# Evaluation of three Radar Product Processors

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# Chapter 1

# Introduction

Currently KNMI is preparing a technical upgrade of the weather radar systems to extend their operational lifetime with another 10 years. Apart from a mechanical overhaul the upgrade will consist of a renewal of the radar (scan) controller, the signal processor, and the product processor. The radar controller and the signal processor are 10-year-old computer systems which have become outdated and difficult to maintain. This technical upgrade is also the reason for a recent review of the current operational clutter removal scheme (Holleman and Beekhuis, 2005). The planned renewal of the product processor is the incentive for this evaluation of three radar product processor packages.

It is our experience that considerable effort is required to check the configuration and to verify the quality of the radar product processor. Therefore, strong emphasis is put on these two aspects in the evaluation. During a tender procedure time is usually lacking to evaluate the offered packages in detail, e.g. by feeding the packages with real-time data and analyzing the output. As a result it is hard to ensure that the radar product processors fulfill the requirements. To get a ahead of this it was decided to evaluate the most likely candidates. In this evaluation the following radar product processor packages have been considered:

**Muran 3** Gamic GmbH is a German company residing in Aachen that provides solutions for radar signal processing and product generation. The radar product processor package of Gamic is called Muran (Gamic, 2005). The Deutscher Wetterdienst (DWD) is currently migrating their operational radar product processors to Muran for its complete radar network consisting of 16 operational radars and 1 research radar. The version we have evaluated at KNMI is Muran 3.

**Iris 8** The Iris radar product processor package (Sigmet, 2002) is provided by Sigmet Inc. Sigmet is based in Boston, MA, and is well-known for its RVP signal processor and product generation software. Sigmet has developed the Iris package for controlling the RVP signal processor and for generation of products from the data. The Iris product processor package has been developed some time ago and is well established and widely used by now. The current version of the Iris package is 8.

**Rainbow 5** Gematronik GmbH is a German radar manufacturer located in Neuss that provides complete weather radar systems, consisting of both radar hardware and software. The radar product processor of Gematronik is called Rainbow (Gematronik, 2005). The Rainbow package is on the market now for more than 10 years. The latest release of Rainbow, Rainbow 5, is a complete remake of the package from scratch.

The outline of this report on the evaluation of the three radar product processors is as follows:

- The setup of the evaluation of the radar product processor packages is described in chapter 2. The used hardware, operating systems, file format converters, and clutter removal procedure are discussed in some detail.

- In chapter 3 of this report a concise general evaluation of the packages is presented. Topics covered include ease of installation, operational stability, maintainability and the ability to generate the products KNMI needs. In addition, the quality of the documentation and properties of the file format are discussed. These topics are stated as “user impressions” meaning that we did not attempt to make quantitative statements.

- As the evaluation of generated products is the main goal of this study, a detailed evaluation of two products is presented in chapter 4. The first product under evaluation is the pseudoCAPPI product because it is the most important link in the radar production chain of KNMI. The pseudoCAPPI algorithm is not complex at all because it is merely a range-dependent weighted average over a number of elevation scans. The other product under evaluation is the weather radar wind profile product calculated from the Doppler volume dataset. The weather radar wind profile is a relatively new operational product based on a complex algorithm and it requires extensive quality control. At KNMI the wind profiles are produced using the well-established Volume Velocity Processing (VVP) algorithm (Waldteufel and Corbin, 1979; Holleman, 2003, 2005). The international exchange of weather radar wind profiles is strongly increasing due requirements from the Numerical Weather Prediction community.

- Finally, in chapter 5 the summary and conclusions of this evaluation are presented. It is concluded that the Rainbow 5 package of Gematronik GmbH fits the requirements of KNMI best and that a transition from Rainbow 3.4 to Rainbow 5 would be relatively smooth.

# Chapter 2

# Set-up of evaluation

KNMI operates two C-band Doppler weather radars from Gematronik (Meteor AC360). The radars have an antenna with a 4.2 m diameter and a beam width of about 1 degree. The peak power and width of the transmitted pulses are 250 kW and 0.8 $\mu$s, respectively. The received signals are sampled and processed by a RVP6 signal processor from Sigmet Inc (Sigmet, 1998). Three different volumes are scanned operationally: a low-elevation reflectivity scan consisting of four elevations (0.3, 1.1, 2.0, and 3.0 degrees) which is repeated very 5 minutes, a full volume reflectivity scan with 14 elevations between 0.3 and 12 degrees, and a dedicated Doppler scan consisting of 5 elevations between 2 and 25 degrees. Rainbow 3.4 from Gematronik (Gematronik, 2003) is used for the operational generation of all single-site radar products.

In this evaluation only data from the radar in De Bilt (5.18E, 52.10N and 44 m above msl) are used. All volume datasets that are recorded by the operational radar in De Bilt are transfered in real time to the Linux workstations on which the radar product processor packages are running. In this way the different radar product processors receive a real-time dataflow which is identical to the operational dataflow. To avoid unwanted interference each radar product processor package was installed on a separate Linux PC. The employed hardware is a “standard PC” meaning a 2 GHz processor, 512 Mb of RAM, and 80 Gb hard disk. All PCs were running Linux and the Linux flavor was chosen by the manufacturer of the packages. The Iris 3 package was running on Red Hat Enterprise (RHEL3), the Rainbow 5 package was running on SUSE 9.1, and Muran was running on Kubuntu.

Usually the radar product processors are in control of the radar hardware, but in our evaluation the packages only have to process the received volumes. The Rainbow and Muran packages were modified by their manufacturers to be able to detect and process the received volume datasets. By default the Iris package is equipped with a so-called “passive” mode for processing of (Rainbow 3) volume datasets, and only some fine tuning was needed to get things running. Naturally the Rainbow 5 package is capable of handling Rainbow 3 volume datasets. For the Muran package, a software module for the conversion of Rainbow 3 volume datasets into Muran volumes has been developed in close collaboration with Gamic GmbH.

A special point of attention is posed by the KNMI clutter removal scheme which is based on distinguishing between the inherently fluctuating Rayleigh-scattered precipitation signals and the relatively stable ground clutter signals (Wessels and Beekhuis, 1992, 1994). In the planned technical upgrade of the weather radars this stepwise procedure for the rejection of (anomalous propagation) clutter will be transformed from a procedure operating on two-dimensional Cartesian radar products to a procedure removing clutter from the three-dimensional volume datasets (Holleman and Beekhuis, 2005). The clutter removal scheme thus gains rationality and is available for all products that are derived from the volume datasets. For this evaluation an application was developed which reads the reflectivity and clutter volume datasets and outputs the clutter-processed reflectivity volume dataset. These clutter-processed volume datasets are subsequently transfered to the radar product processors under evaluation. In this way the new clutter removal scheme was available for all product processors.

After the configuration was completed and the processing was running stable, the different radar product processors have been acquiring data for about two months. In this way an archive has been collected starting 1 May 2005 and ending 30 June 2005 (excluding 14 till 17 May due to network malfunctioning) that contains the processed data as well as the original volume datasets. The output from the radar product processors is stored in the native formats of the packages. Software modules have been developed to convert the output of the different radar product processors (Muran, Iris, and Rainbow) to the KNMI HDF5 format for image data (Roozekrans and Holleman, 2003). In this way all data are available in the same format and the comparison is facilitated.

It should be noted that the setup of this evaluation allows for an evaluation of the product generation only. All of three radar product processor packages have functions to configure, control and monitor multiple radar front-ends. As control of the operational radar De Bilt was neither possible nor allowed, these functions of the packages could not be evaluated.

# Chapter 3

# General evaluation

In this chapter the results of a general evaluation of the Radar Product Processor (RPP) packages is presented. It is stressed that this evaluation is focused on the needs of KNMI and that the current operational output is the reference for this evaluation. The radar product processor packages are evaluated on the following aspects:

**Configuration** The product generation packages have to be configured to be able to perform the required tasks and produce the desired products. The configuration is usually a complex task. The production processor package should facilitate this task by providing an intuitive graphical user interface and by performing consistency checks on the configuration. The "look and feel" of the graphical user interface will be evaluated, and in addition the format and content of the configuration files will be discussed.

**Operational stability** A high operational availability is required by KNMI for the radar product processor, typically $> 99\%$. During the on-line evaluation of the product processor packages which lasted almost 3 months, an impression of the operational stability has been obtained. Apart from the stability, the recovery of the radar product processor after e.g. a computer crash or a power-failure is of crucial importance.

**Geographical projection** An accurate overlay of the radar echoes with topographical data is crucial for further application of the radar data. The module for the geographical projection of the radar data must be able to handle the geographical projection of the KNMI radar images in a correct manner. Details of the geographical projection of the KNMI radar images is given in appendix A.

**Products** The product processor package must be able to replace the current operational product processor and thus all operational KNMI radar products must be available in the package with an comparable or better quality. The operational radar products at KNMI are:

- pseudoCAPPI of reflectivity,
- surface precipitation accumulated over 3 hours and 24 hours,
- echo top heights,
- hail detection based on 45 dBZ echo contours and freezing level heights from a numerical weather prediction model,
- wind profiles based on Volume Velocity Processing (VVP).

In addition, it is planned to start using a warning product based on horizontal wind shear obtained from Doppler radial velocity data. The algorithms used for the product generation will be evaluated using the user documentation. The product generation package should allow for the inclusion of user-build product modules.

**File format** The accessibility, portability, and information content of the internal file format used by the product generation package is important for the conversion of this file format to the KNMI HDF5 data format for operational (image) data. (Roozekrans and Holleman, 2003). The internal file format is ideally based on a non-propriety standard, and the data and metadata should (easily) be accessible using standard programming languages (C, C++, Fortran).

