Monitoring of weather radars: lessons learned from WXRCalMon17 & WXRCalMon19, and recommendations

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Following sections were amended or added:

- Introductions: reference to WXRCalMon2019
- Amendments to “Definitons” p. 3ff
- Include section on “Continuous stability of radar system”, p.11
- Amendments to the section “Sun”, p. 12
- Amendments to the section “Ground Clutter and “bright” scatterers”, p 13
- New Chapter on “WXRCalMon 2019” p.16 ff
- References have been updates extensively, p25

Inhalt

Introduction

With the introduction of polarimetric radars and the increased demand for accurate radar data for quantitative applications, all meteorological services have started to work on monitoring systems in order to meet the demands on data quality and availability. Aside from more standard engineering methods, additional monitoring methods have been established to make use of external data sources which allows an end-to-end characterization of a radar system performance (Atlas, 2002, Tapping, 2001, Huuskonen and Holleman, 2007, Holleman et al, 2010, Figueras et al, 2012, Frech, 2013, Huuskonen et al., 2014, Frech et al., 2017, Richardson et al. 2017, Hubbert, 2017, Gabella 2018). A recent comprehensive paper on how to calibrate a weather radar by Chandrasekar et al (2015) provides a very thorough introduction on the topic of calibrating a radar, and, to some extent, what should be monitored.

In this document we do not intent to duplicate or rewrite existing work. Based on the presentations and discussion of the WXRCalMon 2017 & 2019, we rather want to provide a framework and some basic definition on terminologies so that everyone has a common understanding what is meant with "monitoring". This paper is addressed towards organizations that manage an operational weather radar network. It aims at providing recommendations on monitoring methods that are needed in order to verify agreed target accuracies of radar moments and their accurate geo referencing. Monitoring methods provide an objective approach to identify issues of a radar system and to provide guidance on how to adjust or eventually re-calibrate a radar system, or to initiate a preventive maintenance action prior the failure of a radar system. Standardized monitoring methods eventually can be used to harmonize data quality within a national radar network, and more importantly they can be used to harmonize the data quality between national radar networks. Latter is essential for the generation of e.g. high quality European scale radar products.

WXRCalMon workshop in Offenbach 2017 & 2019

Dualpol weather radar systems are still relatively new technology and the potential for operational services is still being developed. It is recognized that the operation of a dualpol weather radar system requires new methods to achieve the desired data quality. The idea of the WXRCalMon workshop in Offenbach (October 2017 & 2019) was to provide a platform to exchange information, experiences on operating, calibrating and monitoring dualpol weather radar systems. Here we provide a summary of the workshops by noting the most common and useful methods to monitor dualpol systems, and by noting the experiences in running dualpol radar networks and the need for further developments and research.

Radar layout and definition of terms Material and methods

Weather radar systems scan the atmosphere to provide quantitative properties of hydrometeors and their movement. Since the standard radar-principle is used, the data acquisition as well as the navigation of the data needs to be calibrated. There are diverse publications and textbooks dealing with this issue (see also References), therefore this paragraph contains only some general remarks.

Definitions

In radar meteorology, the meaning of the terms “calibration”, “monitoring” and “adjustment” do not have a commonly accepted definition. Here we make the following definitions

Calibration

Basically it means the comparison with a standard reference. Example: for the RF-Power this means to use the reading of a reference power meter. We refer to absolute calibration to indicate the electrical/electromagnetic characterization of the system versus some known reference (e.g., a metal-coated sphere with certified radar cross section). The electrical/electromagnetic characterization of a system considers all components of a radar system which are related to the transmit and receive path. Calibrated microwave equipment are needed here.

Adjustment

A system under test yields data with a constant deviation from the expected value. The system configuration is adjusted to correct for the deviation. After the correction, the system provides the expected values. Strictly speaking, an adjustment should not be confused with calibration. For instance, we especially refer to “adjustment” to indicate the physical/meteorological a posteriori tuning of the radar reflectivity estimates versus a possibly large set of in situ precipitation measurements, which, by integration in time and/or in space, should be made representatives of the radar sampling volumes (annual, seasonal, in some cases event, or daily, mean field bias adjustment). Adjustment can also be performed versus other remotely sensed geophysical variables such as brightness temperature, backscattered radiance, etc. So even a generated “calibration-function” is an adjustment of the systems response to power measurements.

Monitoring

Monitoring describes procedures to monitor the state, functionality and data quality of a radar system. Monitoring is a continuous surveillance of the system behavior and characteristics. In part, it can be viewed as an ongoing calibration, if time series of radar parameters are related to reference measurements. So additionally to a static check against a reference, monitoring provides trends and statistics. Inconsistencies discovered during monitoring can lead to corrective maintenance or calibration or other actions described by the manufacturer. Furthermore, some monitoring results can be used for adjustment. An example is given in the chapter about pointing.

If the “reference signal” is not known in absolute terms (e.g. clutter return or radar cross section of a bright target) but is known to be relatively stable, monitoring reveals trends. These can be used to detect upcoming problems and may be used to trigger further investigations.

Monitoring of the radar system has a considerable influence on radar data quality and therefore radar data application, such as Quantitative Precipitation Estimation (QPE) and data assimilation in Numerical Weather Prediction (NWP) models.

Components of a weather radar

Generally the radar consists of 3 blocks:

- Transmitter/Receiver (Detection of hydrometeor return)

- Pedestal/Antenna (pointing of microwave beam)

- Signal processing/Product generation (digitizing, timing of echos which implies the location of an echo, moment calculation, product generation)

All components deal with quantitative values and need to be calibrated/adjusted/monitored properly. Figure 1 shows a simple block-diagram of the signal path of a radar.

The transmit path goes from transmitter through filters, rotary joints, circulator, etc and dish/radome into the atmosphere. The receive path goes through radome, dish, circulator, etc into the signal processor. In this example a receiver over elevation is shown. The receiver can also be “under” the rotary joints.

For Dual-Pol-radars different transmitter and reveiver designs are used operationally. The different designs range from Dual Transmitter with dual rotary joints to single transmitter with a power splitter at the antenna. Commonly two-channel receivers are employed.

For calibration purposes the diagram gives some definitions, especially for electrical (legacy) calibration. With respect to the radar equation, the reference planes for transmit/receive path ends right before the antenna (see Figure 1). This has practical reasons, since the antenna gain is typically provided by the manufacturer. If the radome losses are not mentioned explicitly, they are added to the transmit/receive losses. It must be kept in mind, that a radome modifies the antenna pattern (Frech et al, 2013). In addition, radome losses depend on the wetness of the radome. For dualpol radars, losses in H and V need to be quantified.

