of the feed. To collect enough information from each spatial segment the rotation speed will be set at > 30 seconds per rotation. The maximal output power will be 20W continuous, which will result in a detection range of 20–30 km.

5. MARG OPTIMAL QPE

5.1 Quantitative Precipitation Estimates

Quantitative estimation of rainfall from radar observations is a complex process. The long time established *reflectivity-based* method is the standard means to derive rainfall intensity data from radar measurements. More recently, research institutions have developed *dual polarization (DP)* methods, but most operational weather radar systems(~98%) still use the *reflectivity* method. With conventional single polarization radar in each range bin the rainfall rate *RR* is derived from the radar reflectivity *Z* using a Z-R relationship:

where a and b are constant; to prevent significant overestimates of rainfall rate, due to hail contamination, values of reflectivity are capped to 55 dBZ. When using the reflectivity method there is a variety of factors that can cause systematic, random and range dependent errors (miscalibration of radar, drop size distribution variablility, vertical profile changes, anomalous echos, etc).The algorithms for MARG *optimal real time* QPE will be developed considering measured radar reflectivity radar and ancillary data (i.e. rain-gauges, disdrometers).

At the first step the MARG will use adjustable parameters for the exponential Z-R relationship. The parameters will depend on the rainfall types as stratiform or convective - identification based on Doppler spectrum and texture based. At the second step the MARG QPE will implement the MFB, RDA methods as a kind of minimum adjustment scheme when rain gauge data will be available. An optional use of a disdrometer for calibration of the MARG sensor and for correction of the precipitation estimates is foreseen also. The MARG QPE algorithm will be implemented in two versions: a "basic" QPE product available directly at the radar platform, and the “full” QPE, comprising the integration of the rain-gauges and the disdrometer, which will necessarily run on a separate machine. The “basic” QPE algorithm will provide a simple polar to Cartesian conversion and apply a fixed/adjusted Z-R relation to generate a georeferenced product (geotiff) which will be then easy to display everywhere

Convective/stratiform classification – CSC
In order to classify whether we are observing stratiform or convective precipitation or different parts of the same precipitation system the algorithm proposed by Steiner in his paper (Steiner et al, 1995) will be implemented in the project. Specifically, the basic idea of this method is to search for peaks of reflectivity’s. If the peaks satisfy specific criteria regarding the ratio of the peak reflectivity to the surrounding background reflectivity, then the peaks, plus a specified surrounding area, are categorized as belonging to a convective precipitation area. The remainder is categorized as stratiform. With MARG it is possible to collect a 360 degree radar scan every approximately 30 seconds: we can therefore apply Steiner's algorithm to each scan, after projecting the reflectivity data on a 2D Cartesian grid, and subsequently compare the output with the output of the immediately preceding scans, in order to guarantee consistency in the results.

Bulk adjustment / Mean field bias correction - MFB
The assumption here is that the radar estimates are affected by a uniform multiplicative error. This error can be due for example to a bad electronic calibration or an erroneous coefficient a in the *Z-R* relationship. The adjustment factor (C) is estimated as a mean field bias,

$$C_{MFB} = \frac{\sum_{i=1}^{N} G_i}{\sum_{i=1}^{N} R_i}$$

where N is the number of valid radar-gauge pairs, Gi and Ri are the gauge and radar rain values associated with gauge *i*.

Range-dependent adjustment - RDA
This method (Goudenhoofdt, 2008) assumes that the R/G ratio is a function of the distance from the radar. Range dependences are essentially produced by the increasing height of the measurements, beam broadening and attenuation effects. The relation between R/G, expressed in log-scale, and range is approximated by a second order polynomial whose coefficients are determined using a least squares fit.

$$logC_{RDA} = ar^2 + br + c$$

where r is the distance from the radar. The range dependent multiplicative factor C_{RDA} is derived from the polynomial fit.