**Documentation** For operational maintenance, configuration, quality control of operational products, and Research & Development high quality documentation of the radar product generation package is required. The documentation should be complete, well-structured, detailed, and clear. Especially documentation on the configuration and algorithms of the products relevant to KNMI has been evaluated.

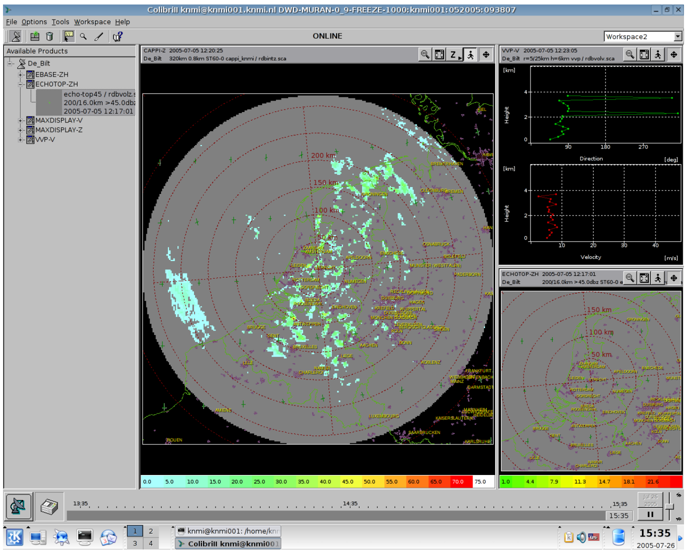

Figure 3.1: Snapshot of the Muran 3 overview window with a few products.

# 3.1 Muran 3

Gamic GmbH is a German company based in Aachen that provides solutions for radar signal processing and product generation. The radar product processor package of Gamic is called Muran (Gamic, 2005). The Deutscher Wetterdienst (DWD) is currently migrating their operational radar product processors to Muran for its complete radar network consisting of 16 operational radars and 1 research radar. The version we have evaluated at KNMI is Muran 3.

## 3.1.1 Configuration

A pre-installed version of Muran 3 on a workstation that was property of Gamic was delivered to KNMI. Therefore we did not gain any experience on the installation of the Muran radar product processor. The Muran package has a feature rich graphical user interface which is nice to see (see figure 3.1), but the drag and drop is somewhat deviant from normal practice. During the configuration of Muran it is sometimes difficult to find the entrance to the configuration items.

## 3.1.2 Operational stability

After the installation at KNMI and interfacing to the real-time dataflows, the Muran 3 application has been running very stable. The log window is very clear

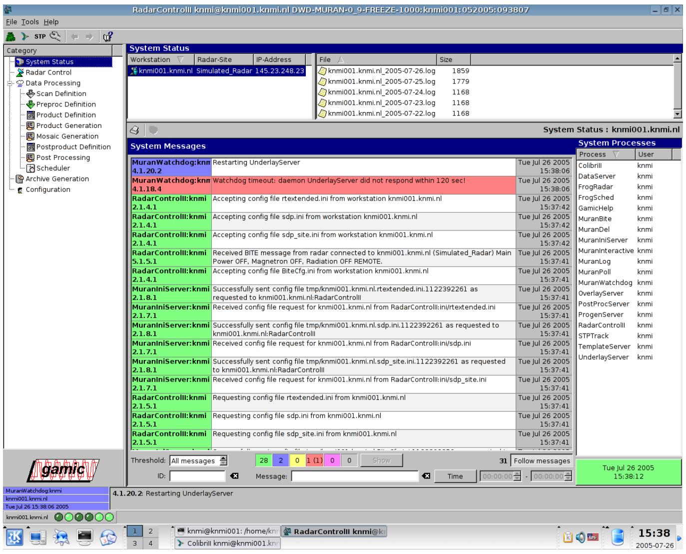


Figure 3.2: Snapshot of the Muran 3 monitoring window with log messages, warnings, and errors.

because of the colors that indicate the fault category: messages, warnings, or errors (see figure 3.2). The user interface for the selection of the fault categories, i.e., messages, warnings, or errors, is simple and effective.

### 3.1.3 Geographical projection

A snapshot of the Muran graphical user interface for entering the geographical projection of the topview radar products is shown in figure 3.3. The geographical projection of radar data is split into two steps in the Muran package. The first step is part of the product definition (see left snapshot in the figure) where a projection function with hard-coded parameters can be selected, e.g. polar stereographic projection with a true-scale latitude of 60 N and an alignment meridian of 0 E. The georeferenced product is automatically centered at the radar site and its extent is matched to the radar coverage. In the second step this single-radar product is used as input for a compositing module (Mosaic, see right snapshot in the figure) where it is reprojected to obtain the desired geographical extent and position. This approach differs from the (current) KNMI approach where the single-radar products have the same geographical projection as the composite and can directly serve as backup for the national composite.

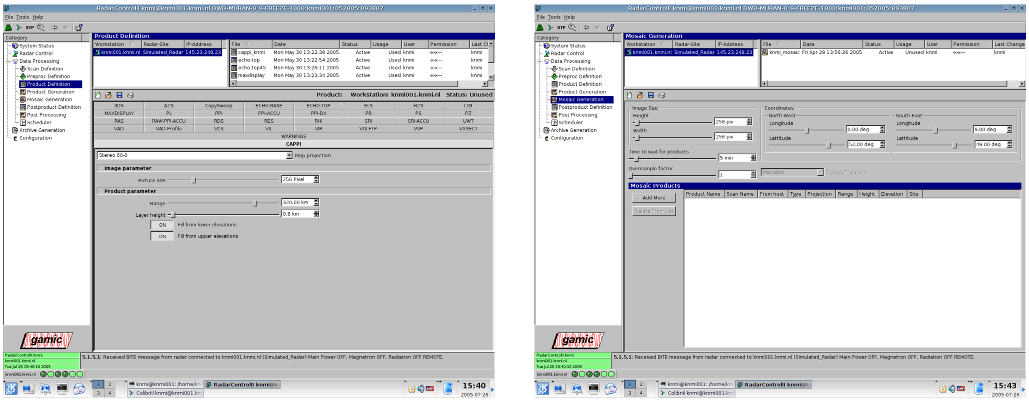

Figure 3.3: Snapshot from the Muran 3 radar product processor of the windows where the geographical projection can be defined.

### 3.1.4 Products

The Constant Altitude Plan Position Indicator (CAPPI) product of Muran provides a horizontal cross section at a selected layer at height $H$ above the radar reference level. Data are obtained from a number of PPI type scans at different elevations. In regions where no radar data are available an extrapolation may optionally be performed thus generating a so-called pseudoCAPPI.

The Precipitation Accumulation (PAC) product of Muran constantly sums the precipitation fallen during a specified period of time using the surface rainfall intensity map product (SRI). Each time a new volume dataset is available an updated PAC product is calculated. The Z-R relationship can be selected via the configuration of the intermediate SRI product. It is not clear whether a minimum/maximum dBZ can be supplied

The Echo Top (ETOP) product shows the maximum height relative to the radar reference height of a reflectivity value. The maximum height of an user-specified reflectivity value in a vertical column over ground is extracted and presented with earth curvature correction. The Muran package does offer a hail detection product based on 45 dBZ echo tops and freezing level data from a Numerical Weather Prediction model (Waldvogel et al., 1979; Holleman et al., 2000; Holleman, 2001). It is not clear whether the freezing level is fixed or can be read from a file. The HAIL product of Muran generates a warning based on the Waldvogel criterion, and it is not possible to calculate a Probability-Of-Hail (POH).

At KNMI Weather Radar Wind Profiles (WRWP) are produced using the well-established Volume Velocity Processing algorithm (Waldteufel and Corbin, 1979; Holleman, 2003, 2005). The Muran VVP algorithm uses data from a multi-elevation volume scan to derive wind speed, wind direction and divergence. The parameters that are calculated cannot be changed in the user interface. Only limited quality control is performed on the raw volume data and the obtained wind profile data.

Muran offers several shear products like radial, azimuthal, and horizontal wind shear products.

### 3.1.5 File format

The data and metadata of the Muran radar products are saved as portable network graphics (png) files complemented with (meta)data structures from the QT library (Trolltech, 1995). The Muran radar products can easily be viewed by a human using a standard image viewer. The metadata structures, however, can only be read using the QT library. The QT library is a frequently-used C++ library and thus the metadata can only be read using the C++ programming language. The Muran files can be read on both little endian and big endian platforms. Important metadata on the geographical projection, e.g., product corners, is missing in the files.

### 3.1.6 Documentation

The documentation of the Muran package is still in a maturing phase, the manual describing the products and algorithms is very coarse. The configuration manuals consist mostly of screen dumps showing what the user should see when everything goes well. Clearly, such a manual is of no use when you are in trouble. There is work to be done by Gamic on this documentation if they want to reach the same level as the other packages in this evaluation.