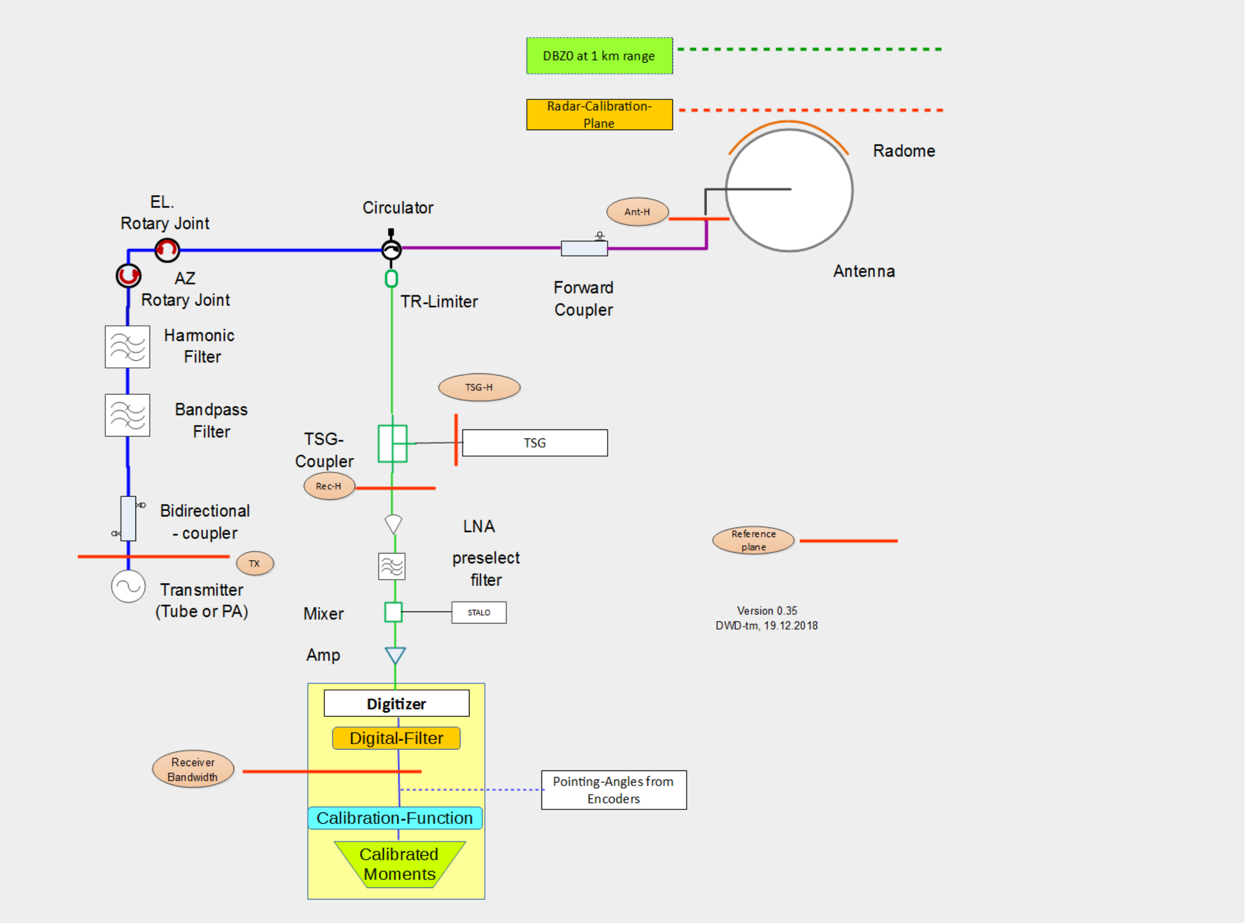

Figure 1: Simplified radar block diagram showing all relevant elements in the transmit and receive signal of a weather radar.

To calibrate the analog and digital part of the receiver, a test signal generator is used as reference. The differences in path losses have to be taken into account.

Transmit/Receive

A radar is an active device that sends out a microwave signal (pulse) and detects the response in terms of intensity and phase (velocity). Typically the transmitter and receiver use the same dish.

To calibrate the measured intensity of a weather signal, the transmit power outside the radome and a receiver calibration function is needed. This “electrical” calibration/adjustment is carried out by using power meters (transmit power), network analyzers (losses), test signal generators (receiver calibration function) and system parameters provided by the manufacturer (Antenna gain, radome losses, etc).

A calibration can be verified with the aid of external sources with known backscatter / radiation characteristics:

Total system (end-to-end):

- Known return of a metal sphere

Receiver:

- Sun signal in comparison with measurements from a sun observatory

For Dual Pol-Systems, where the difference between H- and V-channel contains the signal of interest, the electrical calibration is not sufficient. Here also external sources help:

Total system:

- Return from stratiform rain in vertical pointing mode
- Any meteorological target with known intrinsic backscatter characteristics.

Receiver:

- Unpolarized solar signal (ZDR ≈0)

Navigation

To locate the measured data in space, the distance from the radar and the pointing angles (azimuth and elevation) are needed.

Range

The range of the echo is calculated from the run time of the signal (with speed of light) from the radar to the echo and backwards. Since the time reference in the system is known quite well, only the begin of the data acquisition (=range zero) is typically adjusted.

Method: use a clutter target at known distance, calculate the geometrical distance und compare the displayed distance. If necessary convert the distance offset to a time offset and adjust system configuration parameter accordingly.

Direction

The direction from the radar is defined by pointing angles of the radar beam:

Azimuth: horizontally right handed from North

Elevation: up- and downward from horizontal plane

The angles are measured by angle encoders. The reading of the encoders needs to be calibrated. As a first draft the pointing of the dish is used. Then the comparison of the angle readings with calculated position of the sun relative to the radar position is recorded and used to adjust offsets.

Sources of errors for this adjustment method:

- leveling of pedestal

- accuracy of calculated sun position, including uncertainty in radar position and time

- method to derive sun position from received signal

- nonlinearities in gears and encoders (assuming that anti backlash gears are used, otherwise backlash needs to be taken into account; see Frech et al., 2018)

For a dualpol radar, the pointing accuracy of the radar beam needs to be quantified separately for the two polarizations, since they do not match necessarily. The characterization of the pointing with respect to the electrical axis (what is measured for example when using the sun as a reference) is necessary. An assessment of the mechanical pointing accuracy is not sufficient.

Typically the measured angles are used to point the dish to the correct direction. The gears of the drives are normally not anti-backlash gears. This introduces some jitter in positioning. This does not matter, if the measured and not the commanded angles are used to geo reference direction of the targets.

To calculate the uncertainty of angles, the absolute errors need to be considered, since every single voxel needs to be geo referenced correctly.

Time synchronization

System time

The time of the IT-Components like radar computer, signal processor, radar control unit and other modules holding a time needs to be synchronized with a reference, e.g. by NTP (network time protocol), better than 1 second.

This is, amongst others, essential when using the sun as an external reference to determine the pointing error of the radar system.

Tagging of I/Q-Data

To tag a pulse with the corresponding angle it must be ensured, that there is negligible time delay between angle detection and data acquisition before tagging of the pulse. Since there are usually two signal paths (data and angles) the tagging of the data with angles must not be influenced by time delays in the different acquisition paths. It must be guaranteed, that each pulse is tagged with the correct angle tag. A time delay in one of the branches would result in spatial shift as function of antenna speed. This is obviously especially a problem in azimuth direction.

Monitoring

Purpose of monitoring

There are different motivations to establish methods to monitor a weather radar. There are different levels and perspectives of monitoring. One view is a process oriented consideration of all weather radar system elements and processing steps, starting with the generation of the microwave pulse until the final product that is delivered to the user. For the user of radar data following requirements are the most important

a) Data availability
b) Data quality

With respect to data availability: radars are operated 24/7. The duration of a radar failure (which relates to no radar data available) must be kept at minimum. Typically, radar availability larger than 98% is required which does exclude scheduled maintenance. In order to keep the duration of a radar failure at a minimum, the continuous monitoring of all elements of a radar system is necessary to have an in-time detection of a radar system component failure. This is critical, if radars are operate in remote areas. There are also elements in a radar system, which typically gently degrade with time, such as a TR-limiter. Such degradation not right away leads to the failure of a radar system. If it is possible to detect trends or unusual changes of radar parameters early enough, preventive maintenance may be scheduled so that the actual failure of a radar system can be avoided. Fortunately, modern radar systems continuously provide large amounts information about the radar system state through their BITE (built-in-test-equipment) which can be analyzed and evaluated by a monitoring system.

