ENIGMA - the versatile weather radar signal processing for weather radars - Magnetron, Klystron, TWT and SST

Martin Malkomes

Martin Malkomes and Matthias Toussaint, Dietmar Veerkamp

GAMIC mbH, 52072 Aachen, Germany
Roermonder Str. 151
(Dated: 18. July 2014)

1 Introduction

The GAMIC signal-processor and digital-receiver ENIGMA, sold in its 4th generation, is designed to coherently process weather radar data (IF or video) in a flexible way. ENIGMA is proven to interface to almost any kind of radar using transmitters like Magnetron, Klystron, TWT (traveling wave tube) and SST (solid state transmitter). Many professional services like DWD, BWB and research agencies in Germany Univ. Bonn, KIT, FZJ use ENIGMA and MURAN weather radar processing at their operational and research radars. Internationally ENIGMA is used by major weather radar manufacturers in worldwide projects (1) (2) (4) Air traffic control (ATC) radars are serviced by an ENIGMA weather channel to extract weather information in parallel to aircraft tracking (3).

More than 200 units have been sold over the last 5 years!

This paper presents the large variety of algorithms, available for SPOL (single-) and DPOL (dual-polarization-) radars.

The advanced processing concepts like e.g. **Pulse Compression for TWT and SST radars** are also available and have been installed at operational systems worldwide (4).

Figure 1: ENIGMA IV – IFD – digital receiver

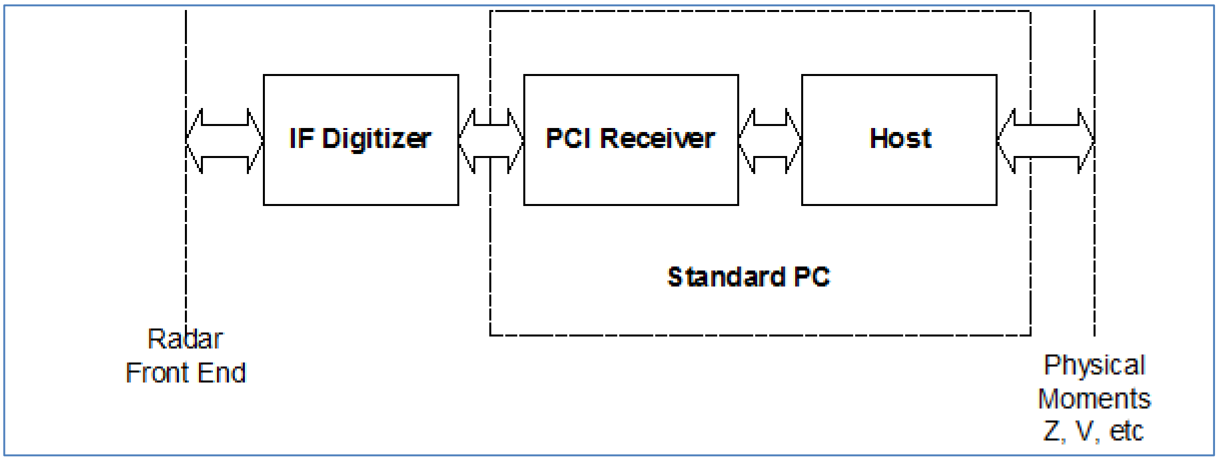
2 History of GAMIC SDP Processors

1995	GSP01	*PC Card for non Doppler Low-Cost Applications*
1996	GSP02	*Stand alone Doppler Signal Processor*
1997	ENIGMA I	*First generation of high performance video baseband Doppler Processor. Up to 2 MAIN boards (3 DSP's) and 3 Expansion boards (8 DSP's) each*

1998	ENIGMA II	*High performance Digital IF Doppler Signal Processor Receiver. Up to 2 MAIN boards (6 DSP's) and 3 Expansion boards (8 DSP's) each.*
2003	ENIGMA III	*High performance FPGA / Linux host based dual polarization IF Doppler Signal Receiver. Signal processor algorithm run on a LINUX based host computer.*
2008 until today	GWSP – ATC radar weather extractor	*Based on ENIGMA III/IV standard HW - High performance FPGA / Linux host based dual polarization IF Doppler Signal Receiver. Signal processor algorithm run on a LINUX based host computer. Passive operation with ATC radar, adapted to the specific radar interfaces using ADAP-Unit (3, 4)*
2007 until today	ENIGMA III+	*High performance FPGA / Linux host based dual polarization IF Doppler Signal Receiver. Greatly improved dynamic range of the IFD by stacking two 16bit A/D converter per channel. Next generation FPGA based IFD.*
2010 until today	ENIGMA IV	*Similar to III+, Available in 3 performance classes:* ***SP, ID, DS with 2000, 4000 and 8000 range bins,*** *processed with ALL algorithms operating – no restrictions!*

3 Processing Concept

The ENIGMA III+/IV Signal Processor consists of two main modules. The IF-Digitizer (IFD) and the Signal Processor host computer. The host computer is basically a Linux based standard industrial PC.