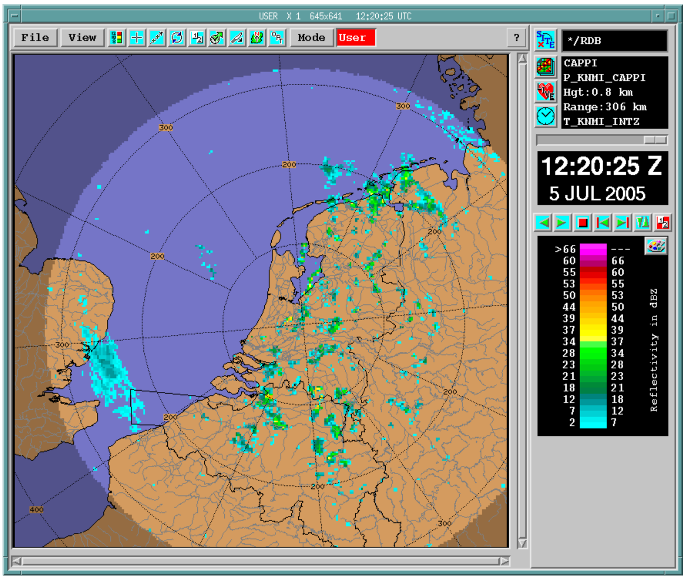


Figure 3.4: Snapshot of the Iris 8 overview window with a few products.

## 3.2 Iris 8

The Iris radar product processor package (Sigmet, 2002) is provided by Sigmet Inc. Sigmet company is based in Boston, MA, and is well-known for its RVP signal processor and product generation software. Sigmet has developed the Iris package for controlling the RVP signal processor and for generation of products from the data. The Iris product processor package has been developed some time ago and is well established and widely used by now. The current version of the Iris package is 8.

### 3.2.1 Configuration

It is advised by Sigmet to run Iris on a Red Hat Enterprise distribution of Linux. Installation of Iris using the supplied installation scripts was straightforward. The documentation of Iris concerning the installation is clear and to the point. After installation you end up with a very clean desktop that offers no frills whatsoever. The Iris window manager dubbed MWM, short for Minimal Window Manager, is exactly what its name suggests. The only functionality it offers is access to the Iris menu and some graphical output windows.

The Iris package uses the famous X11 as the under laying graphical library. This library is nowadays rather old and offers a limited functionality. This makes that Iris looks and feels rather old-fashioned (see figure 3.4). Further develop-

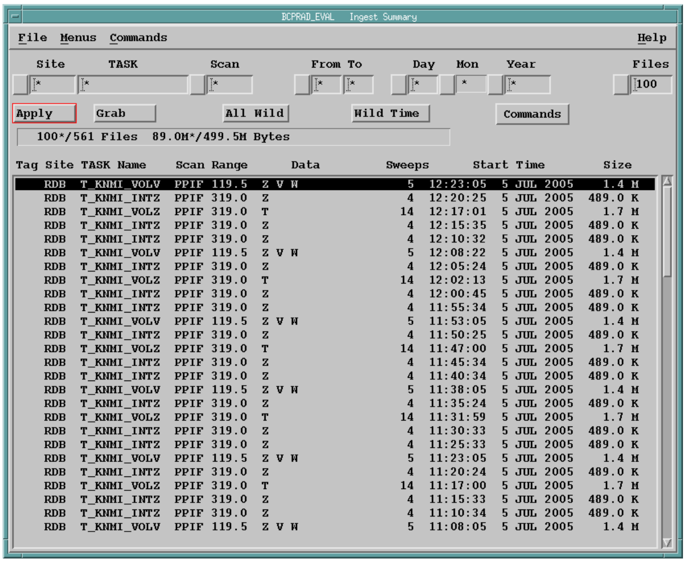

Figure 3.5: Snapshot of the Iris 8 monitoring window with log messages, warnings, and errors.

ments of the Iris package will surely be hindered by this library. Modern graphical libraries, e.g. the QT library (Trolltech, 1995), offer more features in a structured object-oriented manner, not only for displaying but also for access to the operating system.

Configuration of the Iris package is rather counter-intuitive which is clearly due to the age of the package. Where the other packages use hierarchical ordered structures to maintain their configuration, Iris comes with separate configuration menus. The relation between the configuration menus is not evident at first sight. This makes the configuration of the system cumbersome and without the manual one gets lost. Especially tricky is that (sub)configurations are not saved automatically which leads to unexpected behavior after rebooting of the system.

### 3.2.2 Operational stability

The Iris radar product processor has proved to be rock stable. It has been running without any interruption for three months. The Iris status window is a bare text display without any colors or symbols, and it is difficult to discriminate between normal operation and fault conditions (see figure 3.5).

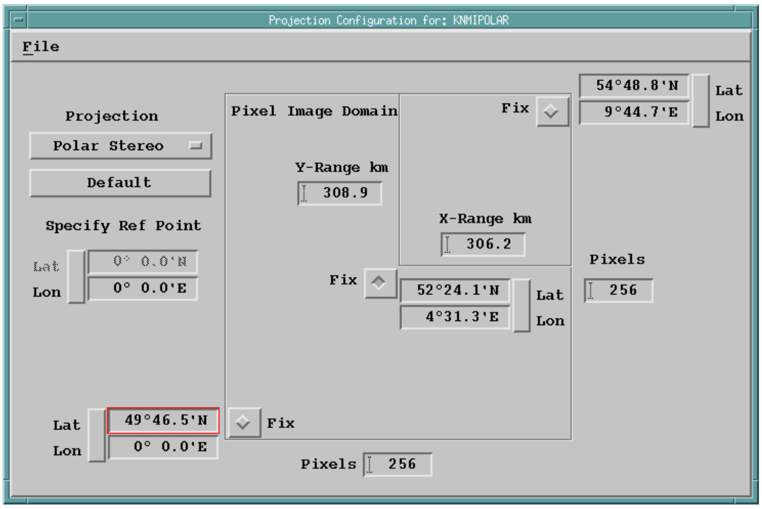


Figure 3.6: Snapshot from the Iris 8 radar product processor of the window where the geographical projection can be defined.

### 3.2.3 Geographical projection

A snapshot of the Iris graphical user interface for entering the geographical projection of the topview radar products is shown in figure 3.6. Going through the list of geographical projections and parameters it is striking that the geographical projection of the KNMI radar products (see Appendix A for details) cannot be configured, because a polar stereographical projection on a non-spherical earth is not available. The snapshot thus reveals the parameters that were used to approximate the geographical projection of the KNMI radar products during the evaluation. For this approximation, the center point of the image domain was fixed at that of the KNMI image (4.521E,52.402N). The north-east and south-west corners were chosen to best match those of the KNMI image. By comparing the geographical coordinates of the north-east (9.745E,54.813N) and south-west (0.000E,49.775N) corners from Iris with those of the KNMI products (see Appendix A), the error of not using the appropriate geographical projection can be estimated. The maximum differences in longitude and latitude are 0.002 degrees ($\simeq 0.2$ km) and 0.005 degrees ($\simeq 0.6$ km), respectively. This spatial error of 0.6 km is clearly unacceptable for KNMI.

### 3.2.4 Products

The Constant Altitude Plan Position Indicator (CAPPI) product of Iris makes a horizontal cut through the atmosphere from a PPI volume scan at multiple elevation angles. The algorithm constructs CAPPIs by interpolating in height and range to the selected height. It is possible to enter a range of heights for the construction of a 3D-CAPPI. When the CAPPI Fill option is selected the highest elevation angle is used to fill the near ranges and the lowest elevation angle for the far ranges (pseudoCAPPI).

The Rain Accumulation product of Iris accumulates CAPPI or Surface Rainfall Intensity (SRI) products in a two step procedure. First, the previous hour's CAPPI or SRI data are used by the so-called "RAIN1" product to estimate the rainfall that fell within that hour. A minimum reflectivity for accumulation can be defined by the user. Then, the individual RAIN1 products can be summed any number of hours using the so-called "RAINN" product. The product output continuously shows the $N$ hours of accumulation.

The Echo Tops (TOPS) product displays the height of the highest occurrence of a selectable threshold dBZ contour using a PPI volume scan. The TOPS algorithm makes a downward search at constant range in cylindrical coordinates to determine when the threshold is crossed. It then interpolates in height to obtain the height of the threshold contour. The Iris package does not offer a hail detection product based on 45 dBZ echo tops and freezing level data from a Numerical Weather Prediction (NWP) model (Waldvogel et al., 1979; Holleman et al., 2000; Holleman, 2001).

At KNMI Weather Radar Wind Profiles (WRWP) are produced using the well-established Volume Velocity Processing algorithm (Waldteufel and Corbin, 1979; Holleman, 2003, 2005). The Iris VVP algorithm is based on the Doppler velocity unfolding algorithm developed by Siggia and Holmes (1991). Apart from the 3D wind parameters, the Iris VVP product can optionally provide the reflectivity, vertical wind, divergence, and deformation profiles. A limited quality control is performed where the inner and outer range of the analysis volume can be adjusted by the user.

Iris offers several shear products like radial, azimuthal, and horizontal wind shear products. An extensive description on the algorithms and their use are available in the Iris manuals.

### 3.2.5 File format

The data and metadata of the Iris 8 radar products are saved as binary blocks of C-structures of strings, integers, and other (sub)structures. The Iris 8 files can, therefore, not be interpreted by a human using some kind of editor. Reading of the Iris 8 files using a C program is straightforward, but the recursive use of (sub)structures in (sub)structures can make the decoding complicated. The portability of the Iris 8 files is limited because the file format is not resistant to little endian/big endian changes.

### 3.2.6 Documentation

The documentation of the Iris package consists of three volumes: the Iris installation & programmers & utilities manual, the radar manual, and the product & display manual. We have intensively used the installation manual to configure the Iris package for the evaluation. The radar manual which describes the interaction with the radar sensor was not used during our evaluation because Iris was running in passive mode only. The product & display manual is truly written with the user in mind. It offers background information on how the radar products are generated and even contains an introductory course on radar meteorology. As a whole the documentation of Iris is outstanding and sets a standard for others.