The other important aspect to users is the data quality. Based on user requirements, the required accuracy of radar data (or that of radar moments) is usually determined, such that algorithms achieve their targets. We have to distinguish here between the absolute accuracy of a radar moment and the associated uncertainty. Latter is mainly determined by the sampling strategy and must be optimized through e.g. a sufficient number of pulse samples (e.g. Husnoo, 2018). Usually, this is taken care through the proper design of a scan definition. Nevertheless, observed variations in the measurements (which may be related to e.g. the scatter of a ZDR measurement) may be indicative of a hardware issue and as such should be monitored. A methodology to assess the system induced variability has been proposed by Cao et al. (2016) which has been used as part the radar system acceptance tests of DWD’s dualpol weather radar network.

The absolute accuracy of a radar moment is usually determined by all components of the transmit and receive chain of a radar which are typically characterized during calibration. So it is obvious that changes in the TX-path (e.g. the transmit loss because of a wet radome or a degrading circulator) will affect the absolute accuracy of all radar moments which rely on the received power measurement. All components of the radar which may affect a radar moment of interest need to be identified and monitored. This does not cover all aspects of the problem, because the scattering target is not involved so far. If we include the scattering target, we realize an end-to-end radar system monitoring (i.e. all elements of the radar equation are considered).

This is one reason why so-called data based monitoring approaches have been established in which essentially well characterized targets or reference measurements are used to quantify the accuracy of radar moments and to detect issues in the radar hardware (Frech and Hubbert, 2018; Frech et al., 2018). Another aspect to mention here is that the uncertainty of engineering measuring techniques is too large when it comes to quantify all relevant elements in the transmit and receive path with in an accuracy of

1 dB for Z, or 0.1 dB for ZDR (see Husnoo, 2018). Therefore integral end-to-end assessments of the system performance have to be considered.

How to use monitoring results

There are different approaches on how to use the results from monitoring

- Passive (1): monitoring results are handed over to the radar operator for further action, if predefined thresholds are exceeded. Then it is up to the user on how the information is used. The radar data are not corrected. A radar operator could be a radar expert team or a supervisor system.
- Passive (2): Monitoring results are encoded as part of the volume data. The DWD-ODIM-HDF5 file format has been proposed to encode the radar state and monitoring information together with the radar data on a sweep by sweep basis. The users themselves can apply corrections if deemed necessary. Postprocessing with improved quality control for e.g. climatological applications becomes feasible with such a data model. As an example, the actual ZDR offset and system offset of ZDR is available for each radar sweep. The proper offset can be applied, noting that the actual ZDR offset is commonly determined from a different source, e.g. by a birdbath scan (at 90° elevation)
- Active: monitoring results are dynamically applied to correct data before the data are disseminated to the user. For the user, this is probably the most convenient approach. But it assumes that each user has the same requirements when it comes to radar data quality. Considering the variety of radar data usage, it is fair to say that certain applications will have different requirements to data quality. For example QPE algorithms demand high accuracy in absolute calibration whereas a hydrometeor classification has a less strict requirement on absolute calibration and differential reflectivity because of the involved fuzzy logic algorithm. Depending on the method based on which a correction is determined, the limitations of the underlying methods need to be understood. For example self-consistency methods are not defined for solid phase precipitation conditions and should not be applied in such circumstances because significant biases may be introduced. Bottom line is that automatic correction procedures must be robust, reliable and well documented before they are introduced.

Monitoring methods

Up to now we have made generalized statements in order to introduce the terminologies and the goal of monitoring methods. The monitoring approaches now have to be stratified according to groups of radar moments and the system pointing accuracy. Typically, for each group different approaches are required. We will list available methods that have been established in radar networks. This section provides an overview on commonly used monitoring elements.

Technical parameters of the radar

BITE

Radar systems nowadays are equipped with extensive BITE, which may indicate the failure of a component or subsystem, or a warning in case of upcoming failure or degradation. This is the most basic form of monitoring that provides information if a hardware component is functional or not. More specific messages help to indicate failure of components remotely, which facilitates the decision to intervene and which equipment needs to be replaced. In principle, every active component needs to be monitored for functionality.

BITE messages and diagnostics must be remotely available, and be grouped per subsystem, to allow the creation of a dashboard that gives an overview of the entire system in a single view. A warning system should be implemented, which notifies the radar operator that a failure or warning BITE message has been generated. Also a daily, weekly and monthly report with an overview of BITE messages helps in the detection of criticalities, by showing the evolution of messages over time.

Next to the BITE messages, also the diagnostics from internal sensors, i.e. the voltages, component temperatures, etc. are to be monitored. This also includes auxiliaries, such as temperature and humidity of the environment in which the radar operates. These can be included into a daily or weekly report. By using timeseries of BITE messages, a reference to an existing system state is provided and allows for post-event analysis. However, BITE data have theirs limitations because their interpretation may be difficult without detailed knowledge of the system. This can make the automatic flagging of a system issue difficult.

IT-Parameters

Since the availability is typically measured for deliverables in terms of radar products, the diverse IT-components in the radar must work properly. These can also be monitored, e.g. system load, disk spaces, network performance.

Continuous stability of radar system

With the benefit of today’s modern radar technology (e.g., low noise amplifiers, fast and accurate Analog-to-Digital Converters) and with careful and regular calibration, it is possible to achieve high system stability during the continuous operation of a radar system. intrinsic uncertainties associated with the radar system are smaller than the uncertainties associated with the intrinsic variability of reflectivity of the meteorological target. For quantitative radar applications, high stability and accurate calibration are mandatory. Monitoring the stability of only the receiver chain or transmitter chain (one-way) is simpler than monitoring the stability of the entire radar system (two-way). This explains why in addition to methods that try to deal with the monitoring of the total system stability (two-way, End-to-End), there are others that split the problem into two simpler, complementary parts: monitoring of the stability of only the receive/transmit path separately (one-way).

Transmit path

Typically, the transmitting power is measured from a coupler in the waveguide, which is standard practice. Continuous monitoring can be achieved, as well as during scheduled maintenance. A more advanced method that has been applied during acceptance tests is the monitoring of the transmitter channel using an external receiver (Gabella et al. 2010; Leuenberger et al. 2017). The pulse duration and waveform can be measured, while the absolute transmitted power can also be retrieved using a power meter. This has the advantage that the entire transmit path is measured, including the antenna feed, antenna and radome.

Receive path

Single Point Calibration

To monitor the stability of the receiver chain, a reference power signal (instead of the received power coming from the antenna), is injected into the LNA input of the receiver and exactly that value (±a given uncertainty) is used for linking the given analogue-to-digital-unit value at the output of the digital receiver to the reference power value. Typically the radar is taken offline for such calibrations, e.g. during scheduled maintenance, but for some radars, the procedure is automated and performed as part of the scan program. For instance, in the case of a climatized antenna-mounted receiver, an effective solution uses a noise source as the reference signal, taking advantage of its high temperature stability (Vollbracht et al., 2014): in this way, it is assessed every 5 minutes what log-transformed analogue-to-digital-unit (dBadu) is associated to the stable reference log-transformed reference power (dBm) by the Noise Source for the given set of measured Temperatures (inside the receiver, in the radome, outdoor).

Noise Figure

The quality of the receiving chain is typically determined by the noise figure measurement. A predefined signal is injected into the receiving chain and a measurement is done once with and another time without the signal. For the a given pulse width, the noise figure and the bandwidth of the receiver can be calculated.

