World Meteorological Organization

Commission for Instruments and Methods of Observation OPAG on Remote-Sensing Technologies

Inter-Programme Expert Team on Operational Weather Radars
Tokyo, Japan, 13-16 March 2017

[Keywords]/[Category]
Submitted by:
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1.Mar.2017
[Status]

WIGOS: Requirements, Design, Implementation and Operations of a Radar Network

SUMMARY

This draft document provides a guidance document for WMO members and potential funding agencies contemplating purchasing weather radar(s). It advocates that services requirements be first considered before specifications and technical requirements.

- Often radars are procured with the requirement for the development of an early warning service for convective weather (strong winds including tornadoes, heavy rain/flash flood, lightning and hail);
- However, hydrology applications for agriculture, wind shear alerting for aviation, general weather surveillance, climate are some of the other valuable applications
- Assimilation of continental-scale radar network data into medium range forecast models have been demonstrated and of the fine scale radar data into high resolution numerical weather radar prediction is still evolving

Sustainability (maintenance, application development) requirements are paramount for on-going operations.

- All observation technology will have its failures and radars are no different. Maintenance requires expertise and is key to the sustainability of radar.
- The deployment of radars leads to new capability in mesoscale meteorology where local weather becomes significant.
- Hence, over time, and with experience, the service and application requirements will be refined leading to scientific and application development for sustainability.
- Therefore, a viable radar program must include technical, meteorological and application development capacity building for sustainability.

Regional cooperation for network design, maintenance and sustainability should also be considered as radars are complex and expensive but enabling observation technology. Advocacy for data sharing will require additional discussion.

The document is written with minimal reference to technology (except in the glossary). A follow-on document on radar technology specifications for procurement purposes is contemplated.

IPET-OWR members **are invited to**:

1. Review the document for organization, figures (provide better ones) and length. A thorough review for grammar will be done post-meeting.

2. Review the cost considerations (initial and life cycle) for a radar program and to provide rough order of magnitude cost considerations (anonymously). See page 31.

3. Provide documents on radar life cycle strategies and sustainability. See page 33.

4. Provide sample tenders. See Annex C, page 63.

WIGOS Requirements, Design, Implementation and Operations of a Radar Network

Comment [PJ1]: Is this the right ti

DRAFT V8 with figures

20 Dec 2016

For Review by IPET-OWR

- Can mark sections that need rewording/rewriting
- Review Comments
- Better figures available?

Homework for IPET-OWR:

1. Complete cost considerations table (see page 31). Review for comprehensiveness, resources (full time equivalents and time), costing (exclude FTE salary, if mentioned in resource column)
2. Provide radar strategy documents if available (see comment on page 33)
3. Submit sample Tenders (see Annex C, page 63).

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Introduction

The document provides guidance on the requirements and implementation of a weather radar network and for its contribution to the WMO Integrated Global Observing System. This is directed to National Meteorological and Hydrological Services contemplating adoption or procurement of weather radar technology and to Funding Agencies who may fund an Early Warning System(s) with radar. Implementation of radars occurs at most every 15-20 years and often much longer, so experience and knowledge of the process procurement is limited.

What is Radar and a Radar Network

Weather Radar

A weather radar can detect signals from precipitation as well as non-weather targets (e.g. airplanes, insects, bird, cars, etc.). The average power of a radar is similar to a house hold light bulb but it is transmitted in a very narrow pulse of energy whose peak power is several hundreds of kilowatts in strength. A weather radar is also a very sensitive instrument being able to detect a single 2 mm drop in a cubic meter at 200 km range. Besides reflected energy (reflectivity), other distinguishing features of operational weather radars are Doppler and dual-polarization. Doppler capability can provide wind information for profiling and mapping. Dual-polarization capability improves precipitation intensity through better quality assurance via echo classification. It can provide precipitation type information, such as hail, rain and snow identification. Precipitation is associated with the heavy rain/snow, hail, lightning and strong winds (including tornados and downbursts). Radars can completely scan the atmosphere in three dimensions with high temporal (order of minutes) and at high spatial resolution (order of kilometers); so, they are used to provide early warning messages that no other instrument can provide (see Fig. 1).

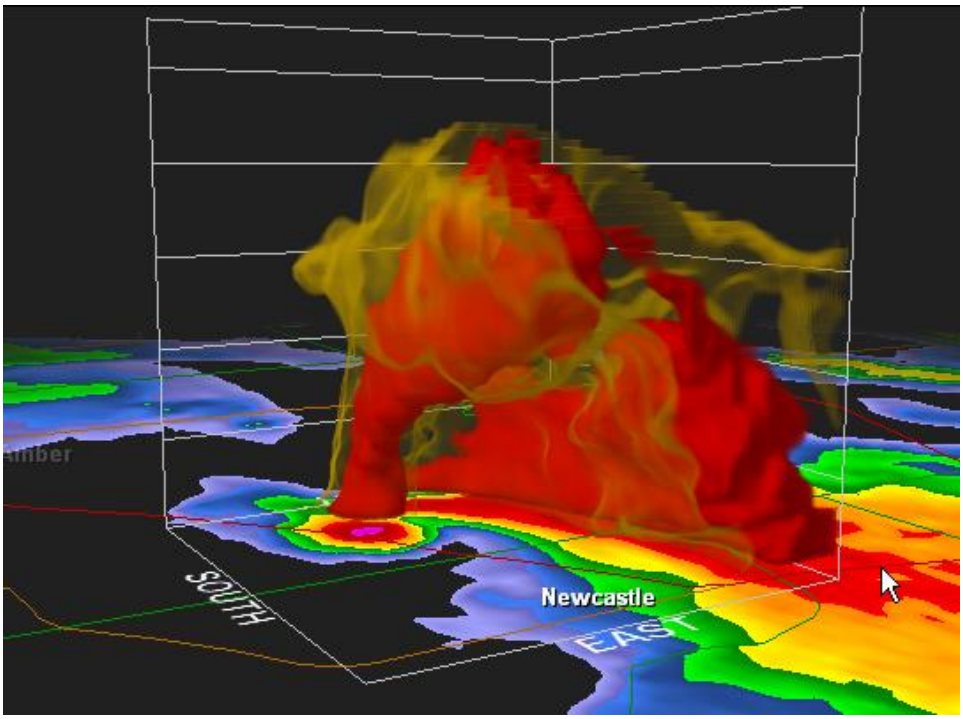

Figure 1: Radar can see into a thunderstorm in three-dimensions every few minutes. The rendering shows a surface 2D map of reflectivity and a volume rendering of the thunderstorm in 3D. No other meteorological sensor can do this.