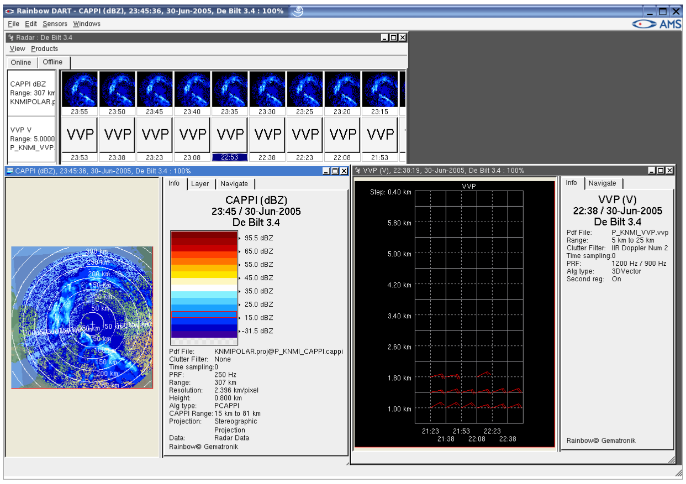

Figure 3.7: Snapshot of the Rainbow 5 overview window with a few products.

## 3.3 Rainbow 5

Gematronik GmbH is a German radar manufacturer located in Neuss that provides complete weather radar systems, consisting of both radar hardware and software. The radar product processor of Gematronik is called Rainbow (Gematronik, 2005). The Rainbow package is on the market now for more than 10 years. The latest release of Rainbow, Rainbow 5, is a complete remake of the package from scratch. Rainbow 5 is intended to control several radars using a single application. The Rainbow application relies on a package called Net Group Server (NGS) that handles all file transfer and messages between the various (distributed) applications of the main application. As Rainbow 5 is completely programmed using platform independent techniques, the package is available for Unix, Linux, and Windows 2000/XP.

### 3.3.1 Configuration

Given a Linux workstation (SUSE 9.1 in our case), installation of Rainbow 5 is straightforward: all that has to be done is to activate the self installing NGS packages and Rainbow 5. Once Rainbow 5 is activated you will find the Rainbow control center window on your desktop. This control center allows direct access to the Rainbow applications with a user interface: RainMan the radar manager to configure the settings of any radar in your network, RainLog that keeps track of system loggings, and RainDart for visualization of the generated products. Configuration of the Rainbow 5 package is done in a hierarchical tree that shows the

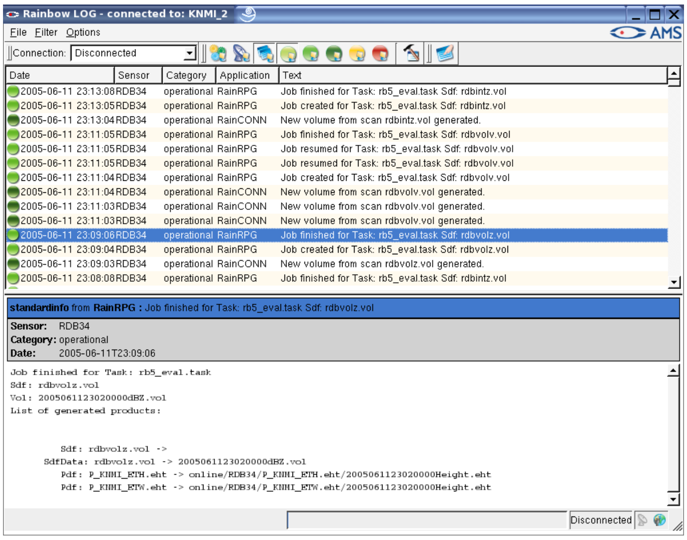


Figure 3.8: Snapshot of the Rainbow 5 monitoring window with log messages, warnings, and errors.

under laying object-oriented nature of the Rainbow application. Configuration of the Rainbow system thus is very intuitive. The interface is well designed and gives clear feedback to the user (see figure 3.7).

### 3.3.2 Operational stability

During the start of the evaluation the Linux computer running the Rainbow 5 package had an occasional hangup. Detailed investigations showed that the SUSE operating system was to blame for these hangups as it neglected to empty some system cache on a regular basis. After the installation of a patch for this bug of SUSE 9.1, the Rainbow 5 application was stable and did its job without any complaints. The status manager of Rainbow 5, RainLog, provides a clear view of the messages, warnings or errors (see figure 3.8) and it allows to select the messages in a simple but effective manner.

### 3.3.3 Geographical projection

A snapshot of the graphical user interface of Rainbow 5 for entering the geographical projection of the topview radar products is shown in figure 3.9. The snapshot reveals the parameters that were used to enter the geographical projection of the KNMI radar products (see Appendix A). The Rainbow 5 product generation package fully supports the KNMI projection, i.e., a polar stereographic projection on

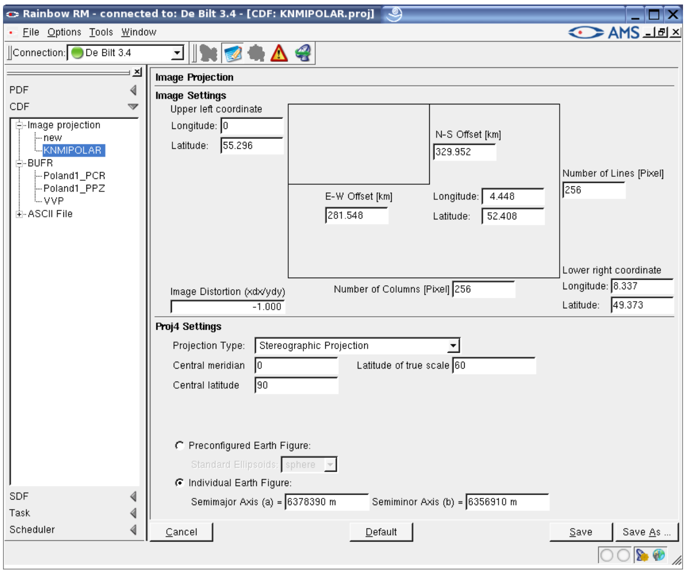


Figure 3.9: Snapshot from the Rainbow 5 radar product processor of the window where the geographical projection can be defined.

an ellipsoid earth model. Moreover, this snapshot and the manual state that the Rainbow 5 projection module is based on the proj.4 library (Evenden, 1990). This library for geographical projection is widely used and has extensively been tested around the world. At KNMI the proj.4 library is already been used in the radar compositing and distribution system (so-called VCRIS) and for research and development (on weather radar). Therefore, the use of the proj.4 library in the product generation package is strongly preferred by KNMI.

### 3.3.4 Products

The Constant Altitude Plan Position Indicator (CAPPI) product of Rainbow takes multiple-elevation polar volume data as input and calculates a cross-section at a user-definable height above mean sea level. The data are derived by a distance weighted average of the corresponding range bins of the higher and lower elevations. Areas above the highest elevation and below the lowest elevation are set either to nodata (true CAPPI mode) or to the values of the closest elevation (pseudoCAPPI mode).

The Precipitation Accumulation (PAC) product of Rainbow accumulates CAPPI, Surface Rainfall Intensity (SRI), or PAC products over user-definable time intervals at repeated action times, e.g. daily. The applied Z-R relation can be entered via the SRI product interface. An extensive description of the PAC algorithm is given in the Rainbow Products & Algorithms manual, but it is unclear whether a minimum/maximum reflectivity for accumulation can be defined by the user.

The Echo Height (EHT) product analyzes vertical columns of polar volume reflectivity data to find out the echo top, echo base, height of maximum echo, and/or layer thickness. The echo top product presents the greatest height within the column where the user-defined reflectivity threshold is exceeded. Linear interpolation is used to determine the echo top heights. At KNMI 45 dBZ echo tops are used together with freezing level data from the Hirlam Numerical Weather Prediction (NWP) model to generate a hail warning product based the method of Waldvogel (Waldvogel et al., 1979; Holleman et al., 2000; Holleman, 2001). Rainbow offers a hail detection (ZHAIL) product closely matching the operational KNMI product. The freezing level can be fixed or read from a file and the conversion of the observed height difference to Probability Of Hail (POH) can be configured by the user.

At KNMI the Weather Radar Wind Profiles (WRWP) are produced using the well-established Volume Velocity Processing algorithm (Waldteufel and Corbin, 1979; Holleman, 2003, 2005). The implementation of the Rainbow VVP product is based on the currently operational product which provides high quality wind profile data. The user interface of the Rainbow VVP product allows for change of the calculated wind field parameters, i.e., only 3D wind, also horizontal derivatives, or complete set. An extensive quality control is performed where the inner and outer range of the analysis volume, the minimum radial velocity (remove bias due to clutter), and the minimum number of points in a 45-degree azimuthal sector can be adjusted by the user. A second regression of the wind field model can be performed after rejection of outliers due to dealiasing errors (Holleman and Beekhuis, 2003). A Vertical Profile of Reflectivity (VPR) product is not yet available in Rainbow 5.

Rainbow offers several shear products like radial, azimuthal, and horizontal wind shear products. The horizontal wind shear product of Rainbow 3.4 has been evaluated at KNMI during the summer of 2004 (Holleman et al., 2005). It is currently not clear whether the recommendations from this study have been implemented in the Rainbow 5 shear products.