Noise Floor

By recording the receiving signal during a period that no echoes are expected, e.g. a long time after the transmitter has fired at high elevation, an estimate of the background noise is obtained. This is standard practice and can be done as part of the regular scan strategy. Recent developments are that the background noise is measured at each elevation, since it can differ. Within NEXRAD and the UKMO network, a ray-by-ray noise estimate is determined (Ivic et al, 2013)

Sun

The radio noise that comes from the Sun has been proven to be an effective reference for checking dual-polarization weather radar receivers and evaluating their calibration accuracy. The sun is an independent source of electromagnetic radiation that can be used worldwide for all weather radars. The Dominion Radio Astrophysical Observatory (DRAO) in Canada continuously measures its power at 10.7 cm wavelength (S-band) since 1947 (Tapping, 2013). Two complementary methodologies have been implemented so far in Europe for operational C-band weather radars: 1) “High Sun-to-Noise ratio”, where the dedicated observations are obtained by pointing (and tracking) the antenna beam axis at the center of the solar disk (i.e. on-demand Sun-tracking); 2) operational monitoring based on the analysis of solar signals in the polar volume reflectivity data produced during the operational weather scan program. Methodology 1) maximizes the Sun-to-Noise ratio, but in most experiments performed so far the radar has to be off-line and the procedure is run manually (Gabella et al. 2016). Recently, a fully automatic version has been implemented for a non-operational X-band radar on wheel (Gabella and Leuenberger, 2017): the Sun-tracking is performed twice per hour hence allowing to observe the presence of sub-daily variability (if any). The great advantage of methodology 1) is the fact that the analysis is based on solar signals recorded in the polar volume data during the operational scan program. Such methodology has been developed to: (A) determine electromagnetic antenna pointing (Huuskonen and Holleman, 2007) and beamwidth (Huuskonen et al. 2014); (2) monitor receiver stability (Holleman et al. 2010a); and (3) assess the differential reflectivity offset in the receive path (Holleman et al., 2010b). Initially, most of the results from such a method had been derived using data acquired in 2008, which was a period of quiet solar flux activity. Later on, it has been successfully applied to active Sun period (Gabella et al. 2015, Huuskonen et al., 2016, Gabella et al. 2017). Typically several tenths of solar hits during a day are pooled together and then a daily estimate of the solar flux is derived through the de-convolution of the antenna radiation pattern (Holleman et al., 2010a; Altube et al. 2015). In OPERA, solar monitoring is applied to all contributing weather radars The detection of the solar signal from operational data requires the transmission of unfiltered data (that means no clutter filter and thresholding is applied). Not all weather services are able to provide unfiltered data so far. The quantitative analysis of the solar signal in order to assess the calibration of the receive path, requires the submission of a proper metadata set. The definition of a proper meta data set is a task within OPERA 5.

End-To-End (E2E)

Birdbath scan for ZDR

Typical calibration of ZDR is done by pointing the antenna in a vertical position and measuring the reflectivity in light rain. Under the assumption of a constant reflectivity and rotating the antenna 360 degrees in azimuth direction, the average ZDR should equal zero (Al-Khatib 1979, Seliga 1979), and the ZDR bias can be obtained. For dualpol systems, it is advised to include the birdbath scan in the scan strategy.

Multi-sensor analyses (rain gauges, MRR, disdrometer, satellite)

Data from weather radar measurements can be compared to measurements from different types of instruments. The challenge lies in converting the measurements into a common output that can be compared, in which usually assumptions need to be made. A classic example is the comparison of weather radar data with rain gauges and/or spaceborne precipitation radars such as the one onboard TRMM (the first ever spaceborne radar) and its dual-frequency successor onboard GPM (e.g., Speirs et al. 2017, the first comparison in the European Alps). Comparison to other sensors has also been done, e.g. to a micro rain radar (MRR), disdrometers or precipitation measurements from satellites (e.g. Frech et al., 2017). In any case, complementary sensors providing a reference for a weather radar need to be well maintained and calibrated. Such methods have the potential to cross-check and possibly improve traceability to international standards, but currently are only employed for research purposes.

Ground Clutter and “bright” scatterers

Under the assumption that the average ground clutter level is known, it can be used to monitor any changes in the radar data chain. T/R limiter degradation can specifically be detected due to its distinct signature at close range (Rinehart 1978, Silberstein et al. 2008, Mathijssen et al. 2018). Recently it has been shown that a peculiar “bright” scatterer within a high range resolution radar bin can be effective for monitoring the spectral and polarimetric signals of a dual-polarization radar (Gabella 2018). In order to be “bright”, a near-range point target with deterministic backscattering properties should be hit by the antenna beam axis. An example is the 90 m tall metallic tower located on Cimetta, at 18 km range and at the same altitude as the Monte Lema radar: it gives an impressive equivalent maximum radar cross section of the order of 43.2 dB square meters. However, because the reference is known to be not constant nor perfectly stable, such methods can only be used for trend analysis, and are currently applied operationally only to a few radars.

Radar –radar comparison: consistency within the network

In the overlap area of two or more radars, the reflectivity can be compared. (Huuskonen et al. 2010; Seo et al. 2013). Due to factors as beam broadening, anomalous propagation a statistical analysis is needed to assess the average agreement of two or more radars, and as such their calibration. Although only used by a selected group of radar operators, it possesses the potential to improve consistency throughout the network, and is advised to be applied on an operational basis.

Active external transponder

Overall, end-to-end, system stability (two-way) can be checked occasionally (e.g., Reimann et al. 2013; Gabella et al, 2013) or continuously using (Kumagai et al., 1995; Schmidt et al., 2015) active dual-polarization calibrators. Benefits are large, but costs can be even much larger. Hence, continuous monitoring has been implemented so far only for spatial missions (TRMM, GPM, Synthetic aperture Radars).

WXRCalMon 2017

The first WXRCalMon calibration workshop took place 18 – 20 October 2017 in Offenbach at the DWD headquarter. 62 participants from 22 countries participated in the workshop. There was a broader interest for this workshop but some colleagues (Canada, Australia, US) could not secure funding for this workshop. Most of the participants were from European countries.

The workshop has been announced as a forum for weather services / organizations which operate a weather radar network, ideally with dualpol technology. It was expected that participants have practical hands-on experiences in operating a weather radar. Due to the recent introduction of dualpol weather radars and increasing requirements on radar data quality additional methods are deemed essential to guarantee the quality and availability of radar data. More or less refined methods to achieve this have been proposed and implemented in the recent years. The fact that those monitoring methods have been developed and implemented by weather services is already indicative that quality control methods and SW implementations are not yet available from radar manufactures. Naturally, with this background information following topics and questions were published in the call for the workshop:

- Which data quality monitoring methods have been implemented? What are the experiences? Are there any further requirements for development? What are the future plans?
- Which radar system monitoring methods have been implemented? What are the experiences? Are there critical radar system components that appear to have issues (e.g. transmitter?) What are the experiences from longterm radar operations?
- Which SW tools are employed? How are monitoring tools used operationally (i.e. web interface, automatic warnings….)?
- Radar information management systems: how do weather services manage the information from their various monitoring tools? Are commercial SW tools suitable for such a managing task?
- Which methods are used to verify system specifications? Sometimes tools used for monitoring purposes originally were developed for acceptance tests.

The idea of this initial workshop was to collect / exchange the knowledge in operating radar systems, and the experiences with the operation of dualpol systems. As a collaborate effort the knowledge / information of the workshop can be used for following purposes:

- Identify standard monitoring procedures and therefore “best practice” methods.
- Identify how monitoring results are used to improve data availability and quality.
- identify areas which need further development of monitoring procedures (could be e.g. an intercomparison of different (SW) implementations, or extensions to existing methods); this may touch upon hardware issues where further developments / optimization by manufacturers are needed.