The World Meteorological Organization's Radar Data Base lists the weather radars used around the world. Operational weather radars are identified by wavelength S, C and X (see Fig. 2).

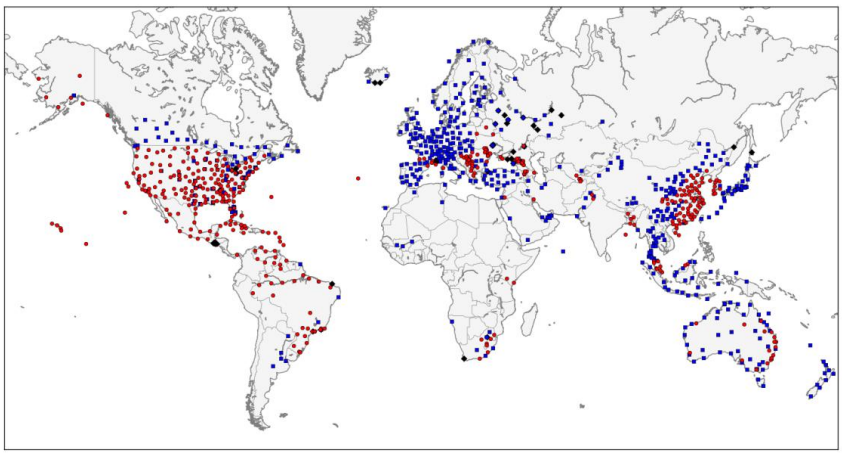

Figure 2: Location of radars around the world from the WMO Radar database. Blue is C and red are S Band radars.

Weather Radar System

Fig. 3 shows conceptually the various components of an autonomous weather radar system. It consists of a site, a radar that is mounted on top of a tower, a shelter to host the radar electronic components including telecommunications equipment, a second shelter to host an uninterruptable power supply (for conditioning the power or momentary power surges) and a diesel generator (for longer power breaks) and fencing for security. Power services are required. On site computers are needed to convert the signals to meteorological data and/or to produce products for the user. Product processing may be performed off-site if there is sufficient capacity to transmit the data. Telecommunications is required to transmit data and/or products and to provide remote access.

Figure 3: A typical radar within the Canadian network showing the major physical components of a radar system. The tower is about 30 m high, with a radome fitted with hazard lights and lightning rod. One shelter houses the transmitter/receiver and computers and the other houses the uninterruptable power supply and diesel generator

Weather Radar Networks

A radar network is a system of systems where the data or products from various single radars (of any kind) are processed together into composite products. Implicit is that radar data quality issues of inter-calibration and artefact removal are addressed

as part of this merging. Radar networks have arisen due to the technical advance of telecommunications, data storage and data processing capability and due to the requirements for greater surveillance range and also prediction capability.

Ideally, data is transferred from the radar site to a central facility for (i) merging with other radars and (ii) integrating with other data (Fig. 4). However, if bandwidth is low, networking can still be accomplished through creation and transmission of limited resolution products at the radar site. Arguably, the most important product is the lowest elevation image of precipitation intensity.

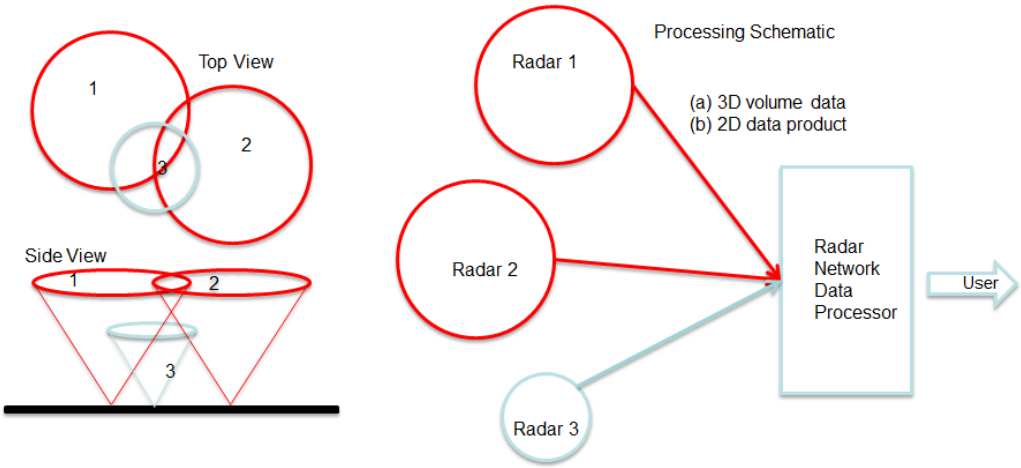

Figure 4: Networking of non-homogeneous radars can extend the surveillance coverage and help fill the low level data gap (left). Networking of radars requires merging data from single radars, resolving quality control/calibration differences into a single product (right).

Benefits and Impact of Radar and Radar Network

Application Overview

Weather radar provides highly detailed and timely observations of precipitation in the atmosphere. Applications include general weather surveillance for forecasting and public usage, aviation wind shear detection, hydrological applications (water resource management, flood forecasting, sewer management), civil protection/emergency management, agriculture, bird migration and hazard, wind profiling, to name a few.

