MIRA-35

Meteorological Ka-Band Cloud RADAR

System Description

Fig. 1: MIRA-35 with scanning unit mounted on top of an enclosed trailer. The radar components and the antenna (here: ∅ 1 m) are mounted on a two-axis positioner.

(Pls. note that this system description includes some optional parts which possibly are not part of an ordered system).

1 General

MIRA-35 is a magnetron based pulsed Ka-Band Doppler radar for unattended long-term observation of atmospheric clouds and fog. In its standard configuration linear polarized signal is transmitted while co- and cross- polarized signals are received simultaneously to detect Doppler spectra of the reflectivity and the Linear De-polarization Ratio (LDR). The reflectivity is used to determine the density of cloud constituents while LDR helps to identify the target type. By rotating the antenna by 45 degrees MIRA35 can be operated to retrieve the Slanted Linear De-Polarization Ratio (SLDR). Alternatively, MIRA-35 can be also configured for operating in "Simultaneous Transmit and Simultaneous Receive" mode (STSR). In order to switch between the different operation modes, the hardware configuration needs to be changed by the operator in a procedure described in a manual delivered with the system.

In figure 2 the vertically pointing version of MIRA35 is shown. The main components of the radar as shown in the left of figure 2 from top to bottom are:

- Cassegrain antenna 1.2 m
- Receiver
- Transmitter
- Radar-PC
- Keyboard, mouse, display
- UPS
- Waveguide drying and pressurization system.

Fig. 2: Samples of vertically pointing cloud radar MIRA-35 installed in an outdoor enclosure for vertical pointing (left) and in an outdoor enclosure with positioner on top (right). In both enclosures the radar components are installed in a 19" rack and are operated in a temperature controlled or air-conditioned environment.

In the outdoor enclosure as shown in figure 2 (left) an air-to-air heat exchanger is used. The outdoor enclosure figure 2 (right) hosts an air conditioning unit. For the scanning version of the MIRA-35 all radar components including transmitter, receiver and waveguide drying and pressurization system are installed on a scanning pedestal (positioner) mounted on top of the outdoor enclosure (see figure 2 right).

The total weight of the positioner including the antenna and the radar components is approx. 400 kg. The air conditioning and the radar PC are housed inside the supporting outdoor enclosure.

2 Antenna

The antennas have a diameter of 1,2 m and are of Cassegrain type. A circular horn feeds the linear polarized transmitting signal upwards to the contra reflector from where it is reflected to the main dish. A polarization splitter (orthomode transducer) is mounted inside the tube of the antenna feed as close as possible to the horn feed to keep losses as low as possible. The cover of the feed is shaped to minimize degradation of the cross-polarization decoupling by water drops. The circular feed is covered hermetically. The waveguides connecting magnetron and feed (including circulator) are pressurized by dry air from an automatic dehydrator. This is needed to allow the high pulse power of the magnetron transmitter. It also prevents corrosion in the waveguides.

For a vertical beam ground clutter is only observed in the range gates below ~ 1000 m (depending on the environment). Such ground clutter can be removed by software which causes almost no degradation of the meteorological signal. Extra clutter fences will be delivered for both systems in order to reduce efficiently side lobes at angles greater than 60 deg with respect to the main beam direction. For suppressing diffraction to horizontal direction, the clutter fences are lined on the inner side with a metallic reflector tape with a spiky rim on its upper side and further with weatherproof absorber material.