- identify areas where new monitoring procedures / methods have to be developed (an example would be a measurement of the transmit phase difference in H&V)

For this workshop, manufactures were not invited to participate. We intentionally decided to do this in order to foster an open information exchange between radar operators who use radars from different manufactures. This was welcomed by the majority of participants. However, for the next workshop it is planned to invite representatives of manufactures for dedicated sessions. Here, the initial idea is to provide direct feedback to manufacturers on specific customer questions and suggestions on an expert level.

What is the essence from this workshop? We are collecting here some of the main findings based on the presentations and discussion during the workshop:

- Data based monitoring methods are essential to assess the calibration of a single and dualpol radar. They mostly represent end-to-end methods because either the full transmit and receive channel or the full receive channel (in case of the sun) are considered. So, the antenna and the radome are taken into account. An end-to-end method relies on scattering target or a well-defined microwave radiation source like the sun. That in turn means that the target or source has to be well known and characterized when quantitative conclusions on a calibration state are deduced. Data based monitoring methods may include external sensors like a disdrometer. Similarily, data from external sensors must be quality controlled and the sensors themselves must be well calibrated.
- For calibration of ZDR: Birdbath is the easiest approach to quantify the offset independent of HM type. The TR-limiter behaviour is important to consider. Different experiences were reported. Overall, TR tubes appear more problematic as previously known. TR-tubes are sometimes kept as site spares at radar sites (MeteoFrance)
- Radar – Radar consistency checks, that are used to assess the consistency of Z should be extended to assess the consistency of dualpol moments (MeteoFrance)
- The potential use of GPM missions to assess the calibration state of a radar should be explored. Studies are underway by MeteoSwiss.
- Methods to assess the pointing and the receiver using the sun are commonly used. The methods appear of limited use for X-band systems, because solar SNR at X-Band is smaller than in C-Band. Further studies are needed and alternatives may have to be developed for X-Band.
- Methods on the use of clutter targets need to be further elaborated.
- Monitoring methods should be applied separately to H and V, and not only H, ZDR.
- Multi-source approaches are essential in order to characterize a radar state / calibration with high confidence, i.e. use more than one method for calibration and derive a best guess.
- The use of monitoring results for adjustment is heterogeneous. Manual and automated procedures on e.g. ZDR calibration that apply on whole range of timescales (i.e. ray-by –ray correction of ZDR compared to the manual adjustment of ZDR, if necessary, every other week).
- The relative phase of the transmitted pulse in H and V is unknown. Manufactures currently do not provide a solution to measure the phase on transmit for magnetron transmitters. User community needs to push for a technological solution.
- Harmonization of SW packages towards an open-source monitoring SW package. There are a number of different SW implementations used (usually developed by the weather services). SW-intercomparisons and verifications are needed.

- Work towards common interfaces / data formats that consider monitoring results in order to facilitate the exchange of those results. Radar based products may benefit from quality information that are based on monitoring results and which are provided as a meta data set with the meteorological data set.
- Further workshops should be established every two years. The 2nd WXRCalMon will be held again at DWD in Offenbach, fall 2019 (30.10. – 1.11.2019). An “unfiltered” exchange of information among the European radar experts is essential for the OPERA program. Such a venue fosters a collaborative community effort that eventually help to optimize the operation / maintenance / monitoring of dualpol radar systems of different manufacturers, and to define “best practices”. This is an essential prerequisite on the path to harmonize the data quality in the OPERA network. It is expected, that, what is defined to be a “best practice”, will also be subject of further development. A workshop of this kind is considered to be an important venue for a “best practice” optimization process.
- Manufacturers should be invited for the next workshop. The format is still under discussion, but it may be for dedicated sessions.

All presentations are available on https://www.dwd.de/EN/specialusers/research_education/met_applications_specials/wxrcalmon2017_presentations/wxrcalmon2017_presentations_node.html

WXRCalMon 2019

The second WXRCalMon took place in Offenbach 30.10-1.11.2020. Over 60 participants from over 19 nations participated in the workshop. Based on the feedback of the participants from the previous workshop, manufactures were invited for a full day (30.11.2020). In total six manufacturers and service providers contributed to the workshop with presentations and posters. We asked the companies to focus their presentation on their recommended calibration methods.

Aside from getting a feedback from the manufacturers, the goal of the workshop was to

- Further advance towards best practice guides from WMO and also OPERA
- Consolidate the common understanding on calibrating Z, ZDR, and pointing accuracy
- Further advance on the goal to harmonize calibration methods,
- Further advance towards a common understanding on meta data definitions, which are needed for proper interpretation of radar data,
- And of course to provide a venue to foster the exchange of experiences, knowledge in operating a weather radar among the countries and organizations.

All contributions from this workshop can be found on http://www.dwd.de/wxrcalmon2019

In the following, we summarize outcomes of the workshop. References refer to the presentations given at the workshop:

- From a user perspective, the most extensive experiences with solid state power amplifier (SSPA) transmitter polarimetric weather radar systems can be found with JMA (Japanese Meteorological Agency), who started to work on SSPA transmitters for weather radars in 2008. JMA installed the first operational system at Haneda airport in 2016. Additional three system were installed since then which adds up to about 11 years of operational experience with this TX technology. In Japan, the C-Band frequency band has been curtailed such that a new transmitter technology had to be introduced for weather radars. JMA presented an extensive overview on their experiences with a focus on calibration aspects. An extension of monitoring and calibration methods are necessary for SSPA systems, in order to blend and calibrate the short/longpulse range of those systems. An example is that a birdbath scan cannot be used for the long pulse because there is typically no weather echo available at the long pulse range.
- Attending manufactures start to have dualpol SSPA systems in their portfolio. Manufactures presented software / methods to monitor, calibrate and characterize radar systems. The criticality of generalized monitoring methods was pointed out by one manufacturer, who has to deal with heterogeneous (HW & SW) radar networks. That is also an essential effort within OPERA.
- Radar-radar comparisons to determine the difference in calibration in order to adjust the overall radar network calibration and thus homogenize the radar calibration have to be carried out in a very careful manner. Even if the data are filtered for specific intensity levels in order to reduce the uncertainty, there remains still substantial variations and deviations as a function time. For example wet radome attenuation (one radome surface being wet, and the other not) may be one source of the observed variations (Huuskonen et al., 2019).
- An improved scaling coefficient for the solar flux conversion from S- to C-Band leads to reduced bias, which is demonstrated based on four radars from four different meteorological services (Gabella et al, 2019). For a meaningful intercomparison from different meteorological services,well defined and well established meta data, such as the radar constant, are essential.
- The challenges to use of bright scatterers (i.e. a clutter target) to monitor the C-Band dualpol performance are discussed by Gabella et al. (2019). In his case, the bright scatterer (a 90 m tall Telecom-tower) provides reproducible and stable results for differential phase delay, rhoHV, ZDR and Zh and Zv. Some issue are observed when evaluating DR (that is a proxy of the circular depolarization ratio and is a function of ZDR and rhoHV), where further investigations are needed.
- The importance of proper noise sampling in particular for low SNR situations has been illustrated by Darlington (2019).
- The discussion of the performance and the limitation of two self-consistency methods for the French radar network shows the strong dependency on the chosen Kdp estimate. The self-consistency principle using Kdp determined from Phidp ray-by-ray to be much more robust and suitable for calibration monitoring purposes. The noisiness of Phidp measurements prevents an easy and direct calibration of reflectivity data (Gaussiat et al., 2019).
- The use of spaceborne radar reflectivity measurements are an additional, and complementary source of data to monitor the absolute calibration of surface based weather radars. Results for the Bonn X-Band radar and the DWD weather radar network illustrate the potential of this approach (Pejcic et al, 2019)
- Based on NCAR’s S-Band S-POL a thorough analysis on the sources of ZDR biases based on temperature effect shows, that the ZDR bias is a function of antenna temperature and transmit frequency (Hubbert et al., 2019). The cross-polar power technique appears to be a robust

method to calibrate ZDR because it does not rely on precipitation. However, manufactures currently do not offer this functionality in their weather radar product lines.