Severe Weather/Surveillance/Aviation

Radar gave rise to the field of mesoscale meteorology. The high resolution and detailed observations enables the detection of small scale hazardous phenomena such as tornadoes, downbursts, thunderstorms that evolve rapidly in time. Pattern recognition skills of the forecaster or within algorithms are used to diagnose and identify the timing and location of severe weather to issue weather warnings. Fig. 5

shows a radar image, approximately 40 x 40 km, which is smaller or about the spacing of surface observation station separations in many national networks. A tornado vortex signature is identified as an away/toward (red/blue) couplet on adjacent range bins (see arrow on right image) that is embedded within a larger scale rotation called the mesocyclone. The image on the left shows a classic hook echo in reflectivity data which is one of the common radar signatures of localized severe wind and perhaps a tornado. All this detail is required to provide early warnings and would go undetected with other observations.

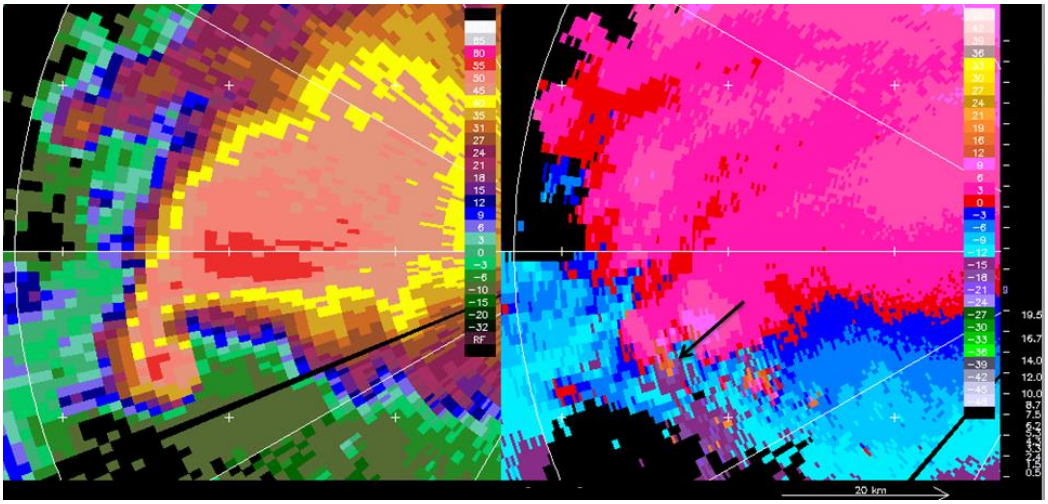

Figure 5: Radars are used by forecasters to look for patterns of small scale features (~1-10 km) indicative of damaging weather that cannot be seen by any other observing technology. The general convention is to use warm or red colors for away or positive Doppler velocities and cool or blue colors for toward or negative Doppler velocities.

Doppler capability is now standard features of a weather radar and permit the analysis of wind fields of different scales from kilometer-scale damaging downbursts for aviation. They measure the component of the wind parallel to the direction of the radar (radial velocity). Fig. 6 illustrates various kinds of wind shear that can occur at the same time and may require different warning messages. Multiple mesocyclones (A-B) are observed along a squall line and show both rotation and convergence. Rotation is identified as couplets of relative away (red) and toward (blue) velocities at constant range and convergence offsets the couplet in range. Mesocyclone labelled "C" is a purely rotating and has a hook shape in reflectivity (left image). Feature D is a downburst where the toward (blue) and away (red) velocity couplets are aligned along a radial. Downbursts exists at heights of < 500m and if encountered on take-off or landing, they can lead to critical and dangerous flying conditions. Due to the ephemeral nature of the downburst (<20 minutes for a complete life cycle), fully automated detection systems have been developed. Data refresh is required every 20-30 seconds and high spatial resolution (~100 meters) is required.

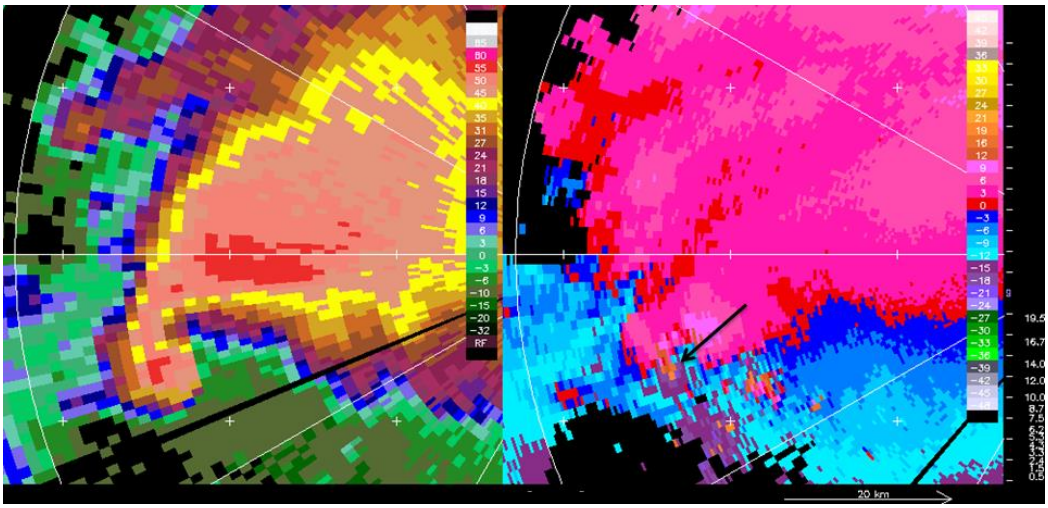

Figure 6: There are various kinds of wind shear . The size of the image is approximately 100 x 100 km and show multiple mesocyclones (A-B) with rotation and convergence, pure rotation (C) and pure divergence (D).

The radar can provide wind profile information on the scale of the domain of the Doppler data (~100km). A time height display of wind profiles is illustrate in Fig. 7.