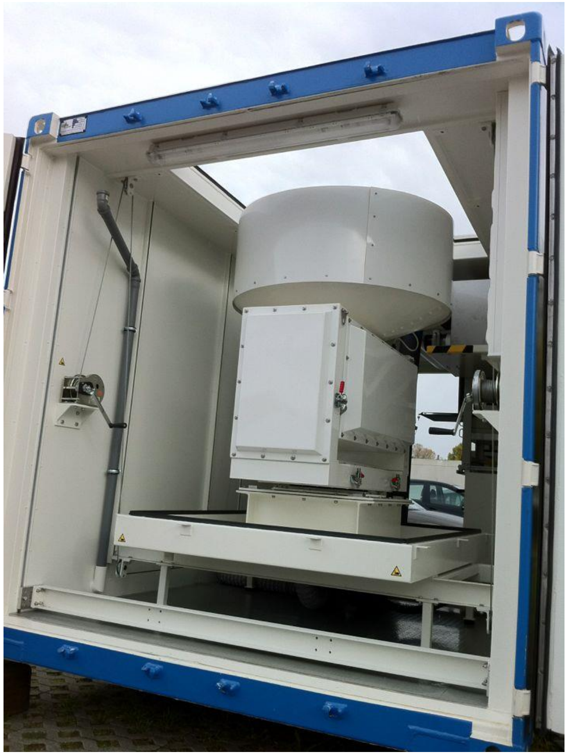

Fig. 3: Antenna with clutter fence mounted on positioner in a sea container with sliding roof top.

A regulated optional heating will be installed below the antenna dishes to prevent degrading of the beam shape and polarization decoupling in case of ice and snow. Rainwater or melting water are conducted through drainage holes in the center of the antenna dishes.

3 Transmitter

The transmitting signal is generated by a magnetron providing a max. pulse power of approx. 30 kW with pulse lengths adjustable to 100, 200 or 400 ns at duty cycles up to 1/500. Due to the high pulse power a very fine range resolution is possible without using pulse compression technique.

The guaranteed magnetron lifetime is one year. Lifetimes of more than 5 years of continuous operation have been reached regularly with several systems which still do not show any degradation or aging effects.

According to the ECC requirements magnetron frequency is adjusted to 35.1 GHz. Depending on pulse width, pulse repetition frequency and temperature the magnetron frequency may deviate up to 80 MHz from the nominal frequency. The local oscillator of the receiver automatically adjusts to the actual magnetron frequency avoiding any loss in radar performance.

In case that future telecommunication regulations do require even a closer match between the actual and the nominal frequency, it is possible to adjust the magnetron frequency mechanically. An automatic mechanical adjustment can be developed on request.

The transmitter is mounted in a 19" rack-mount enclosure with a height of 9U (1U = 1.75 inch). It includes magnetron, modulator, high voltage power supplies, pulse driver, filament power supplies and controllers for operating and protecting the hardware.

4 Receiver

The receiver has two channels, one for the co- and one for the cross-channel (V- and H- channel in case of STSR configuration). Couplers for the direct and the reverse wave are integrated in the receiver. These couplers allow continuous monitoring of the transmitting power and the antenna reflection (VSWR). The low noise amplifier (LNA) at the input of each receiver channel is protected by a chain of PIN modulators.

The amplified signal of each channel is down converted in two steps. Depending on the magnetron frequency the first mixer converts the signal to (1100 +/- 100) MHz. The frequency of the local oscillator of the second converter adjusts automatically so that the receiving signal is converted to (281.25 +/- 3) MHz. The noise of the image band is reduced in both conversions by band pass filters.

The 281.25 MHz signals of both receiver channels (co- and cross-channel) are processed by a digital receiver. This approach eliminates DC bias and Doppler image problems caused by the I-Q phase detectors. The signals of both receiver channels are digitized by two 125 MHz/16 bit ADCs.

Although the ADCs have a dynamic range of 80 dB (LTC2218) they are the bottle neck in the dynamic range of the receiver. To overcome saturation in the lower ranges without losing sensitivity for higher clouds a 15 dB attenuation device for altitudes below 1500 m can be switched on (STC-mode). The STC-mode can be activated by setting a receiver parameter or by automatic gain control.

The receiver is mounted in a 4U 19 " rack-mount enclosure. It includes all the receiver components including the digital receiver and the main controller which arbitrates between the controllers of all the radar modules and the PC.