### 3.3.5 File format

The metadata of the Rainbow 5 radar products are saved in an XML file and the data are saved as binary-large-objects (BLOBs) in the XML structure. The metadata of the Rainbow 5 files can easily be browsed using a text editor or an XML viewer. The Rainbow 5 files contain abundant metadata on the radar, the scanning, and the product (generation). The BLOBs containing the actual (binary) data are, unfortunately, violating the XML format which only allows for printable characters. As a consequence, a standard library for reading XML files (libxml) cannot handle the Rainbow files. In addition, the documentation on the BLOBs, which are written using the QT library, was not providing all information needed and some iterative programming was needed decode the BLOBs. The Rainbow files can be read on both little endian and big endian platforms using standard programming languages.

### 3.3.6 Documentation

Documentation of the Rainbow 5 package is on a high level and it is rather complete. The Rainbow user manual is very descriptive, but it is written from the developers point of view. At some points, the user manual lacks the extra depth the user of the package will need when things go wrong. The product manual with the descriptions of the applied algorithms and quality control is illustrative and clear.

# Chapter 4

# Evaluation of products

In this chapter the results of the product evaluation from the three radar product processors are presented. Data from two different radar products have been analyzed: the pseudoCAPPI product and the weather radar wind profiles based on Volume Velocity Processing. The former is the backbone of the KNMI radar production chain and is also exchanged operationally within Europe. The latter is a relatively new operational product based on a complex algorithm and it requires extensive quality control. The international exchange of weather radar wind profiles is strongly increasing due requirements from the Numerical Weather Prediction community.

## 4.1 PseudoCAPPI product

The pseudoCAPPI product is used for the generation of the national and European reflectivity composites, for precipitation accumulation, and for the international exchange. The evaluation of the pseudoCAPPI products is performed for one case where images from all radar product processors are compared with a reference product. On 12 June 2005 at 1900 UTC a cold front was moving from west to east over the Netherlands. A rainfall intensity of roughly 2 mm/h during 10 minutes and a temperature of 12 °C were observed in De Bilt around that time.

In figure 4.1 the pseudoCAPPI products obtained at 1900 UTC on 12 June 2005 with the Muran 3, Iris 8, and Rainbow 5 radar product processors are presented. In addition, the pseudoCAPPI product obtained using the off-line software developed at KNMI for research purposes is shown in the upper-left image. The color scale of the images in the figure displays a large reflectivity range from $-29$ up to 59 dBZ in 4 dB intervals. The features with strong reflectivity in the four images resemble each other rather closely, but especially at longer ranges and for weaker reflectivities remarkable differences can be seen. The most striking dif-

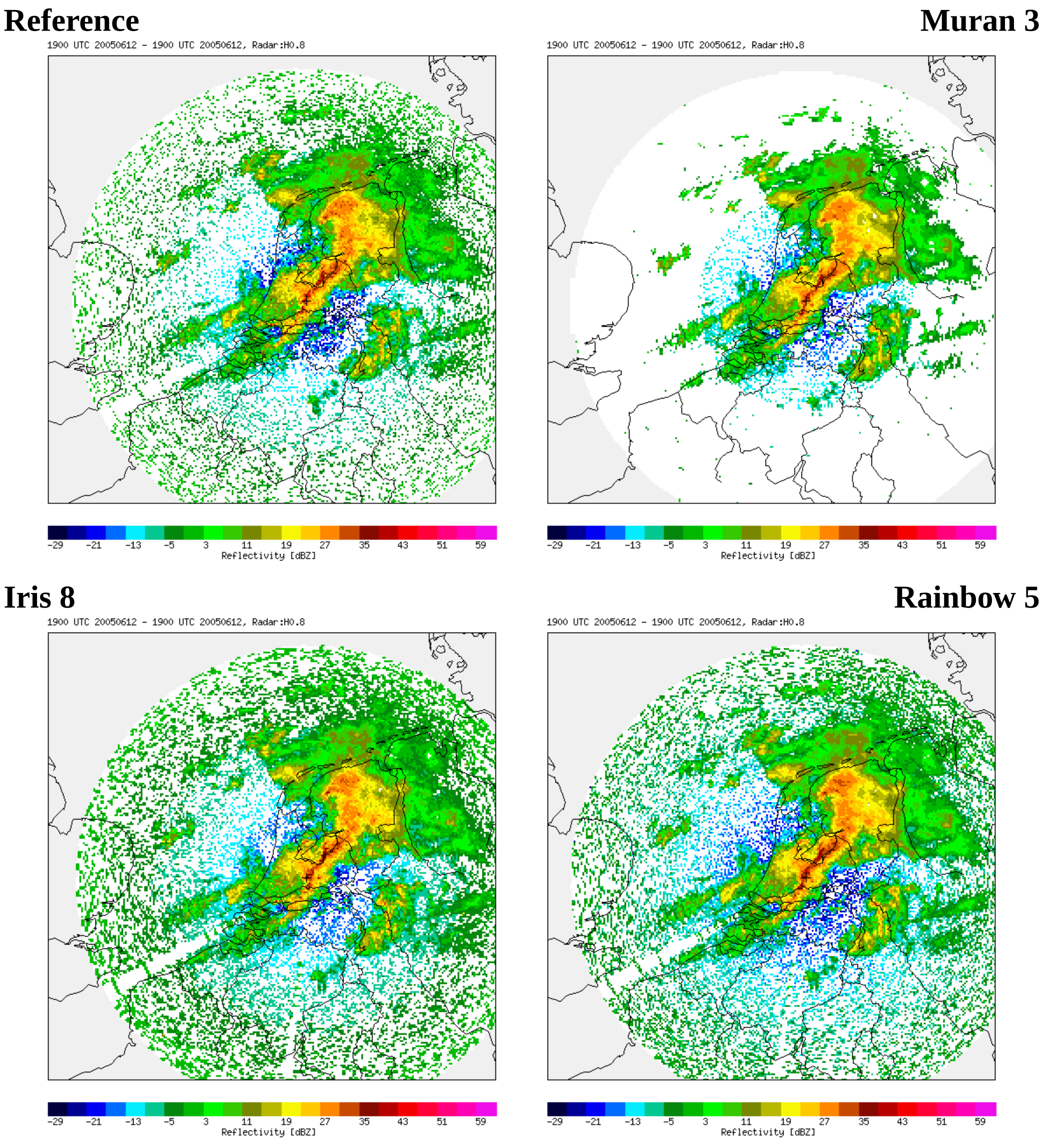


Figure 4.1: This figure shows the pseudoCAPPI products of radar reflectivity at 1900 UTC on 12 June 2005. The top-left image is generated using off-line software developed at KNMI, the top-right image is generated using Muran 3, and the bottom-right and bottom-left images are produced using Iris 8 and Rainbow 5, respectively.

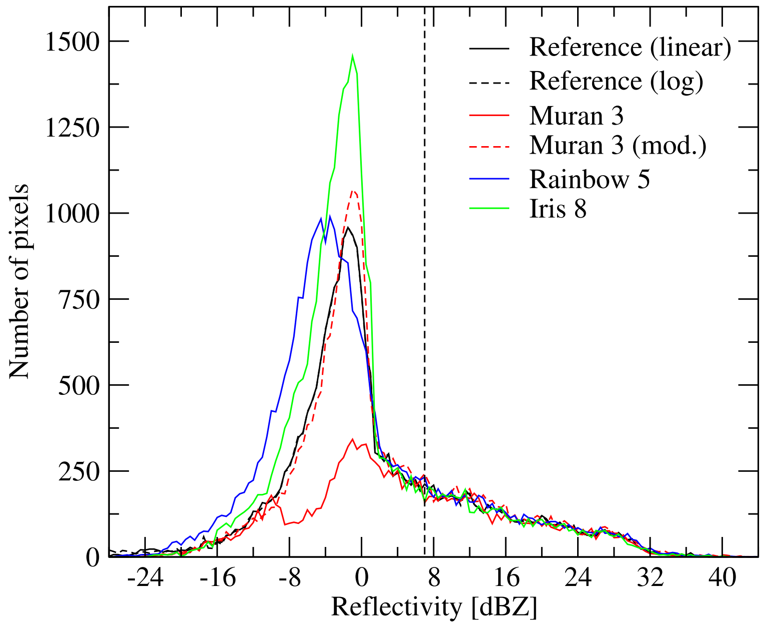


Figure 4.2: Histograms of the radar reflectivity values obtained from the pseudoCAPPI products in figure 4.1 are shown in this figure. Two histograms are shown for the reference using either linear interpolation of the Z values (linear) or the dBZ values (log). For Muran 3 a histogram of a modified pseudoCAPPI product (see text) is also shown.

ference is the absence of "noise" pixels at ranges beyond approximately 150 km in the Muran 3 pseudoCAPPI product (upper-right image). From a closer examination of the Muran 3 product it seems that some kind of spatial smoothing is applied to the data. Another distinct difference is the larger spatial extent of the "noise" pixels at long ranges in the Iris 8 product (lower-left image). This is most likely due to a spatial smoothing during the polar-to-Cartesian conversion. Finally, it appears that the density of the "noise" pixels in the Rainbow 5 pseudoCAPPI product is slightly higher than that in the reference product.