ENIGMA III+/IV performs two main tasks:

- Digital Receiver Functions to obtain I, Q and Burst Pulse statistics. This processing is performed on the IFD and includes matched-filtering and extraction of dynamic "I" and "Q" values. In addition the burst pulse is analyzed with respect to frequency, phase and amplitude to provide digital phase locking, AFC and advanced processing and control features not present in traditional radar's.
- Weather Information extraction to obtain Intensity, Velocity, spectral width and dual polarization moments like ZDR, LDR, KDP, PHIDP and RHOHV. This operation includes Doppler and Intensity processing to extract the calibrated reflectivity, the mean velocity and spectrum width. Clutter filtering by Doppler filtering in the time- or frequency-domain, thresholding and velocity unfolding by dual PRF and dual PRT as well as random phase based second trip processing for magnetron radars.
- In addition to the weather moments a wide variety of quality factors like SQI, CCOR, etc. can be output. All moments can be output in any combination and with selectable resolution of 8bit, 16bits or 32bit IEEE floating point.

The IF Digitizer Module is housed in a sealed box. The main purpose is to digitize the analog IF signals with a minimum of additional computational effort. The fiber optic link ensures the galvanic isolation of the IF Digitizer Module from the rest of the digital components, thus avoiding additional ground loops and other stray effects. Note, that the "Uplink" serial coaxial cable is isolated as well from the IF Digitizer Module. Due to this technique, distances up to 100 meters between the IF Digitizer module and the signal processor can be realized.

4 Algorithms and Specifications

The following algorithms are available, details can be found in the ENIGMA user and algorithm manuals:

Number of bins	4096 ... 8192, Single and dual polarization version
Typical base resolution	25 - 125m
Range	10-640km
PRF	10-3000 Hz
Number of Pulse widths	4 with independent configurable matched filters (up to 1280 taps)
Dual PRF Stagger Modes	None, 2/3, ¾, 4/5 and 5/6
Output data (moments)	- Corrected reflectivity Z - Uncorrected reflectivity UZ - Radial velocity V - Spectral Width W - Clutter power CCOR - Signal quality index SQI - Inphase/Quadrature signal I, Q - Logarithmic power LOG - Censor Map - Power spectrum DFT - RhoHV (Dual polarized radar) - PhiDP (Dual polarized radar) - KDP (Dual polarized radar) - ZDR (Dual polarized radar) - LDR (Dual polarized radar H-transmit) - RhoH (Dual polarized radar H-transmit)
Processing Modes	- Pulse Pair Processing (PPP) - FFT Processing (FFT) - DFT Processing (DFT) - Dual PRT Processing (DPRT)
PPP	- Selectable 40dB and 50dB IIR filter coefficients - Filter width adjustable in 8 steps (Allpass, Filter 1-7) - Range adjustable 1-400km - Rangemask for range and elevation dependent filter selection - Filter zeroing on/off - Configurable filter stabilization delay' - Clutter micro suppression
FFT and DFT	- Adaptive frequency domain interpolation filter width adjustable in 8 steps (Allpass, Filter 1-7) - Range adjustable 1-400km - Rangemask for range and elevation dependent filter selection - Clutter micro suppression - Selectable interpolation: - DC cancelation - Interpolation - Dual slope interpolation - Selectable tapering window (Rectangle, Hamming, Blackman-Harris 3, Blackman-Harris 4, Bartlett, Hann, Welch, Kaiser-Bessel)
DPRT	- Filter width adjustable in 8 steps (Allpass, Filter 1-7) - Range adjustable 1-400km - Rangemask for range and elevation dependent filter selection - Clutter micro suppression
Time averaging	Adjustable time samples (16-1024) or Dynamic angle syncing (0.05°-5°)
Data quality algorithms	- Rain attenuation correction - 1/r² range normalization - Gas attenuation correction - Configurable reflectivity speckle remover (2 Dimensional) - Configurable velocity speckle remover (2 Dimensional) - Configurable spectrum width speckle remover (2 Dimensional)