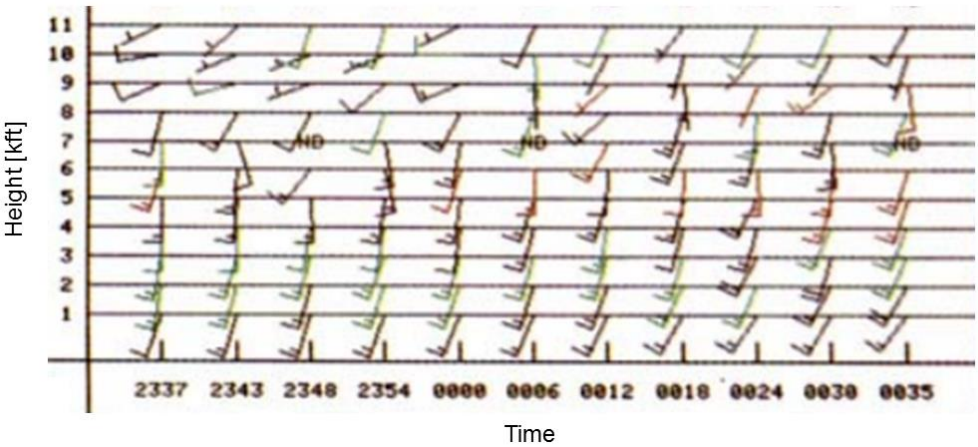

Figure 7: Doppler weather radars can also be used for wind profiling in both precipitating and clear air situations. This type of product is used to identify, with high resolution in time, passage of different air masses.

Dual polarization radar distinguish between different types of radar echoes and identify hail (Fig. 8). They are able to measure the power returned from horizontal and vertical polarizations.

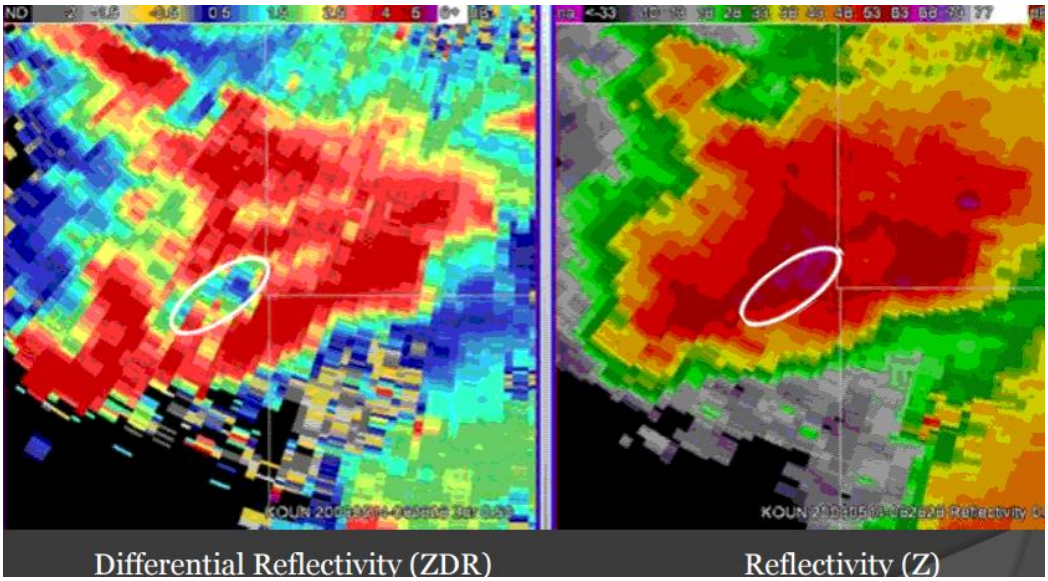

Figure 8: Dual-polarization can identify hail. The ellipse shows a positive differential reflectivity (Z_{DR}) value (left) in a high reflectivity zone (right) due to non-spherical large particle which is interpreted as hail.

Sensitive radars are able to detect clear air echoes, which are due to insects or atmospheric turbulence. This extends wind mapping and profiling to non-precipitating conditions but also for the identification of the location of atmospheric boundaries which indicate the location of convergence lines and future location of thunderstorm development (Fig. 9). Lines of weak echoes (marked A and B) are interpreted as convergence lines and therefore of upward motion. One line (A) is due to a lake breeze while the other line (B) is due to a thunderstorm outflow. The convergence is best seen as an away (red)-toward (blue) radial velocity pattern (right image, arrow). The circle shows the intersection of the two lines where there is enhanced convergence. Thunderstorms can be expected to form there.

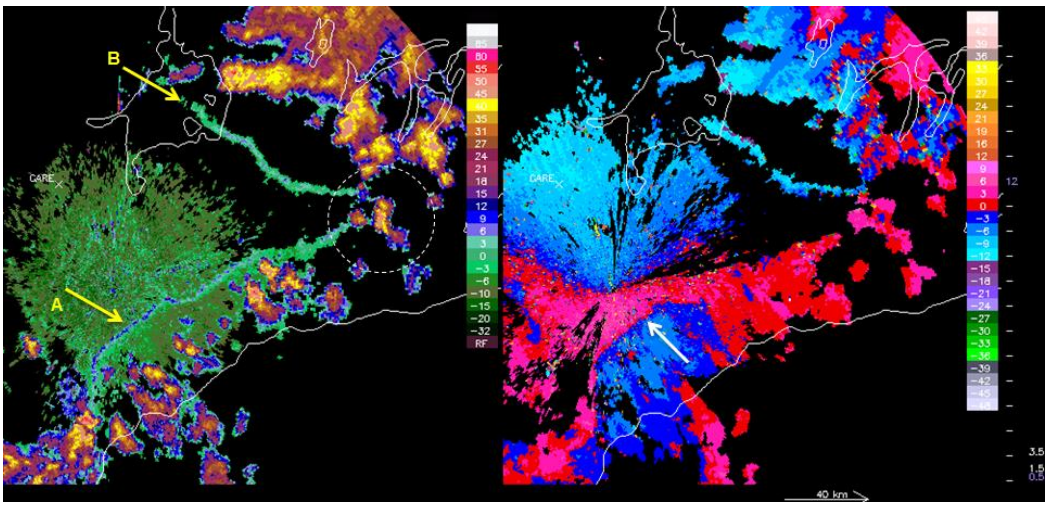

Figure 9: An example of clear air echo lines. They are general weak echoes (<20 dBZ). These have been demonstrated to be insects (has a polarization signature) that are caught up in a convergence line of upward motion. Turbulence has no preferred orientation and therefore has no polarization signature.