5 Doppler Technique

The Doppler capability of MIRA-35 utilizes a “coherence-on-receive” technique. Signal from the transmitted pulse is coupled into the co-channel receiver. From this signal the phase of the transmitted pulse is measured and used for correcting the receiving signal. Typically, a Pulse Repetition Frequency (PRF) of 5 kHz is used and the signal of 256 pulse cycles is processed by one FFT per range gate. In this mode the un-ambiguous velocity range is +/- 11 m/s, the velocity resolution of the spectra is 0.08 m/s, and the minimal temporal resolution is 0.05 s (no incoherent averaging). Due to the high pulse-to-pulse frequency stability of the transmitter and the quality of the phase correction the spectra of fixed echoes are almost concentrated to the FFT line at zero-velocity even if the finest velocity resolution of 0.01 m/s is selected (PRF=2.5 kHz and NFFT=1024).

With incoherent averaging velocities can be estimated with even higher accuracy than given by the FFT resolution.

6 DSP

The digital receivers including FFT-processing, noise floor detection, and moment estimation (power, Doppler velocity, and Doppler spread) are implemented in a MicroBlaze based FPGA. All processing can be performed for 2*800 range gates (co- and cross-channel) without skipping any sampled data even if no spectral averaging is selected. The moments with the spectra or raw I-Q data are passed to the PC via gigabit Ethernet.

7 PC

A PC mounted in a 1U 19” rack-mount enclosure performs the following tasks:

- Reading the data from the signal processor via Ethernet
- Saving the data to hard disk
- Making the more elaborate data processing like target classification
- Communicating to the radar hardware via Ethernet
- Providing the network service for control and data clients

(see section Software below).

The radar-PC is operated under Linux. Network clients as GUI and command line interface for controlling the radar and for viewing radar data are provided for Windows, Linux, and Mac.

8 Built in Test Equipment (BITE)

Each module of the radar electronics (transmitter, high voltage power supply, modulator power supply, receiver, LO frequency controller, scanning controller) is equipped with a microcontroller with analog and digital in- and outputs for controlling the operational mode and for providing diagnostic information. If the values of any diagnostic parameter are outside the allowed ranges, the radar operation is stopped automatically to prevent damage.

Once per second approximately 50 measured parameter values are transmitted to the radar PC and saved in a log file which simplifies troubleshooting. The BITE data are analyzed continuously, and e-mail warnings are sent out automatically in case of suspect parameters.

9 Calibration

A permanent on-line calibration system is included in the radar. A fraction of the transmitted signal is coupled to a thermistor detector to monitor the average transmitting power (=peak power x duty cycle). The receiver calibration can be derived by two alternative methods:

- The receiver noise is measured at the end of each pulse cycle after the TR-switch has opened. This noise corresponds to the thermal noise produced by a matched load multiplied by the total noise figure of all receiver components. It is determined by the receiver bandwidth, the noise figure and the losses on the receiving path. As all these quantities can be determined accurately and the sum of their values is constant within +/- 0.3 dB the thermal noise can be regarded as a calibration source with known absolute power.

  If the amplification of the receiver is reduced to prevent saturation in case of heavy rain the effective noise figure of the receiver is increased. In such situation the "receiver noise based" calibration cannot be used.

- At the end of each pulse cycle (i.e., after the receiver noise measurement) and after the PIN modulators of the TR switch are opened, the signal from a reference noise source is introduced at the TR-switch. The power determined in the reference noise gate can be used for receiver calibration in all situations (even with horizontally tilted beam and rain). The power of the reference source can be determined by the first calibration method during no-strong-rain situations when it works correctly.

Both calibration methods are adjusted during system testing with help of an external calibrated noise source.

10 Radiometric Measurements

Although MIRA-35 is a radar the radiometric emission of rain, liquid water clouds, and fog can be observed in the radar data due to its synchronous calibration system and due to its very sensitive receiver. The equivalent radiation temperature of the clear sky at 35.1 GHz is about 50 K. During heavy rain it is close to the temperature of the rain (~280K). This causes the noise in the receiving spectra to be about 1 dB higher during heavy rain than during clear sky measurements (this radiometric noise is observed in all range gates as it is not correlated to the transmitting pulse).

The variations in this noise can be monitored with high accuracy as the noise floor of all range gates which have a signal to noise ratio of less than ~ 20 dB can be averaged. The receiver stability which is needed for such measurements is achieved by relating the averaged noise floor taken while the receiver is connected to the antenna to the receiver noise taken while the receiver is disconnected from the antenna by the TR-switch.