- The combined use of data based monitoring methods (birdbath and solar measurements) can be used to assess and quantify the influence of a radome on dualpol radar data quality. This is demonstrated for two different radome designs (multi-panel design versus seamless radome; Figueras et al., 2020).
- If we add up the various contributions to the pointing uncertainty (tower leveling, gear drive design, backlash, data tagging) and therefore uncertainty of ray angles, an uncertainty of up to 0.3° may be expected. The estimate is of course dependent on, for example, the radar design. It is obvious that pointing accuracy needs to be monitored. Data should be tagged with monitoring results (Mammen et al., 2019).
- Monitoring the pointing accuracy and characteristics of the antenna assembly based on operational data is now established and longterm results are available. Together with appropriate meta data, this method will also provide a reliable characterization of the receive path calibration (Huuskonen, 2019)
- Absolute pointing accuracy: pointing bias in azimuth relative to the sun is dependent on azimuth radar positon. This is due to the inherent mechanical nonlinearity of the gear drive system of a weather radar. DWD presented results from extensive measurements from the Hohenpeißenberg research radar analyzing a large number of solar boxscans taken every 10 minutes throughout the day. It is important to note that azimuth bias estimates from operational scanning are typically valid from only a small portion of the azimuth angle range. This is particularly true in the summer months when the elevation of the sun is quickly above the highest elevation for typical scan theorems (maximum elevation of the DWD volume scan is 25°; Frech et al., 2019).

A survey was carried out to assess the current implemented procedures from the attending meteorological service. The procedures where categorized into “Monitoring”, “Calibration” and “Adjusting”.

Monitoring (M): procedures are implemented to only track the quality of a system parameter

Calibration (C): a procedure is implemented for calibration

Adjusting (A): a procedure is implemented to adjust the radar system based on e.g. monitoring results

The participants were requested to indicate for their organization if the following procedures are implemented, and if yes, at what level are the results applied in their operational network (M/C/A). The survey aims at established methods which ultimately provide best possible operational radar data quality

1. Radar reflectivity
2. Differential reflectivity ZDR: e.g. birdbath method
3. Pointing bias based on solar signals from the operational scanning
4. Solar power based on solar signals from the operational scanning; this information characterizes the RX path calibration of the radar
5. Solar box scans (“Sun box”): a scan option, which allows a better sampling of the solar signal at the radar frequency, which in turn provides a more accurate characterization of the pointing accuracy of the radar and receive path including the antenna and radome.

6. Self-consistency: provides an information on the absolute calibration bias based on differential phase measurements.
7. Radar-Radar comparison: a method to quantify differences in absolute calibration of radars within a radar network.

Various presentations from this and the previous workshop covered the aforementioned methods or topics. The results from this survey are shown Figure 2 and Figure 3 and are summarized in Table 1.

Table 1: Survey results on the monitoring, adjustment and calibration procedures.

Organization	Z	ZDR	Pointing based on solar monitoring	Solar power from solar monitoring	Solar box scans	Self consistency method	Radar / Radar intercomparison
MeteoSwiss	M/C/A	M	M/-/-	M	(M)/C/A	M/-/-	M/-/-
SMHI	M/C/A	M	M/-/A	M	A	-	M
FMI	M/C/A	M/C/A	M/C/A	M/C/A	M/A	-	M/C/A
DWD	M/C/A	M/-/A	M/-/A	M	M/A	-	-
JMA	M/C/A	M/C/-	C	-	-[1]	-	C[2]
Norway	-/C/A	-/C/A	-	-	-/C/A	-	-
UKMO	M/C/A	M/-/A	M/-/A	M	-	M	-
ESTEA	M/C/A	-/C/A	-	-	-/C/A	-	-
MeteoFrance	M/C/A	M	M/C	-	M	-	-
Icelandic MO	M/C/A	C/A	M/C	-	M/A	-	M/A
DMI	M/C/A	M/C	M/C	M	M	-	M
KNMI	M/C/A	C	M/C	M/C	-	-	-
CHMI	M/C/A	M/A	-	-	M/A	-	M
SHMV	-/C/A	M	M	M	M/A	-	M

In total 14 met services participated in the survey. In the survey, we have not made a distinction in automated or manual procedures.

Summary of survey results:

- Most of the met services have procedures to monitor (13), adjust (14) and calibrate (14) the radar reflectivity Z(h)
- Most of the met services have procedures to adjust and calibrate differential reflectivity ZDR, but some met serices (4) do not monitor ZDR yet. Here, one cannot make a clear distinction in calibration and adjustment, since ZDR calibration means an adjustment of ZDR through an offset, such that ZDR = 0 dB when looking vertically upward.
- A majority of the met services monitor the pointing bias from operational scanning using the solar signal (10). A fraction of met services use the information to calibrate and adjust the pointing accuracy (8)

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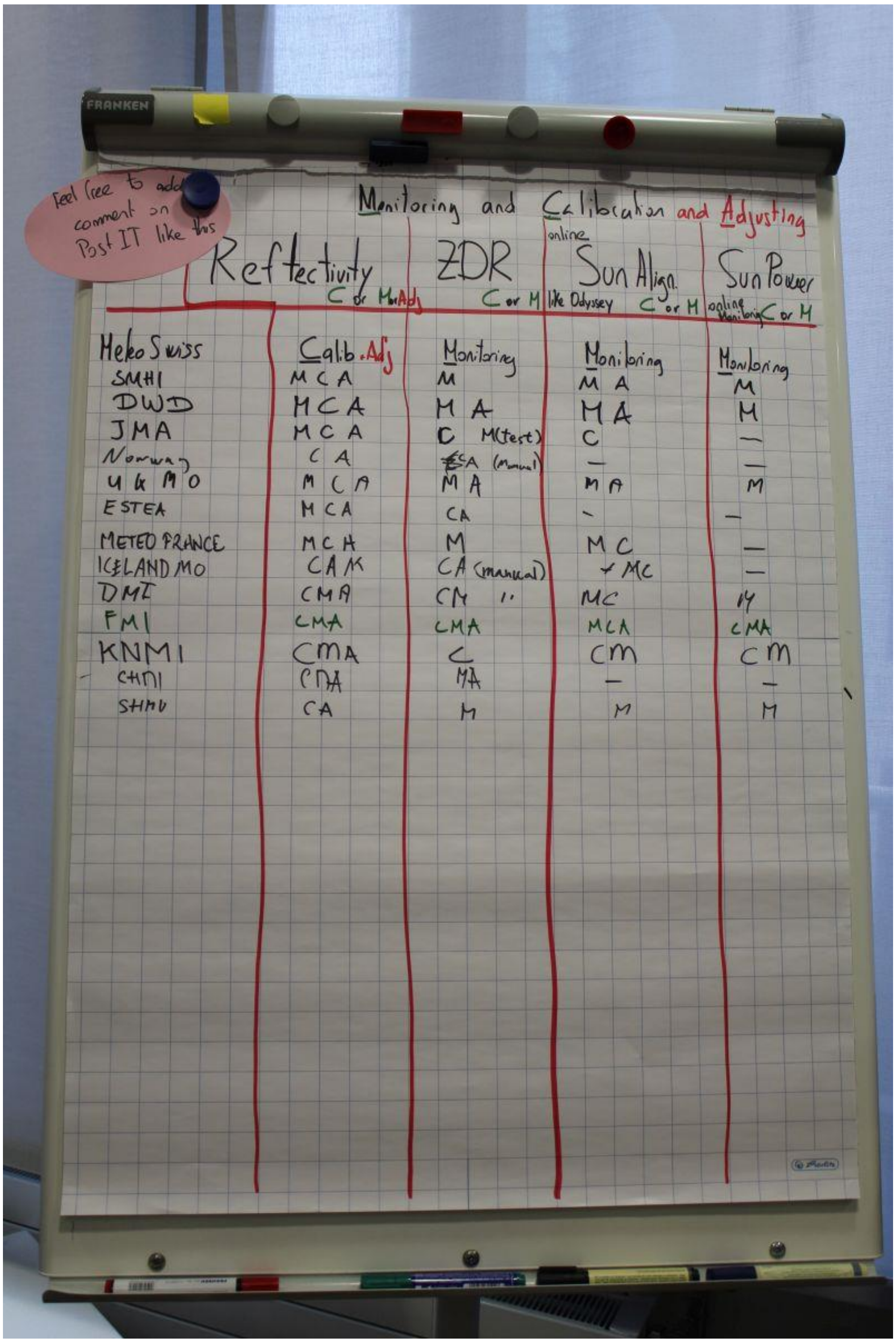
[1] Capability is there
[2] Currently tested