Networks of radars are able to provide large scale weather surveillance at extended spatial scales, such as, in the case of hurricanes or major extra-tropical storms (both summer and winter, Fig. 10). They can extend nowcasting/versy short range forecasting to longer lead times (from 60-90 minutes to several hours) and assimilation into regional or local scale models are aimed at even longer lead time(3 to 12 hours). Radar data is needed for the verification of high resolution numerical weather prediction models.

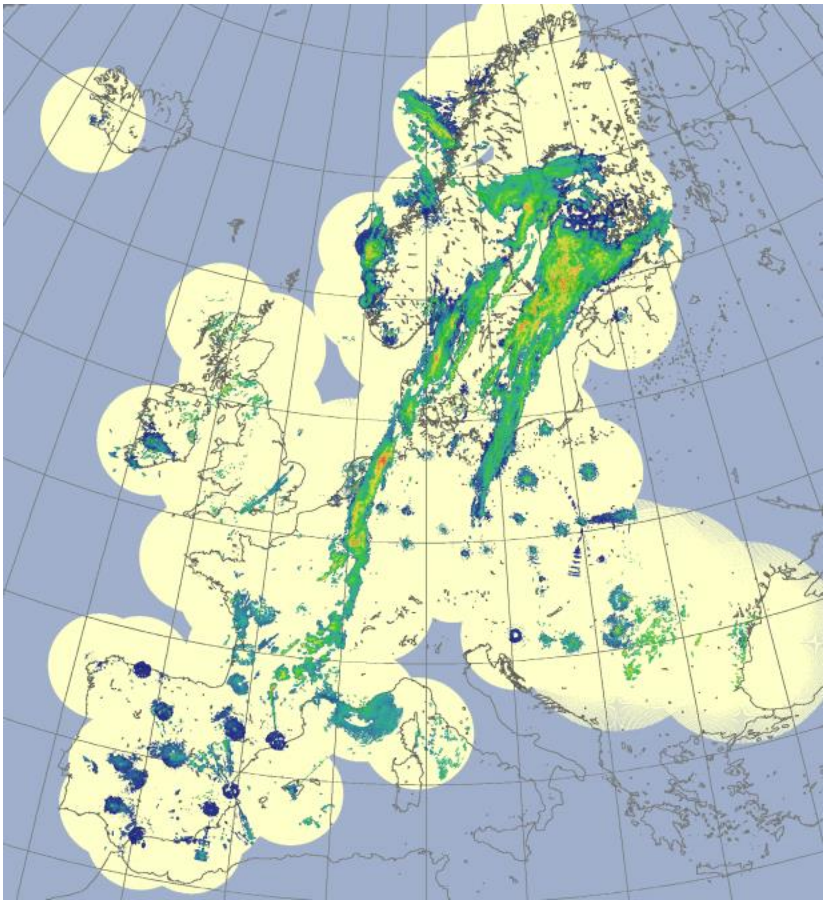

Figure 10: An example of the OPERA (Operational European Radar) composite showing that only the composite can capture the entire cold front. The most popular application is using weather radar network products to identify the location of the precipitation (or weather). Generally, a low level, rain rate, coarse resolution product presented on the web or TV every 30 to 60 minutes is sufficient.

Hydrology

Weather radars are used to derive estimates of precipitation intensity for the quantitative use for hydrological applications (Fig. 11). It requires a sound quality management program and significant data processing to remove artefacts due to external sources and due to physical processes such as evaporation or growth

below where the radar beam height. For hydrological applications, high quality data and estimates are required. Precipitation products require automated and significant processing to overcome the artefacts. Simple conversion of reflectivity to rainfall rate for climatological applications (long time periods) can be effective. However, short term precipitation estimation by radar is a challenge due to the ambiguities in drop size distribution .

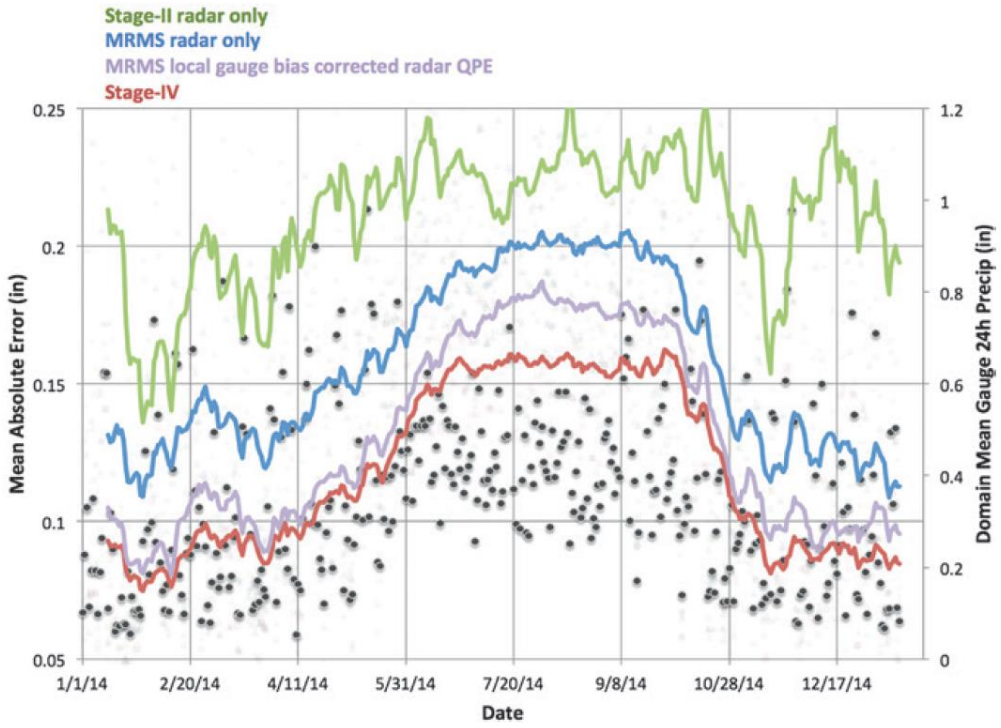

Figure 11: Mean absolute error of 2 radar only estimates (green and blue lines), a gauge corrected radar estimate (purple) and a manually generated estimate (red) that uses radar, satellite, gauge -adjustment and monthly climatologies. The comparison is against an independent but limited high resolution community based gauge network in Colorado, U.S.. There is a evident seasonal dependency.