5.2 Data Management and User-specified Services

The MARG sensor will produce a vast amount of data concerning rates of precipitation, with the required spatial resolution (50 meters). The data management system will provide transparent transfer of the data from the microwave sensors to the user’s equipment. The reflectivity (dBZ) to rain rate (R) algorithm will run on each sensor's computer, which will store, process, and transmit precipitation data to the user center. Taking into account a proposed range of 30 km, a spatial resolution of 100 m, and 8-bit amplitude resolution, the sensors will provide approximately 10 MB of reflectivity data per minute. This raw data will be processed by the dBZ to R algorithm, which is detailed above. The compressed data will then be transmitted *via* 3G or Ethernet. This data will be organized and stored on the user center's web server, using a database that is compliant with database standards such as gbXML. The database will contain the precipitation data, the measurement identification, and all available auxiliary meteorological data (e.g., temperature, and air pressure). Within this system, the precipitation data will be integrated into the geographical database, resulting in a real-time precipitation map of the target area. The MARG system will provide precipitation data to the users by means of a web server in the "user center module".

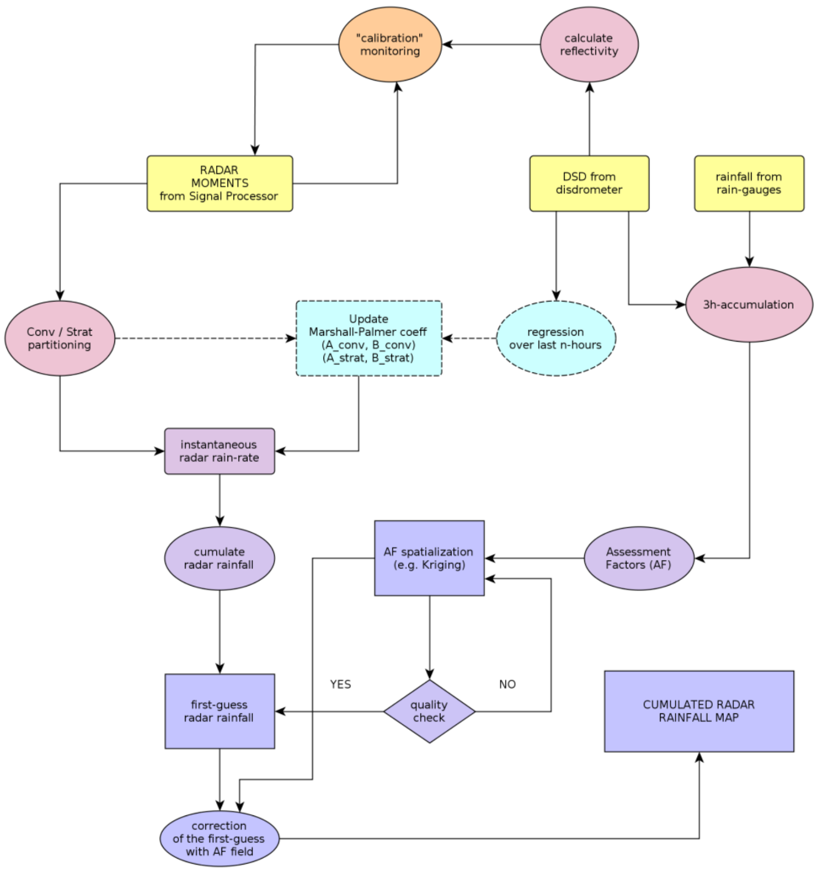

Figure 4. *. The QPE algorithms for MARG (with authorization of MARG consortium)*

5. RESULT

Based on the MARG concept a Consortium was organized and a Project proposal was formulated for realizing the MARG concept and to develop a high resolution, low cost, microwave, short range precipitation measurement system called MARG.

The Project proposal has received funding from the European Community's Seventh Framework Programme (FP7/2007-2013) under grant agreement N° 315296.
MARG project start date: November 1, 2012,
MARG project duration: 24 months
Funding Scheme: FP7 Research for the Benefit of SMEs
Website: www.marg-project.eu
Consortium members:
RTD partners: TU GRAZ, ARPA Piemonte, MFKK
SME partners: BHE, ON-AIR, MET-ENV, GEOGRAPHICA, PESSL.

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