	- Configurable dual polarization moment speckle remover (2 Dimensional) - Configurable thresholding with NOISE, CCOR, SIGPOW, RHOHV and SQI - Second trip removal
I/Q Recorder	Pulse wise I/Q recording in 32Bit IEEE floating point format to the internal harddisk
Configuration	FROG/MURAN Network capable GUI, telnet or through the built in HTTP server (comprehensive browser interface).
Matched filter designer	GUI program for semi automatic calculation of matched filter coefficients (for transmitter pulse) and verification. Comprehensive AFC configuration and visualization.
Status information	- Host CPU load, CPU temperature and Memory usage - Host Voltages - IFD power supply - IFD temperatures - A/D converter status - AFC Status - Sector blanking status - Number of pulses for autocorrelation

4.1 Clutter filtering examples

The following example shows a good proof of the ENIGMA processing algorithm qualities (as an example for the many others)

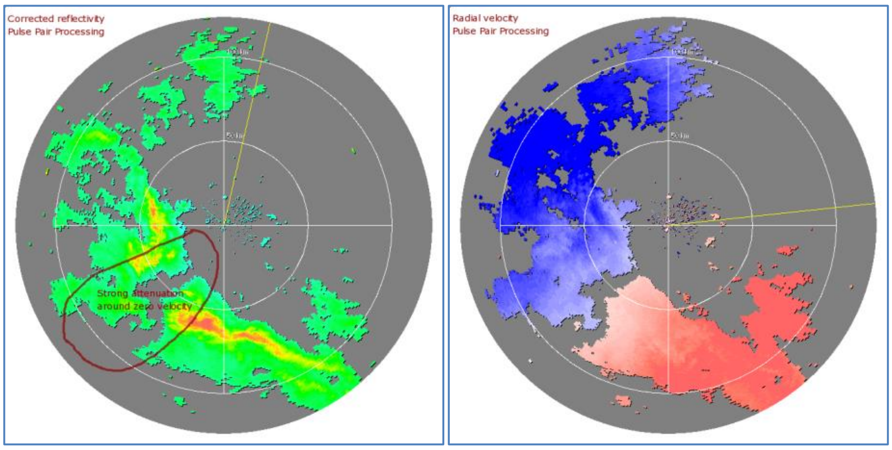


Figure 2: Pulse Pair Processing

In the above shown examples the clutter has been removed by **time domain filtering**. They show strong attenuation in the weather at zero velocities.

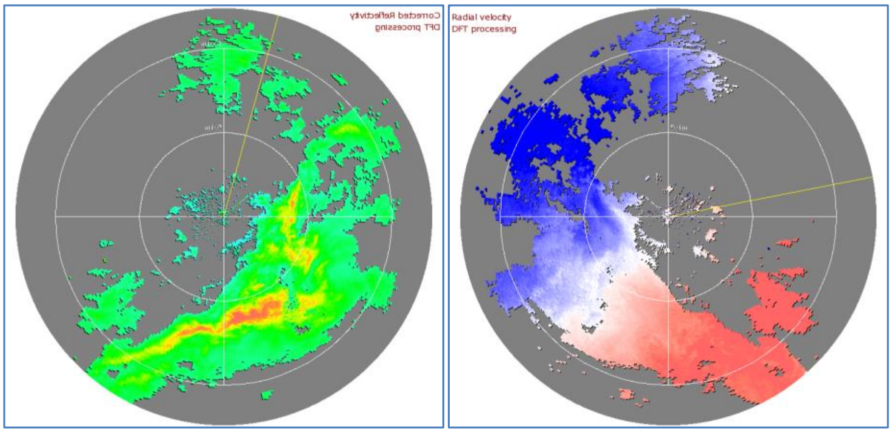


Figure 3: DFT Processing

The same weather situation using **frequency domain filtering**. The difference and the advantage of frequency domain filtering in respect to time domain filtering is quite obvious.

5 Extended Dynamic Range

The ENIGMA IFD+ provides internally stacked converters. There is no need for an external coupler. The coupler range separation is ~20db. By this means a typical dynamic range of the IFD is more than 110dB, to cope with the weather dynamic (80dB) plus range attenuation (30dB).