The different pseudoCAPPI products are evaluated quantitatively using histograms of the reflectivity values in the images. In figure 4.2 the calculated histograms for the pseudoCAPPI products shown in figure 4.1 are plotted. The vertical dashed line marks the reflectivity threshold for the operational weather radar displays at KNMI. For the "reference" pseudoCAPPI two histograms are shown: one for a pseudoCAPPI obtained using interpolation of the linear reflectivity $Z$ (linear) and one obtained using interpolation of the reflectivity in dBZ (log). It will be detailed below that for Muran 3 an additional histogram is shown for a

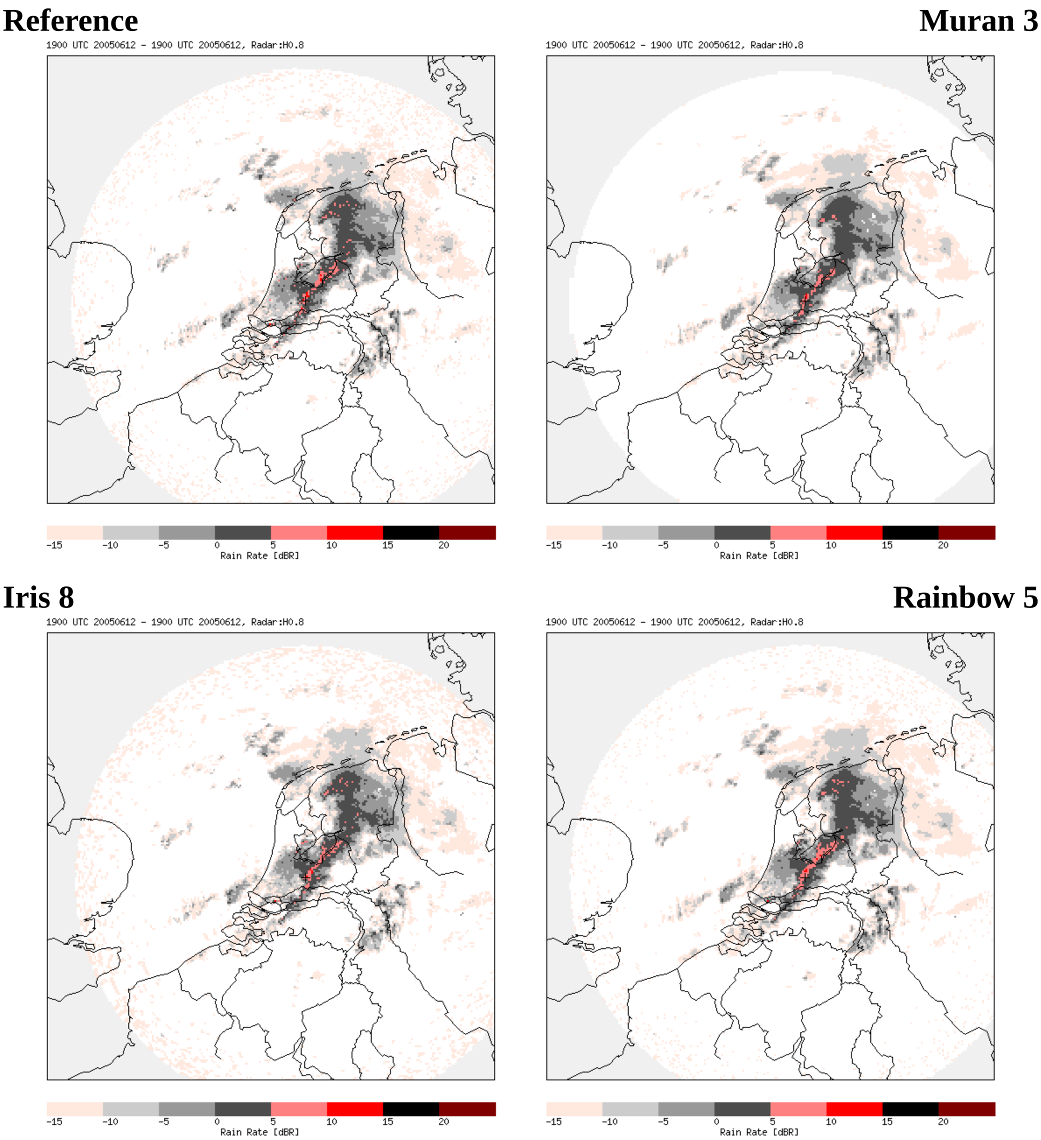


Figure 4.3: This figure shows the pseudoCAPPI products of radar rainfall using the levels and colors of the operational KNMI display at 1900 UTC on 12 June 2005. The top-left image is generated using off-line software from KNMI (reference), the top-right image is generated using Muran 3, and the bottom-right and bottom-left images are produced using Iris 8 and Rainbow 5, respectively.

modified pseudoCAPPI product.

It is evident from the histograms in figure 4.2 that the different pseudoCAPPI products are rather similar for reflectivities above the display threshold of 7 dBZ. Below the display threshold, however, large differences between the histograms are found. Most pseudoCAPPI histograms exhibit a maximum around $-1$ dBZ, but in the Muran histogram this maximum is completely absent. The absence of the peak around $-1$ dBZ is due to the missing noise pixels at long ranges in the pseudoCAPPI product from Muran. The missing noise pixels are due to rather stringent thresholding of the data during the calculation of the pseudoCAPPI in Muran. Figure 4.2 also shows a histogram from a modified pseudoCAPPI product using milder criteria for the data thresholding, and this histogram closely resembles that of the reference product.

The low-reflectivity maximum of the Iris histogram is clearly much higher than those of the other histograms. This indicates that the number of pixels with a reflectivity value around $-1$ dBZ is much larger than in the other images. This is in line with the observed larger spatial extent of the “noise” areas at long ranges in the Iris pseudoCAPPI product. Finally, the low-reflectivity maximum of the Rainbow 5 histogram is shifted to lower values by approximately 3 dB. The reason for this shift of the Rainbow 5 histogram is not yet clear and needs to be sorted out before Rainbow 5 could be used operationally.

From the analysis of the histograms it appears that the different pseudoCAPPI products resemble each other above the display threshold used in the operational radar displays. In figure 4.3 the different pseudoCAPPI at 1900 UTC on 12 June 2005 are shown with colors indicating the rain rate. The reflectivity values have been converted to rain rates using the standard Z-R relation ($Z = 200R^{1.6}$) and the colors correspond to those of the KNMI radar display. Two colors have been added, however, at the low end ($-15$ dBR equal to 0.03 mm/h) and high end of the color scale (20 dBR equal to 100 mm/h). It is evident that the different pseudoCAPPI products are rather similar (when the pink pixels are discarded), but subtle differences can be seen. All in all, it is remarkable that even for a base product like a pseudoCAPPI the different radar product processors are so inconsistent.

## 4.2 Weather Radar Wind Profiles (VVP)

The wind weather radar wind profile is a relatively new operational product based on a complex algorithm and it requires extensive quality control. At KNMI the wind profiles are produced using the well-established Volume Velocity Processing (VVP) algorithm (Waldteufel and Corbin, 1979; Holleman, 2003, 2005). The international exchange of weather radar wind profiles is strongly increasing due

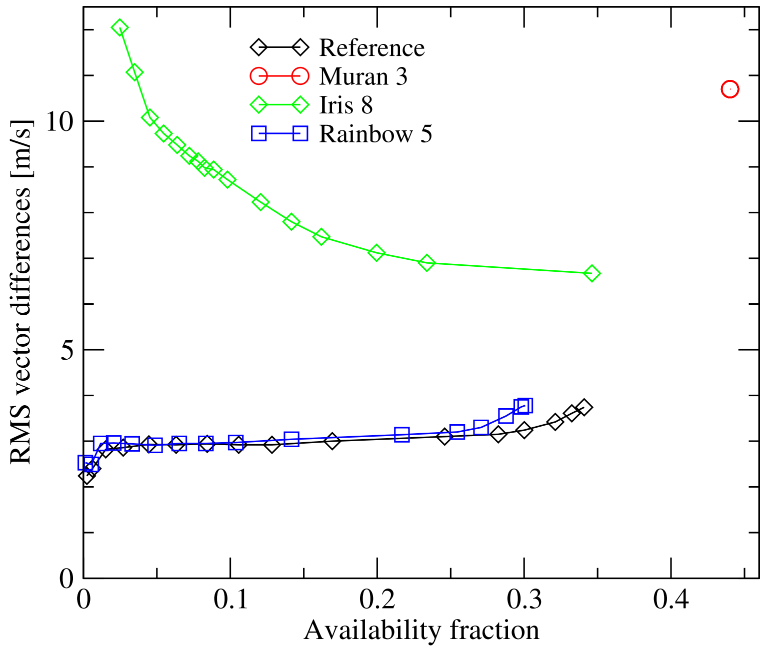


Figure 4.4: The rms vector differences between radar (Reference, Muran 3, Iris 8, Rainbow 5) and Hirlam wind vectors as a function of the availability fraction of the radar wind vectors are shown in the figure. The availability fraction is varied by changing the standard deviation threshold (if available). Wind vectors between 0 and 6 km altitude collected between 1 May 2005 and 30 June 2005 are used to compile this figure.

requirements from the Numerical Weather Prediction community, see for instance Rossa et al. (2005). The wind profiles from the different radar product processors have been evaluated by comparing approximately two months (May and June 2005) of radar data with the corresponding profiles from the Hirlam Numerical Weather Prediction model Unden et al. (2002).

In figure 4.4 the rms vector differences between the weather radar wind profiles and the Hirlam profiles are plotted as a function of the availability fraction for the three radar product processors (Muran 3, Iris 8, and Rainbow 5) and the reference (Rainbow 3). Currently, the weather radar wind profiles are produced operationally at KNMI using the Rainbow 3 package (Gematronik, 2003). The availability fraction of the retrieved wind vectors is varied by changing the threshold on the radial velocity standard deviation. Increasing this threshold from 0.5 to 5 m $s^{-1}$, the availability fractions and rms vector differences of the reference data increase from 0 to 0.33 and from 2.2 to 3.6 m $s^{-1}$, respectively.