Numerical Weather Prediction

Numerical Weather Prediction have advanced such that high resolution radar data is needed on a regional and global basis. Assimilation of continental scale radar derived precipitation data into global models can improve the 4 to 5 day prediction forecasts a continent away (Fig. 12). Unlike hydrological applications, assimilation systems can handle poor quality data as long as it is known.

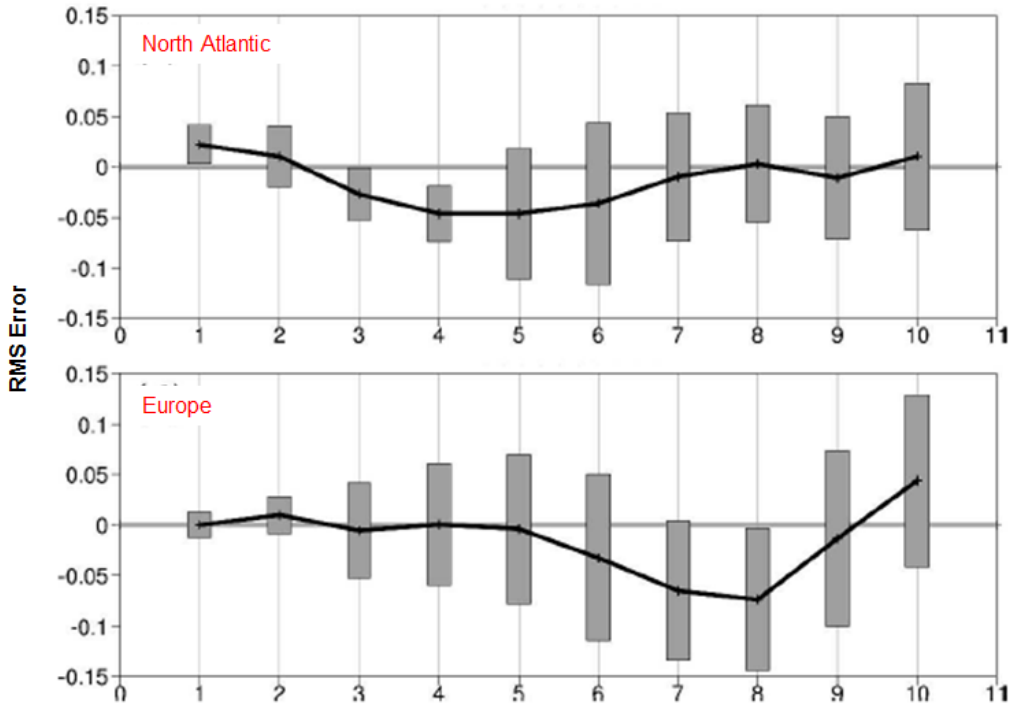

Figure 12: Assimilation of U.S. 6 hour precipitation accumulation from radar data affects the global model results at ECMWF. Top graph is for the North Atlantic and the bottom graph is for Europe. Root mean square errors are lower, showing significant improvement.

Climate and Environment

The value of archived radar increases with time. It allows for climatology studies to be conducted for development of resilient cities and societies through the development of building codes and insurance standards. They are also used for the validation of large scale satellite based climate products.

Commercial

Many local media stations own radars and some with Doppler capability performing limited low level scans. They are mainly used to enhance the presentation of their on-line weather forecasts and some have very attractively presented products. Some national media outlets will bring or produce network radar products.

Radar and WIGOS

System of Systems

The core concept of WIGOS is the "system of systems" where there is an integration or networking of various kinds of radars for weather applications.

As weather radars are highly linked with precipitation measurements, the concept extends to the integration with other related observing systems such as ground

based gauge networks, space based precipitation products to complete the global observing system concept.

Integrated Network of Radars

Radars are operated by different agencies and for different purposes. There are radars used for other purposes, such as aeronautical surveillance, that may be suitable for weather applications. Integration may occur (i) within an agency, (ii) amongst agencies within a member state, and (iii) amongst member states.

Data sharing, data quality and quality management is and will be a major issue for integration as different radar systems will have different operating and processing characteristics. The differences start with the radar network design, the technology, calibration, operations and maintenance. Fig. 13 illustrates the integration of parabolic weather (WSR88D, TDWR) and aeronautical fan beam (ASR9) radars in the north-east United States. The ASR9 are designed for aircraft surveillance for terminal operations but have weather capability (able to process signals for quantitative measurements). The fan beam results in a physical integration of the radar data with altitude and can be combined with with the same product produced by digital integration from the weather radars. The red circles (bottom right image) show the ASR9 fan beam radars and the black circles show the location of the pencil beam weather radars. The purpose of the integration is to enhance the low level (<500 m altitude) for wind shear detection.