11 Examples of Data

In Fig. 6 a screen shot of the "data client" is shown. This easy-to-use program is provided to visualize the currently measured data. The following plots can be selected:

- Profiles of the SNR = power
- Profiles of the radial velocity
- Profiles of the RMS = Doppler spread
- Profiles of the ratio of the power from co- and cross-polarized signal (LDR)
- The spectrum of a selected range gate.

All plots can be displayed as 2D-representations showing the newest profile and as color coded time/height cross sections showing the 256 most recent profiles. Each time an averaging cycle is completed the new profiles are shifted from the left into the color-coded plots. The newest spectra are shifted to the top of the image. Additionally, color coded PPI and RHI displays are available.

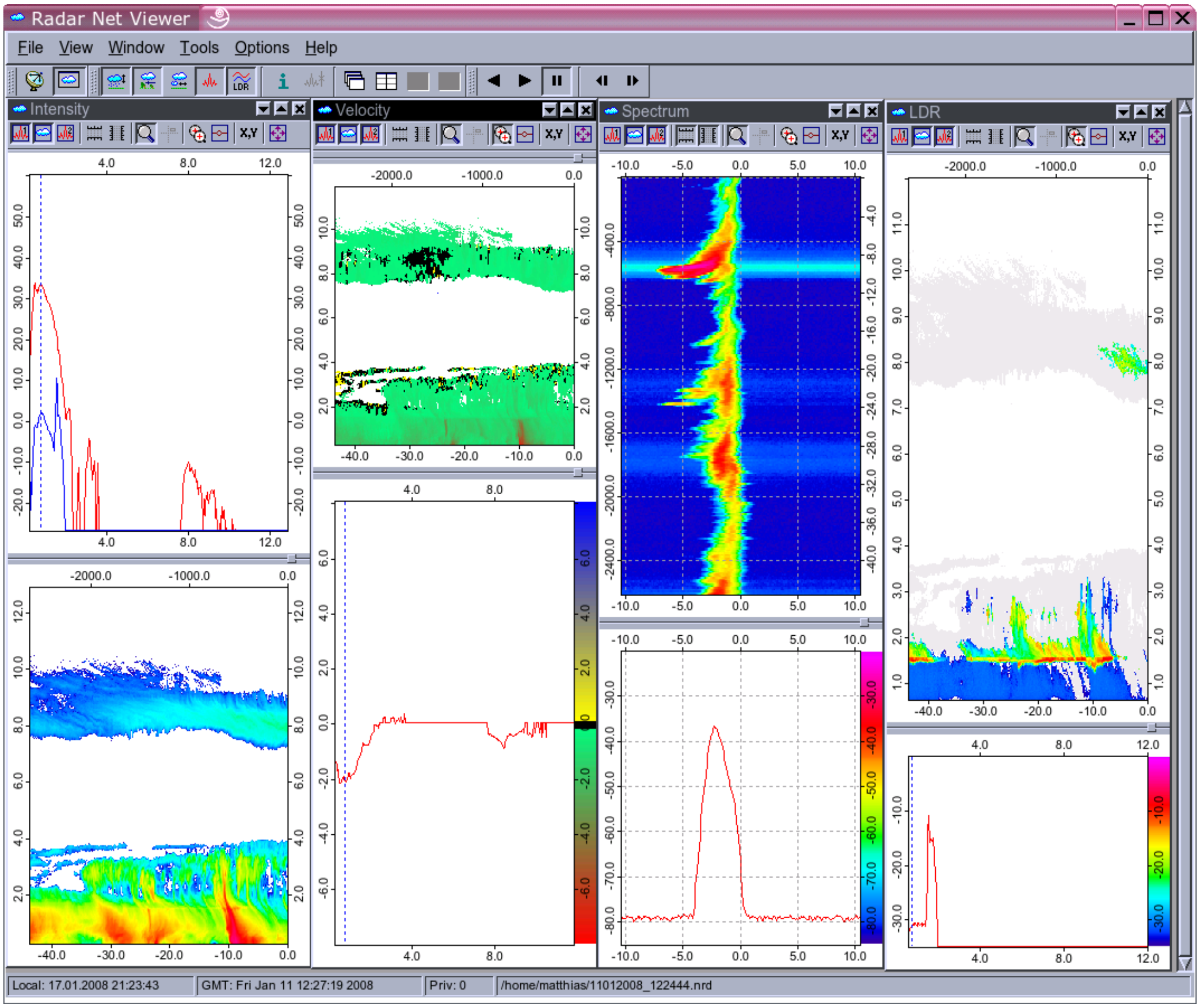

Fig. 4: Screen shot of the data client. From left to right:

- Signal to noise ratio [dB]
- Doppler velocity [m/s]
- Spectrum of one selected range gate [dB] (height as indicated by the dotted line in the other plots)
- LDR [dB]. The color-coded plots show height-time cross sections of the most recent 45 minutes. (The 2D plots show the most recent profiles, co-channel in red and cross-channel in blue.)

The peak at 1400 m in the LDR profile and less pronounced in the SNR profile is caused by the melting layer. This can also be recognized by observing the fall speeds below and above 1500 m (when no speed could be detected the velocity is set to the default zero).

The spectra show a limitation for the “in spectrum dynamic range” (ISDR). In range gates where strong signal is received the noise floor of the spectra is raised. The limitation of the ISDR is caused by the pulse-to-pulse frequency variations. ISDR is 55dB for ground clutter and 45dB in the example above due to the broader spectral distribution.

12 Software

12.1 Radar Server

The radar server is the core of the radar operation and monitoring. It is installed as a service on the radar PC and performs the following tasks:

- Communicating over Ethernet with the MicroBlaze controller which communicates to the controllers in the transmitter and receiver units.
- Reading saving the BITE data from the MicroBlaze controller.