6 Dual polarization moments

Enigma measures the following moments which are then further on processed by FROG-RTNG and MURAN:

Z	Average of horizontal and vertical corrected reflectivity
Zh	Corrected reflectivity (corrected for both clutter and second trip) horizontal channel
Zv	Corrected reflectivity (corrected for both clutter and second trip) vertical channel
UZ	Average of horizontal and vertical uncorrected reflectivity
UZh	Uncorrected reflectivity horizontal channel
UZv	Uncorrected reflectivity vertical channel
AZh	Rainfall attenuation corrected, clutter corrected reflectivity horizontal channel
ZDR	Differential reflectivity from clutter corrected data
UZDR	Differential reflectivity from uncorrected data
AZDR	Rainfall attenuation corrected, clutter corrected differential reflectivity
ZDR1	Differential reflectivity from clutter corrected data (1^{st} LAG algorithm)
UZDR1	Differential reflectivity from uncorrected data (1^{st} LAG algorithm)
AZDR1	Rainfall attenuation corrected, clutter corrected differential reflectivity (1^{st} LAG algorithm)
Vh	Radial velocity from corrected timeseries, horizontal channel
Vv	Radial velocity from corrected timeseries, vertical channel
UVh	Radial velocity from uncorrected timeseries, horizontal channel
UVv	Radial velocity from uncorrected timeseries, vertical channel
VFh	Folded radial velocity from corrected timeseries, horizontal channel
VFv	Folded radial velocity from corrected timeseries, vertical channel
UnVFh	Folded radial velocity from uncorrected timeseries, horizontal channel
UnVFv	Folded radial velocity from ucorrected timeseries, vertical channel
Wh	Spectral width from corrected timeseries, horizontal channel
Wv	Spectral width from corrected timeseries, vertical channel
UWh	Spectral width from uncorrected timeseries, horizontal channel
UWv	Spectral width from uncorrected timeseries, vertical channel
CWh	Spectral width corrected for decorrelation caused by antenna rotation, horizontal channel
CWv	Spectral width corrected for decorrelation caused by antenna rotation, vertical channel
PHIDP	Differential phase from corrected timeseries

UPHIDP	Differential phase from uncorrected timeseries
PHIH	Differential phase for horizontal transmit only (from corrected timeseries)
UPHIH	Differential phase for horizontal transmit only (from uncorrected timeseries)
KDP	Specific differential phase
RHOHV	Cross correlation coefficient from corrected timeseries
URHOHV	Cross correlation coefficient from uncorrected timeseries
RHOH	Cross correlation coefficient for horizontal transmit only (corrected timeseries)
URHOH	Cross correlation coefficient for horizontal transmit only (uncorrected timeseries)
LDR	Linear depolarization ratio from corrected data
ULDR	Linear depolarization ratio from corrected data
SQIh	Signal quality index, horizontal channel
SQIv	Signal quality index, vertical channel
CCORh	Clutter power correction, horizontal channel
CCORv	Clutter power correction, horizontal channel
Ih	Inphase timeseries (last pulse from batch)
Qh	timeseries (last pulse from batch), vertical channel
Iv	Inphase timeseries (last pulse from batch), horizontal channel
Qv	Quadrature timeseries (last pulse from batch), vertical channel
LOGh	Logarithmic amplitude $10*\log(I^2 + Q^2)$, horizontal channel
LOGv	Logarithmic amplitude $10*\log(I^2 + Q^2)$, vertical channel
SNRh	Raw signal noise ratio horizontal
SNRv	Raw signal noise ratio vertical
DFTh	Signal spectrum (amplitude), horizontal channel
DFTv	Signal spectrum (amplitude), vertical channel
CMAP	Censor map
NM	Result of continuous noise power sampling (power and standard deviation)

Enigma represents THE STATE-OF-THE-ART weather radar signal processor to service any pulse radar type or brand on the market – new or upgraded.

Acknowledgement

We would like to thank the DWD radar group (Hamburg and Hohenpeissenberg) for their critical testing of the ENIGMA’s at their radars, which has led to many improvements of the product.

References

(**1) The new radar data processing software for the GermanWeather Radar Network, M. Malkomes, M. Toussaint**1**, and T. Mammen** Proceedings of ERAD 2002

(2) The Sivam Project: weather radar network for the Amazon region, M. Malkomes, F. Fukuda, F. Rocheleau, and J.Werner Proceedings of ERAD 2002

(3) **Primary ATC –RadarWeather Extractor – Weather Signal Processor GWSP An alternative to weather radar? ,** Martin Malkomes , Matthias Toussaint, and Dietmar Veerkamp, Proceedings of ERAD 2008

(4) The Morocco weather radar modernization project and national network operation results, Martin Malkomes, Mostapha Saadi, Zaidouni Taoufik, Proceedings of ERAD 2010

(5) Pulse Compression for weather radars, practical implementation and case studies, Martin Malkomes, Matthias Toussaint, Dietmar Veerkamp, Proceedings of ERAD 2010