Figure 4.4 shows two important aspects of the wind profile retrieval meth-

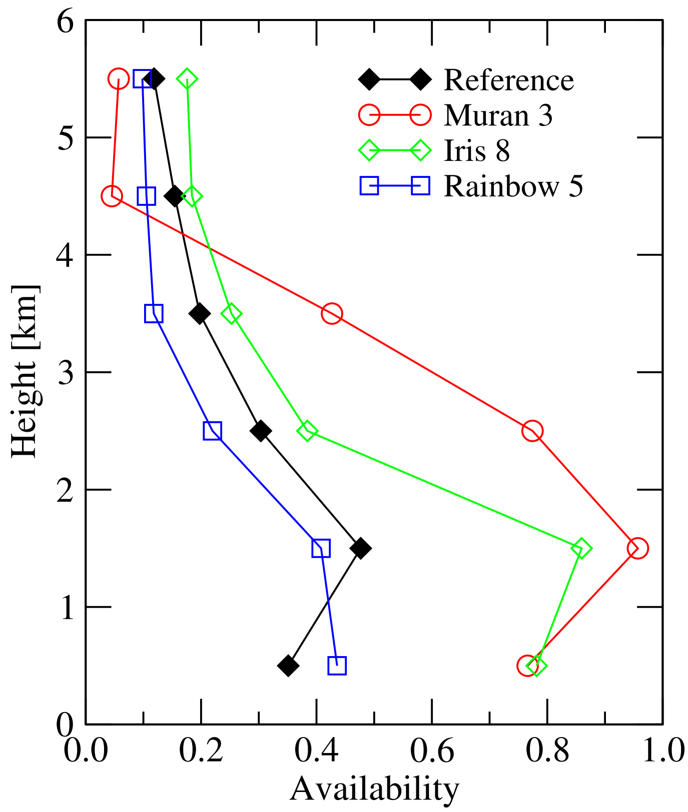


Figure 4.5: The availability fraction of wind vector data is shown as a function of height for the different product generation packages. This figure has been compiled using 2 months of data and a standard deviation threshold of 2.0 m $s^{-1}$ (for Rainbow data).

ods: quality and availability. Wind profiles that combine high quality (low rms vector differences) with high availability are preferred. It is evident from the figure that the performance curves of the Rainbow 5 profiles and the reference data (Rainbow 3) are rather similar. Moreover these performance curves are closely resembling those in figure 4.4 of Holleman (2003) in which 20,000 vectors pairs correspond to an availability fraction of 0.35. During the analysis of the Iris 8 wind profiles it was found that the data contained a certain fraction of vectors with an extremely high wind speed, i.e., $>$100 m/s. It was not possible to remove these outliers based on the Iris quality indicators, and therefore wind speeds that are 10% higher than the unambiguous Doppler velocity (48 m/s in our case) have been removed from the Iris profile data prior to further analysis. For the (quality controlled) Iris 8 profiles a completely different performance curve is still observed. The rms vector differences are much larger (>6 m/s) and they increase when the availability fraction is decreased. This suggests that the radial velocity standard deviation provided by Iris is not a good quality indicator which is most likely due to insufficient quality control during the wind profile retrieval, e.g. no second regression after removal of outliers. For the Muran 3 profiles it is not possible to change the availability fraction because the radial velocity standard deviation is not saved and thus only a single point is plotted in figure 4.4. From the figure it is evident that the Muran profiles combine a high availability with a rather poor quality.

In figure 4.5 the availability fraction of the wind vectors is plotted as a function of height for the different radar product processors. All available wind profiles (2 months) and a standard deviation threshold of 2.0 m $s^{-1}$ for Rainbow 5 and the reference have been used to calculate these fractions. Especially in the boundary layer, the availability of the Rainbow 5 and reference profiles is (much) lower than that for the Iris and Muran profiles. Between 1 and 2 km altitude the availability fraction of the Muran profiles is approaching unity implying that hardly any quality control is performed.

Figures 4.6 and 4.7 show the bias and standard deviation of the wind speed and direction for the different radar product processors and the reference as a function of height. These quality measures have been obtained from verification against the Hirlam profiles over May and June 2005. The results for Rainbow 5 and the reference (Rainbow 3) are shown in figure 4.6. For both product processors and all heights, the wind speed bias is slightly positive ($\approx 1$ m/s) and the standard deviation of the wind speed is around 2 m/s. This positive bias for the Rainbow wind speeds is most likely due to the rejection of radial velocities below 2 m/s (Holleman, 2003, 2005). The wind direction bias for the reference and Rainbow 5 profiles is small (<2 degrees) at all heights. The standard deviation of the Rainbow wind directions is slowly decreasing from roughly 25 degrees at low altitude to about 15 degrees at the highest altitude. The wind direction is determined from the ratio of the horizontal wind field components and this ratio has a larger error for lower wind speeds which are more common at low altitudes. These results are in good agreement with those presented in Holleman (2003, 2005).

The verification results for the Iris 8 and Muran 3 wind profiles are shown in figure 4.7. Note that the horizontal scales of this figure are quite different from those in figure 4.6. For the Iris profiles a wind speed bias and standard deviation are increasing from $-1.9$ m/s and 3.2 m/s to $+2.3$ m/s and 4.9 m/s, respectively, with increasing height. The wind direction bias of the Iris profiles is mostly negative and relatively small ($< 5$ degrees). The corresponding standard deviation is 60 degrees at low altitudes and drops to about 25 degrees at a height of 6 km. The quality of the Muran wind profiles is considerably worse. The observed biases are comparable to those for the Iris wind profiles, but the observed

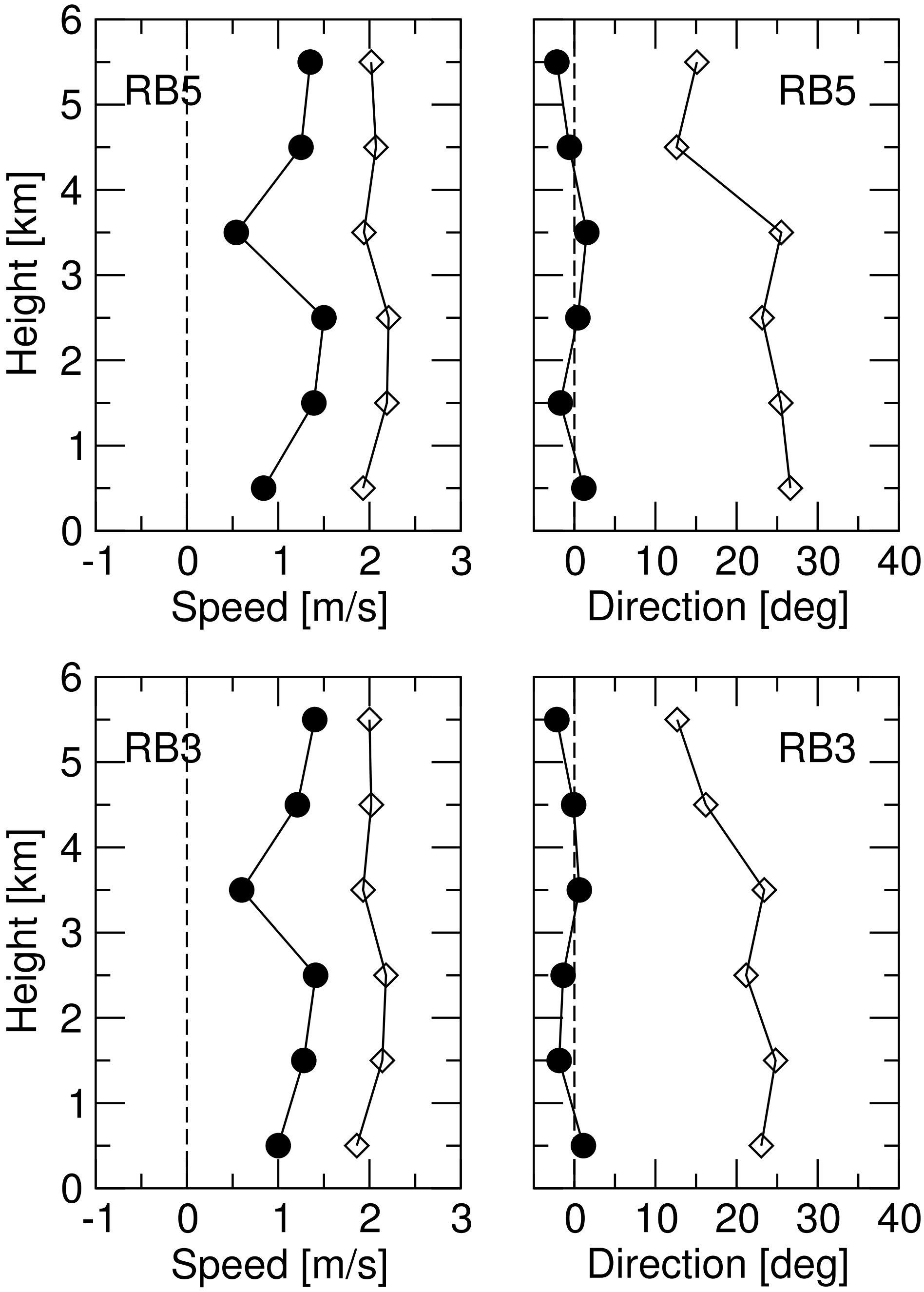


Figure 4.6: Profiles of the bias (•) and standard deviation (⋄) of the wind speed and direction from the verification of the reference (top frames) and Rainbow 5 (bottom frames) wind data against Hirlam.