- Reading the processed radar data (spectra and moments) from the DSPs and writing them to files.
- Providing a service which allows to connect the control and data clients via TCP/IP.

12.2 GUI Control Client

The radar operation can be controlled by a convenient GUI tool available for Windows, Linux, and Mac OS. This control client may be run on any PC which is connected to the radar PC by network or on the radar PC itself. It performs the following tasks:

- Switching the radar components on and off.
- Setting system parameters like the pulse width, the FFT size and others.
- Observing and visualizing the BITE parameters like magnetron current or local oscillator frequency.

12.3 Text Oriented Control Client

Alternatively, the radar can be controlled by text based “server commands” which can be sent to the radar server by a simple command line interface. For instance, these server commands can be used for scheduling different operational modes by cron jobs. With help of the GUI client the server commands needed to perform certain operations can easily be learned.

12.4 GUI Data Client

The data client is an easy to use GUI tool for visualizing the radar data. A screen shot of the data client is shown above in Fig. 4. Data clients can be run on any PC having a network connection to the radar PC and it is also available for Windows, Linux, and Mac OS. Both GUI clients can be used even if the network connection is very slow.

12.5 Visualization

IDL programs for analyzing and plotting the meteorological and the BITE data are provided as source code (IDL is provided by exelisvis.com). These programs are command line controlled so they can be used for automated procedures like hourly creation of pictures for presenting the data on a web page. Many features like generating movies from sequential RHI images are available. A time height cross section produced by this program is shown in Figure 5.

12.6 Software for Target Classification

IDL Programs for multi peak detection and peak classification are provided (pls. refer to the “Extended Abstract of the 33rd Conference on Radar Meteorology”). These programs can be operated in real time on the radar PC if spectral averaging is greater than 1 s.