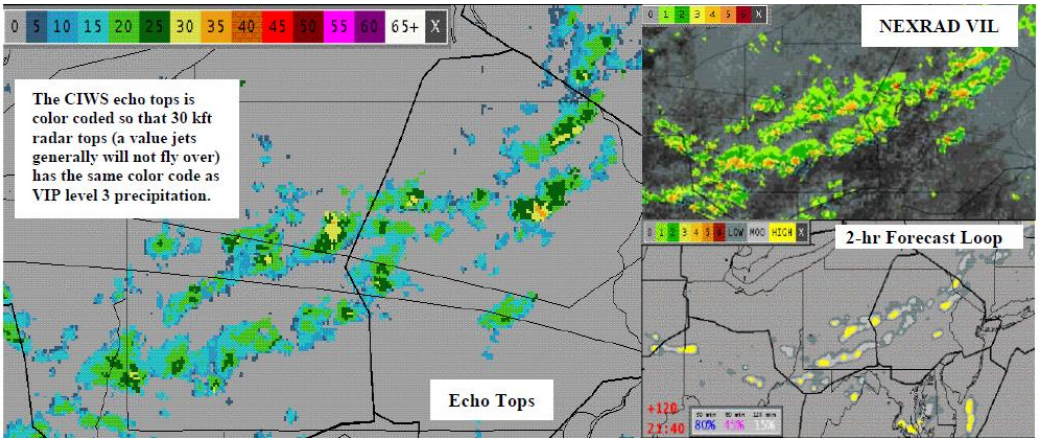

Figure 13 : Pencil beam (WSR88D, TDWR) and fan beam (ASR9) radars can be integrated into a non-homogeneous network. The red circles (bottom right image). Show the ASR9 fan beam radars and the black circles show the location of the NEXRAD and TDWR pencil beam radars.

Integrated Observations of Precipitation

A primary application for weather radar is quantitative precipitation estimation. Weather radars are ground based and provide precipitation fields with ~1 kilometer and ~10 minute, spatial and temporal scales. Space borne radiometers are calibrated and validated, in various ways, to provide precipitation estimates over oceans, polar and other data sparse regions where there is no or insufficient ground

based weather radar coverage with ~50km and ~3hour time scales. It is natural to combine and integrate these data (Fig. 14). The challenges of integration of these remote sensing observations with sparse in-situ observations are considerable but it is the only way to make observations of precipitation on a global basis.

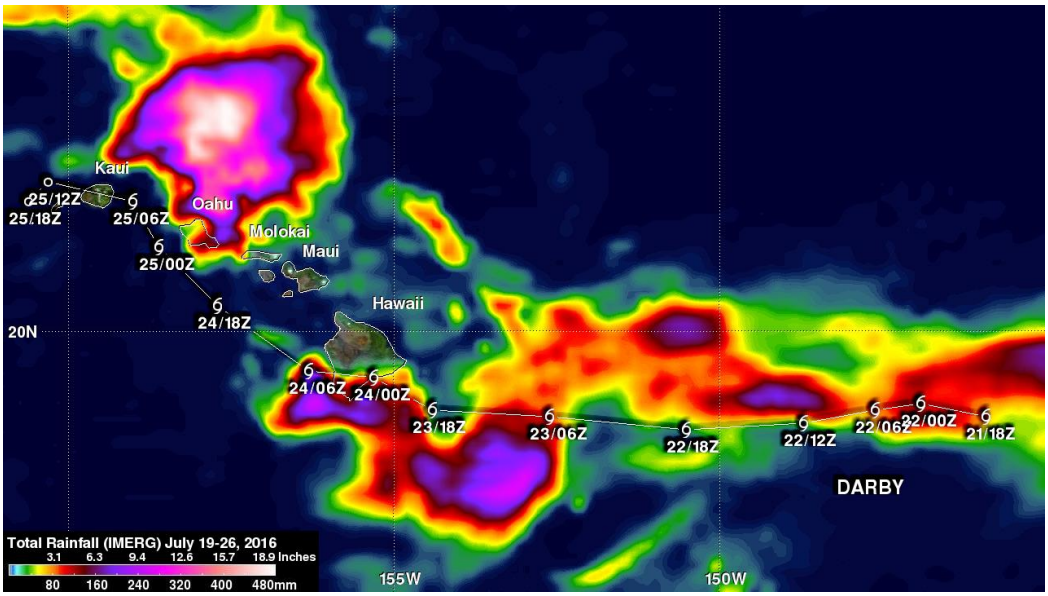

Figure 14: Merged precipitation by satellite (iMERG product from NASA GPM), This product is based on satellite radiometer data calibrated using precipitation gauge data, space based and ground based radar and rain gauges.

Integrated Observations of Wind and Other Weather Elements

Doppler weather radars can produce wind profiles either with precipitation or clear air targets. In a similar concept to precipitation, wind profiles are produced by weather radar and integration with radiosondes, Doppler lidars, wind profilers, ADM Aeolus are the only way to make wind observation on a global scale.

Advanced research radar processing systems (Variational Doppler Radar Analysis System or VDRAS) assimilate radar data (reflectivity, Doppler) and other data (surface, wind profiler, radiosonde) to produce very high resolution analysis and short term prediction of radar reflectivity, wind fields, temperature and humidity fields (Fig. 15). Radar data is integrated with all available data (surface, upper air, wind profilers) and assimilated into a cloud model to produce diagnostic wind and temperature perturbation at high resolution.