- Using the solar monitoring, 8 met services monitor the received solar power and thus the receive path calibration. Adjustment and calibration procedures are implemented at two (2) met services.
- Solar box scans are used by 11 met services to monitor, calibrate or adjust the pointing and, in principle, the receive path calibration. The important point here is that software is available to acquire boxscans to a majority of services.
- Only two met services use the self-consistency method for monitoring, but none to adjust or calibrate the radar system (MeteoFrance has the plan to introduce this within an ongoing project).
- Radar-Radar intercomparison: About 8 met services monitor the calibration of radars within their network, but only two met services use the result to calibrate / adjust the radars.



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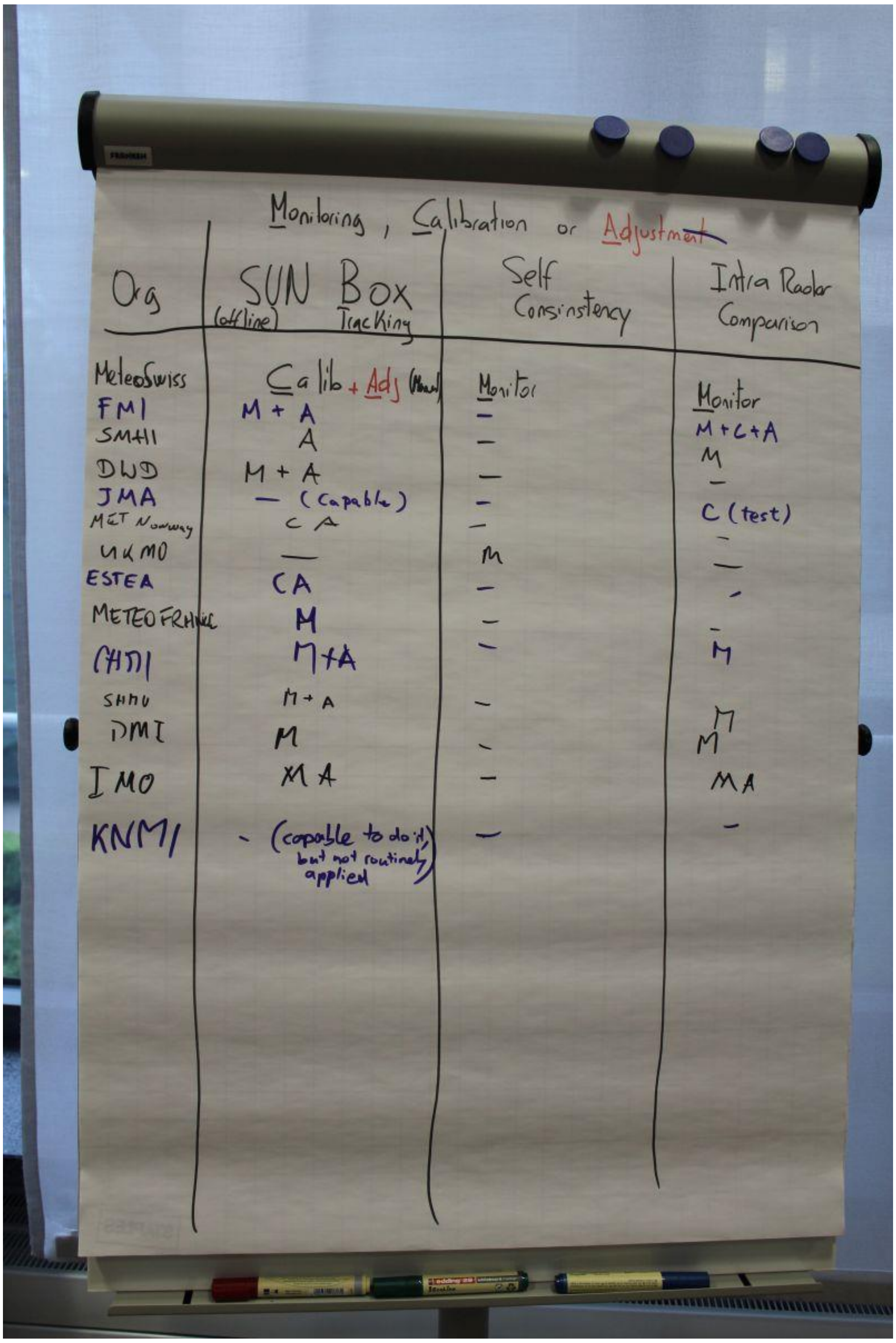
Monitoring and Calibration and Adjusting

	Reflectivity C or M or Adj	ZDR C or M	online Sun Align. like Odyssey C or M	Sun Power online Monitoring C or M
MeteoSwiss	Calib. Adj	Monitoring	Monitoring	Monitoring
SMHI	MCA	M	MA	M
DWD	MCA	MA	MA	M
JMA	MCA	C M(test)	C	—
Norway	CA	~~C~~CA (manual)	—	—
UKMO	MCA	MA	MA	M
ESTEA	MCA	CA	–	—
METEO FRANCE	MCA	M	MC	—
ICELAND MO	CAM	CA (manual)	+ MC	—
DMI	CMA	CM "	MC	M
FMI	CMA	CMA	MCA	CMA
KNMI	CMA	C	CM	CM
CHMI	CMA	MA	—	—
SHMU	CA	M	M	M

Figure 2: WXRCalMon2019 Survey on implemented methods (part 1).