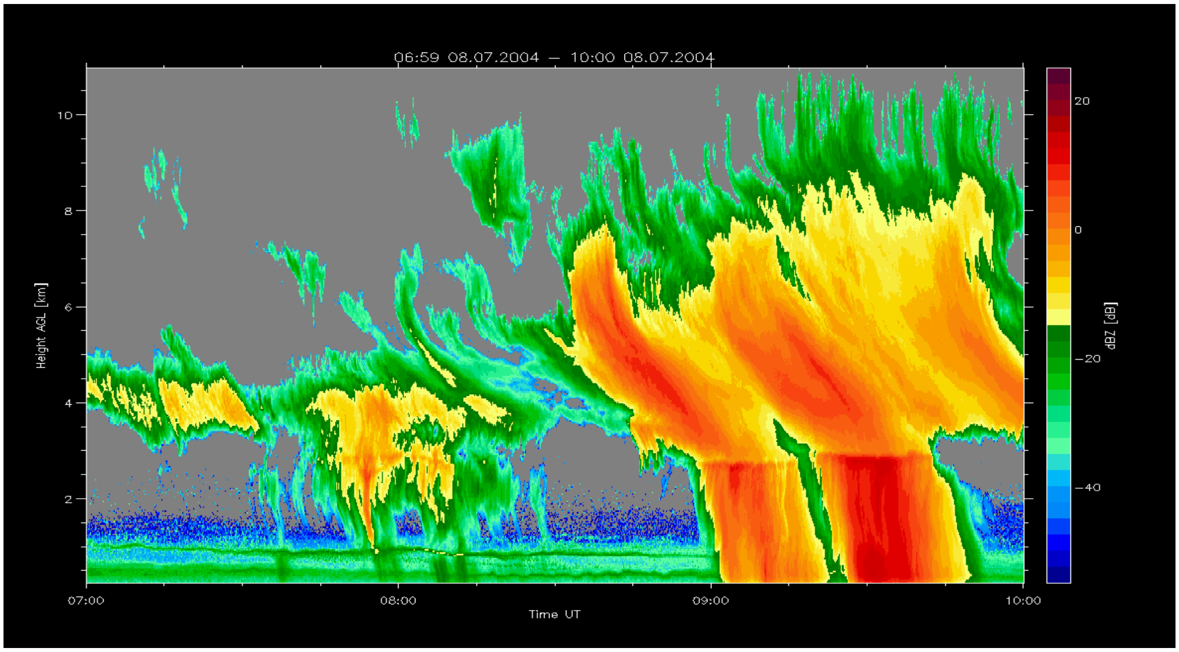

Figure 5: Time height cross section of the reflectivity / dBZ plotted by viewpds

12.7 Data Saving

The speed of the data link between the MicroBlaze DSP and the radar PC is fast enough to allow saving the raw I-Q data or the un-averaged power spectra. In this case the data rate is very high. Such amount of data is usually stored only for testing purpose.

Data Rate = 2*bpIQ * zchan * zrg * PRF < 80 Mbyte/s

with

bpIQ = bytes per I or Q value = 2 Bytes
zchan = 2 (co and cross channel)
zrg = number of saved range gates < 800
PRF = pulse repetition rate < 10 kHz

The raw I-Q data or spectra from the DSP are saved in a documented binary format. Programs are available for converting them to NetCDF which makes the files much easier to extract.

Because meteorological data is caused by the interference of the signals from many targets with statistical phases the un-averaged spectra have a large statistical noise. To reduce this noise before signal/noise thresholding and moment estimation the power spectra are averaged. With the standard settings of PRF=5000 Hz and NFFT=256 about 20 spectra are generated per second. So, averaging the spectra for 2 s reduces the amount of data by 40, which is still 7 GBytes per hour.

By saving only the parts in the spectra where signal is above the noise threshold the size of the resulting compressed spectra is reduced by a large factor depending on cloud coverage and Doppler spread. Even during heavy rain and clouds with large vertical extend this compression reduces the spectra size by a factor of 50. Such compressed spectra can be saved in an efficient binary format or in NetCDF format by replacing the noise floor of each spectrum by the constant noise floor level and making use of the gzip feature of NetCDF version >= 4, which makes extracting the spectra much easier. Programs for converting between both formats and off-line processing (ground clutter filtering, moment estimation, target classification) of both formats are in the radar software package.