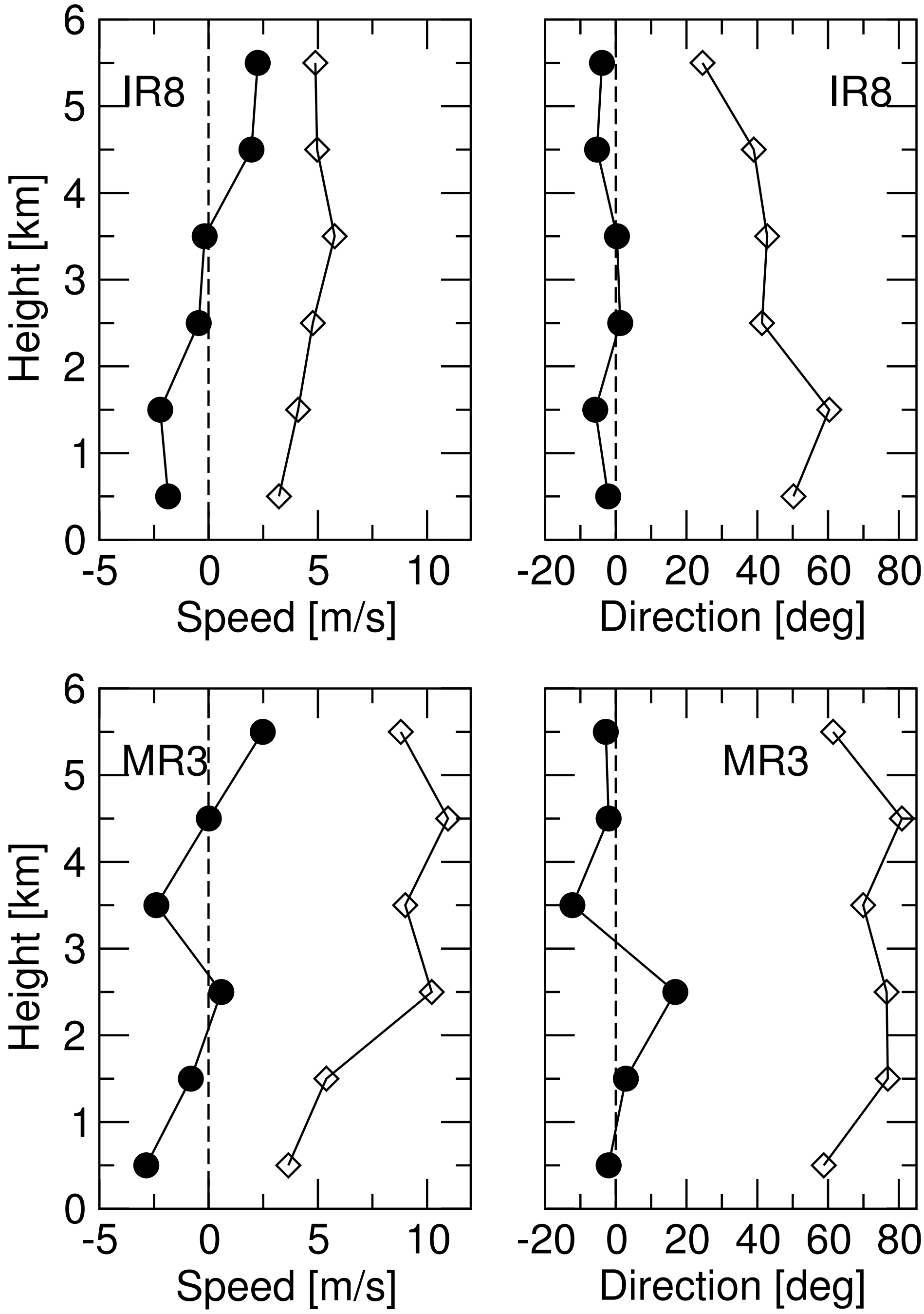


Figure 4.7: Profiles of the bias (•) and standard deviation (◇) of the wind speed and direction from the verification of the Iris 8 (top frames) and Muran 3 (bottom frames) wind data against Hirlam.

standard deviations are clearly much larger. The standard deviation of the Muran wind speeds varies between 3.7 and 11 m/s and that of the Muran wind directions between 60 and 80 degrees. The observed quality of the Iris and Muran wind profiles is considerably lower than that of the Rainbow wind profiles. Taking into account the results of figure 4.4, it is clear that a different balance between quality and availability is chosen in the Iris product processor and that even basic quality control is lacking in the Muran wind profile product.

# Chapter 5

# Summary and conclusions

In light of the planned technical upgrade of the KNMI weather radars, an evaluation of three different radar product processor packages has been performed. For this evaluation the Muran 3, Iris 8, and Rainbow 5 packages have been installed on separate Linux workstations and connected to the real-time dataflow of volume datasets for the weather radar in De Bilt. A number of software modules for conversion of the operational dataflow, i.e., Rainbow 3 volume datasets to the native formats of the radar product processors and for the conversion of the native output formats to the KNMI HDF5 image format, have been developed in collaboration with the manufacturers. The different radar product processors have been acquiring data for about two months, starting 1 May 2005 and ending 30 June 2005, and an archive has been built containing the processed data as well as the original volume datasets. First of all, a general evaluation of the radar product processors was performed in which the configuration, the operational stability, the geographical projection module, the product algorithms, file formats, and documentation were assessed. Subsequently the output of two distinct products, the pseudoCAPPI product and the weather radar wind profiles, has been analyzed in detail.

It turns out that the operational stability is very good for all radar product processors and that all processors are capable of generating the products that KNMI requires. Unfortunately, the geographical projection module of Iris cannot handle the standard geographical projection of the KNMI radar products (see Appendix A). The configuration of the Muran and Rainbow packages was straightforward but the configuration of the Iris package was rather tedious. The documentation provided with the Rainbow 5 and the Iris packages is at a high level, but that of Muran is rather incomplete. Finally, the analysis of the pseudoCAPPI output revealed minor problems with all three packages and the analysis of the wind profile output revealed huge differences in quality and availability. The results from the general evaluation (6 items) and product evaluation (2 items) of the

Table 5.1: Summary of the general evaluation and product evaluation of the product generation packages.

| Item | Muran 3 | Iris 8 | Rainbow 5 |
|---|---|---|---|
| Configuration | + | − | ++ |
| Operational stability | + | ++ | + |
| Geographical projection | 0 | −− | ++ |
| Products | 0 | 0 | ++ |
| File format | + | 0 | + |
| Documentation | − | ++ | + |
| PseudoCAPPI | 0 | + | + |
| Wind profiles | −− | 0 | ++ |

three radar product processors have been summarized in table 5.1. All in all, it is evident that the Rainbow 5 package of Gematronik GmbH fits the requirements of KNMI best and that a transition from the current Rainbow 3.4 package to the new Rainbow 5 package would be relatively smooth

## Acknowledgments

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# Appendix A

# Geographical projection of KNMI radar images

In this appendix the details of the geographical projection of the KNMI radar images, both single site data and the national composite, are listed. The radar images are projected according to a stereographic projection with the north pole in the projection origin. A stereographic projection also uses a so-called alignment meridian (Greenwich) which is equal to the longitude of the projection origin and a latitude of true scale (60N). The stereographic projection is a conformal projection which implies that the angles are conserved during the projection. The meridians are projected into straight lines starting from the north pole and latitude circles are projected as circles centered at the north pole. It is important to stress that the KNMI radar images are projected using an ellipsoid earth model (Hayford). This makes the projection equations substantially more complex, but it enables a more accurate overlay of the radar echoes with the topographical data. The parameters of the geographical projection of the KNMI radar images are listed in the table below:

| Parameter | Value |
|---|---|
| Projection | Stereographic |
| Projection origin (lon,lat) | 0E, 90N |
| True scale (lat) | 60N |
| Earth radius (equator,polar) | 6378.388 km, 6356.912 km |
| Pixel size at true scale (x,y) | 2.500 km, −2.500 km |
| Offset of image corner (i,j) | 0.0, 1490.9 |
| Number of rows | 256 |
| Number of columns | 256 |

The geographical projection of the radar data from the azimuthal equi-distance projection (“radar projection”) to the polar stereographic projection can be done using the “proj.4” library (Evenden, 1990). This library has been developed at the USGS and is used world-wide in numerous applications. The geographical projection of the KNMI radar images is described by the following “proj.4 string”:

```
"+proj=stere +x_0=0 +y_0=0 +lat_0=90 +lon_0=0 +lat_ts=60 +a=6378.388 +b=6356.906"
```

After the geographical (re)projection the resulting image only has to be scaled and shifted linearly using the given pixel sizes and offsets of the image corner. The pixel size in $y$-direction is negative because the images lines are plotted from north-to-south and the $y$-axis is pointing in the opposite direction. The projection parameters define the geographical corners of the KNMI radar images. The corners of the KNMI radar image are:

| Corner | Lon [deg] | Lat [deg]) |
|---|---|---|
| north-west | 0.000E | 55.296N |
| north-east | 9.743E | 54.818N |
| south-east | 8.337E | 49.373N |
| south-west | 0.000E | 49.769N |