Monitoring , Calibration or Adjustment

Org	SUN Box (offline) Tracking	Self Consinstency	Intra Radar Comparison
MeteoSwiss	Calib + Adj (Manual)	Monitor	Monitor
FMI	M + A	–	M + C + A
SMHI	A	–	M
DWD	M + A	–	–
JMA	– (Capable)	–	C (test)
MET Norway	C A	–	–
UKMO	–	M	–
ESTEA	CA	–	–
METEOFRANCE	M	–	–
CHMI	M+A	–	M
SHMU	M + A	–	M
DMI	M	–	M
IMO	M A	–	M A
KNMI	- (capable to do it, but not routinely applied)	–	–

Figure 3: WXRCalMon2019 survey on implemented methods (part 2).

The workshop closed with a session where initial ideas on the next workshop where collected:

- There is a consensus that manufactures should be invited to the next workshop. However, there needs to be a discussion, on how to get their contributions better focused on the goals of the workshop.
- We want to keep an ERAD style organization without an affiliation to a governmental or some other umbrella organization (e.g. WMO).
- Workshop attendance should be made possible without fees.
- The number of participants on the order of 60 is thought to be ideal.

- It is proposed to consider “data quality” as a topic, aside “Montitoring” and “Calibration”.
- Emphasize that the workshop especially addresses personnel, who have hands an expert experience with weather radars. Their knowledge and experience is an essential contribution for a successful workshop.
- Interference detection and mitigation: formalize and harmonize procedures for interference detection.
- This workshop is open to participant from all continents.
- We need to setup a permanent website to save contents of the calibration workshops. The last two workshops will be kept available through the official DWD website
- There is strong interest in SSPA developments for Dualpol weather radars.
- There was also a discussion on establishing a European solar flux measurement site which provides continuous high-quality solar flux data at C-Band similar to the Canadian DRAO observation site. There is a consensus that this would be highly desirable since solar flux measurements have become an essential component to monitor and guarantee radar data quality. The push should be initiated by OPERA.

The next workshop will be hosted by MeteoFrance in 2021.

Best practice

When implementing some basic procedures, radar operators and radar data users obtain access to essential performance parameters. It is proposed, that the adjustment or calibration of a radar should not rely on just one method. The adjustment / calibration of a radar should be based on and consider at least one method that includes an end-to-end characterization of the radar system. If there is evidence, based on one of the methods, that the radar needs an adjustment / calibration, this evidence must be reliable. The reliability can be assessed by re-checking the result for data analysis issues or consistency with other methods or previous results.

For radar operators, monitoring information helps to deduce information on the maintenance state of a radar system, they provide an early hint on possible hardware issues, and they provide guidance on the necessity to adjust / calibrate the radar system.

Data user can employ the monitoring information to assess the data quality and the performance of subsequent algorithms based on radar data.

It is essential that monitoring results are securely stored and are made available to the users. It is recommended to include monitoring results as part of a metadata data set in the DWD-ODIM-HDF5. In doing so system state and health becomes traceable especially if radar data are used for climatological studies. If you use a native data format it is recommended to switch to an open source data format like ODIM-HDF5.

Standard legacy calibration:

It is assumed that routine maintenance includes what is called a standard legacy calibration. A standard legacy calibration should include a well calibrated external TSG, and on a regular basis (i.e. once a year) measurements of TX and RX losses. It is proposed, that the standard legacy calibration should be always carried out according to the procedures of the radar manufacturer. The results should be documented but not applied to the system configuration, unless the results appear consistent with results from other monitoring sources.

Routine 1-point calibration during operations (i.e. once a day) using a built-in TSG should be employed in monitoring mode, without applying deduced calibration parameters as the new calibration of the system. If a bias is observed (bias in terms of calibration data in the system), re-produce the result and initiate a preventive maintenance to identify the source of the deviation.

Use **Solar monitoring** for both Single- & Dualpol systems using the methodology based the work of Huuskonen and Holleman (see the "Receive path" subsection and references therein). When implementing this methodology, the following information becomes available

- Pointing accuracy of the radar system (H & V). Adjustements should be considered if the bias is larger 0.2° in azimuth and 0.1° in elevation.
- Bias of receiver calibration (H & V): the bias should be within 1 dB
- Solar differential RX power: target differential is 0.1dB.

Aspects to consider

- Use SNR, if available. Proper meta data are essential.
- Use DRAO solar flux as reference.
- Use Dualpol data for quality control of solar hit data (i.e to check for precipitation, which may relate to attenuation effects.
- Use only data in the free atmosphere (> 10 km agl) in order to avoid clutter effects
- alternatively, data at a height larger 4 km may be considered if range bins with precipition and clutter are filtered out.

How to use the monitoring results:

If a bias is computed, use additional sources (if available) to verify the monitoring result before the system configuration is adjusted.

This could be

- Clutter target with well know coordinates and scattering properties
- Built-in sun track of the maintenance software: check of pointing accuracy and the receiver sensitivity. For example how does the measured solar SNR compare to the SNR computed from the solar monitoring routine.
- Legacy calibration.

In addition: check drives in the radar system with respect to damages (if there is a hint for a pointing accuracy).

Experience shows that hardware issues usually become visible through sudden changes or steady trends in the monitored quantities. "Real" day to day variations seen in e.g the pointing accuracy is uncommon. If you observe this you might want to check the implementation of the monitoring algorithms.

Save the solar hits in a data base for reprocessing and more detailed analysis.

Birdbath:

Birdbath scans are the most straight forward approach to determine the ZDR bias and thus the ZDR offset. ZDR of HM should be zero when looking vertically upward in precipitation. At least one full sweep needs to be acquired in order to remove canting effects. ZDR needs to be filtered in order to capture clutter free data and precipitation bins only. Only data in the antenna farfield should be considered. Caution is required to avoid the influence of the two TR-limiters on ZDR data in rangebins close to the radar. DWD experience shows that ZDR data from a range starting 1 km can be used, while other NMS use rangebins only at ranges > 5 km or more. Testing is needed because there appears to be radar hardware dependence. On a diurnal basis it is recommended to use at least 6 ZDR estimates (meaning 6 birdbath profiles) to calculate the ZDR offset (Frech and Hubbert, 2018).

Ideally birdbath scans should be included into the operational scan schedule. At DWD, birdbath scans are run every 5 minutes. It should be considered, that birdbath data are also a valuable source of meteorological information above the radar site.

ZDR offset monitoring must be complemented with a solar ZDR bias estimated from solar monitoring. This allows the detection of possible changes in ZDR bias in case there is no precipitation over the site for a longer time period. In addition, the ZDR bias due to the TX and the RX path can be separated.

Birdbath data can be used to monitor the absolute calibration of the radar using reference measurements close to the radar (Frech et al., 2017)

Further recommendations and summary

Based on the literature survey and the outcome of the WXRCalMon workshop following topics emerged (there is no prioritizing involved so far)

- Intercomparison of SW packages: Verification of methods using well defined reference cases with known result.
- Issues addressed by the workshop participants (e.g. phase measurements of the transmitted phase)
- Define procedures on how to use monitoring results in order to adjust the system (i.e. when/how to correct angle data)
- Establish criteria (thresholds) and procedures on how to use monitoring results. This includes: when is it necessary to react and adjust / recalibrate the radar system settings.
- Start monitoring dualpol data in OPERA
- Establish a common data format (model) for monitoring information.

There is another important aspect for users about the monitoring of a radar system, which has not been addressed and should be mentioned here. From an information management point of view, the user is not only interested in the case that there is a radar system failure but when this system is scheduled to be back in operation. This is of significant importance because radar data are often an essential component in automated warning algorithms where dedicated backup procedures have to be initiated in order to eventually mitigate the effect of missing radar data. If there is a radar related issue (failure or limited data quality) which has an impact on a e.g. warning algorithm, customers would like to know when a normal state again can be expected.

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