For many applications it is sufficient to save the moments of the peaks in the spectra instead of their shape which can be regarded as further data compression. The radar software calculates the following “moments”:

- 0^{th} moment, radar reflectivity factor Z
- 1^{st} moment, radial velocity
- 2^{nd} moment, Doppler spread
- 3^{rd} moment, skewness
- 0^{th} moment of the cross-channel / 0^{th} moment of the co-channel, LDR
- Differential phase between the signals in the co- and cross channel, DPS
- Phase-correlation between the signals in the co and the cross channel, RHO_LDR

These moments are saved in NetCDF format.

12.8 Technical Data

Radar type	mono static, pulsed, magnetron
Frequency	35.1 GHz +/- 100 MHz
Peak power	30 kW
Duty cycle	1:500 max; 1:1000 typically
Pulse width	100, 200 or 400 ns according to 15, 30, and 60 m range resolution
Minimum height	Typically, 100 … 150 m, (full sensitivity …- 6 dB) above 300 m, full sensitivity above 450 m
Maximum height	Is limited by the pulse repetition frequency (PRF) 0.5*c*(1/PRF-8 µs), 8 µs due to calibration e.g. for PRF=5 kHz max. height = 28.8 km. The max. number of range gates is 2*800 (two polarizations)
Pulse repetition frequency (PRF)	2.5 … 10 kHz according to a velocity un-ambiguity of 11 – 42 m/s
FFT length	128, 256, 512, 1024 With PRF=5kHz this corresponds to 16cm/s…2cm/s Doppler speed resolution.
Number of spectral averages (nave)	1 to 1000 corresponding to a time resolution of nave*nfft/PRF
ADC for sampling the 280 MHz IF signal	125 MHz / 16 Bit / digital receiver
Instantaneous receiver dynamic range	80 dB See STC-Mode
Antenna type	Cassegrain
Antenna diameter	1.2 m (2 m only on special request)
Antenna beam width (6 dB/two-way)	0.6° x 0.6° for the 1.0 m antenna 0.5° x 0.5° for the 1.2 m antenna 0.3° x 0.3° for the 2.0 m antenna
Antenna gain	49.0 dB for the 1.0 m antenna 50.2 dB for the 1.2 m antenna 54.6 dB for the 2.0 m antenna
First side lobe	< -20 dB for the 1 m antenna < -19.5 dB for the 1.2 m antenna < -20 dB for the 2 m antenna
Polarization de-coupling ICPR = LDR detected in case of spherical targets	< -30 dB for the 1 m antenna < -28 dB for the 1.2 m antenna < -28 dB for the 2 m antenna
Noise figure of the receiver	3.3 dB (LNA) + 2.5 dB (T-R-switch) + 0.4 dB (circulator), 0.3 dB (couplers and flanges) = 6.5 dB (total noise figure receiver input)

Sensitivity with 1.2 m antenna, prf = 5 kHz, pulse width = 200 ns, nfft=256, averaging time 10 s, see "theory of data processing"	-53 dBZ at 5 km -67 dBZ at 1 km (with 400 ns pulses 6 dB better sensitivity)
Magnetron lifetime	> 1 year guaranteed, normally much longer
Dimensions and weight (approx.)	transmitter: 19" 9 U, 28 kg receiver: 19" 4 U, 16 kg PC: 19" 1 U, 10 kg air drying system: 19" 2 U, 12 kg UPS 19 " 2 U, 28 kg Positioner (option): 276 kg antenna: diameter = 1.25 m, height = ~48 cm, ~30 kg and ~38 kg including heating The outdoor enclosure, positioner and antenna will be designed to fit in a 20 ft. high cube sea container for shipping.
Power consumption	Radar: 950 W at 1/500 duty cycle 600 W at 1/1000 duty cycle PC: 150 W Air dryer: 55 W max incl. pressurization Components above are supplied by an UPS which has a maximal power consumption of 16 A while charging. Antenna heating: on demand, typically 1200 W Air conditioning / heating installed in the trailer: 1000 W max (2000 W max in case of the scanner) The power line must always provide a voltage of 230 VAC +10% … -15%.
Positioner	Scanning range: azimuth 0 … 360°, with continuous rotations elevation -1° … +181° Scanning speed: azimuth 20°/s elevation 20°/s Accuracy: 0.1°

Table 1: Technical data of the cloud radar MIRA-35