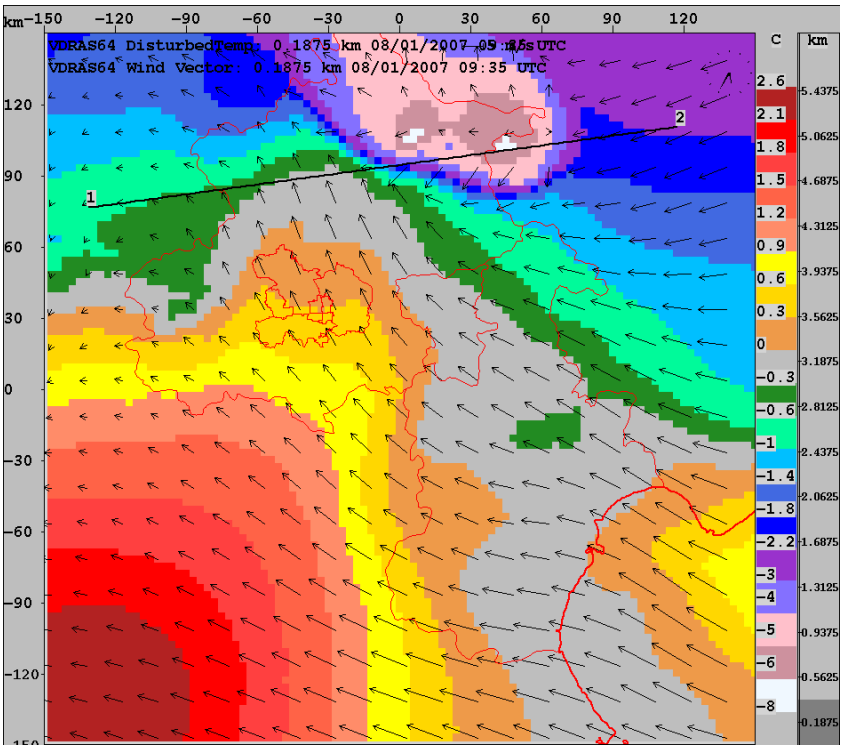

Figure 15: Radar data is integrated with all available data (surface, upper air, wind profilers) and assimilated with a cloud model to produce diagnostic wind and temperature perturbation at high resolution The domain is approximately 200 x 200 km.

Radar Network Programme Development

Introduction

The considerations for the development and implementation of a radar network are intertwined and the following aspects must be considered:

1. Levels of service
2. Applications and their requirements
3. Weather and needs analysis
4. Operational Programme Design

Service Level Requirements

Consideration of implementing a radar or radar network is often to respond to a societal need frequently driven by a catastrophic weather event or disaster requiring early warning. This could be an hurricane, tornado, flood or even a drought. Optimization of its use and having many clients and many applications is normal. It is critical to be able to articulate and prioritize the high level goals as there are a myriad of technical details that will confound the clearest of minds.

- Is it for severe weather warnings for a broad area or for specific aviation wind shear hazard at airports?

- Is the application for agriculture or for flash flooding and does the radar cover the critical basins .
- Is the radar to provide coverage over a Lake or over an urban environment?

The first step is determine that a radar is the most appropriate tool for the expected service and service levels. The primary and often the prime rationale for implementing weather radars is to provide weather warnings for heavy rain, strong winds, hail and lightning associated with rapidly evolving summer convective weather. Radar is an enabling technology that can result in the provision of "take action" type of early warning service.

This can result in a change in the office organization as it requires continuous monitoring of the observations and in particular the weather radar when there is the existence or potential for severe weather. Continuous interpretation and analysis of the radar products at very small scales is required to provide immediate and appropriate warning messages at the correct time, the correct location and the correct weather element is the challenge. Then, the service challenge is to properly and accurately portray the risk and impact to a variety of clients. The lead time is highly dependent on the weather but can be of the order of minutes for rapidly developing hazards.

Radars are also used to provide "imminent danger type of messages" or "watches for weather". These messages indicate the potential of severe weather and is less specific and immediate than a "warning" when the environmental conditions are predicted to be favourable for severe weather but only weak thunderstorms is occurring. With a single radar, the maximum possible lead time is about 60 to 90 minutes. Networking of the radar will extend the lead time of these watches to several hours (depending on the weather) and be most useful for large scale storm systems such as hurricanes and extra-tropical storms.

In many countries, the prime use of the radar is for hydrological applications such as flash flooding warnings, distributed hydrological models and water resource management. Radar is particularly suited for small basins and urban applications. This requires a higher level of maintenance, calibration and data processing to overcome the confounding external factors.

Research into the assimilation of weather radar data into high resolution numerical weather prediction is still very active and is aimed at improving the accuracy and precision and extend the lead time of watches and warning.

Application Requirements

Overview

The second driver is the application as it strongly impacts the radar technology selection and netw ork design. In this section, a discussion is provided on how the application can impact on the technology is configured.

Requirements for Severe Weather

- Convective severe weather evolves rapidly and requires volume scan updates at least every 10 minutes and preferably faster.
- Three-dimensional patterns of reflectivity (and hence precipitation) are used to diagnose and understand hazardous storm morphology and to predict its life cycle.
- Doppler data is used for diagnose hazardous small scale wind features such as rotation (indicative of mesocyclones) or low level divergent winds (indicative of microbursts).
- Polarization data is used to determine the presence of hail and non-precipitating echoes.
- As precipitation features aloft are critical to early warning, volume scans with high elevation data are needed.
- Radar sensitivity is a critical radar attribute to be able to observe and diagnose the initiation and development of thunderstorms using weak clear air echoes.
- While, human interpretation is tolerant to biased data (calibration). However, filtering of high intensity targets due to anomalous propagation and ground echoes is needed for automated severe thunderstorm detection.
- Some severe weather applications (e.g. intense wind shear in the lowest 500m at airports) have specialized siting (must be near airports) and scanning (must be 1 minute or faster) requirements for a dedicated radar.
- For synoptic scale features or hurricanes, radar networks and merging with satellite precipitation or cloud products are essential.

Requirements for QPE and Hydrology

- The variability of precipitation is of the orders of seconds and meters.
- Hydrological applications need high quality near-surface radar derived precipitation products.
- Accurate (unbiased, low variance) near-instantaneous estimates are required particularly at the high intensities for flood forecasting particularly in small or urban application which may require 1 minute updates;
- Agricultural applications may require daily or weekly average precipitation estimates;
- Resource management requirements may require seasonal accumulations of rain or snow fall.
- Volume scan or vertical information is only required to extrapolate vertical spatial reflectivity profile patterns to the ground at long ranges (>80 km) where the beam is well above the ground and below which the precipitation rapidly evolves
- Doppler zero velocity filtering to remove ground clutter and anomalous propagation is required

- Dual-polarization is needed for quality control of the radar data (precipitating vs non-precipitating echoes, rain vs snow vs hail, etc) and to correct for attenuation, particularly at short wavelengths.

Requirements for Numerical Weather Prediction

- For verification and validation studies of QPE, the requirements are the same as for hydrological applications.
- For data assimilation purposes, non-precipitation must be removed (unless they are modelled) and require data of "known quality" (that is, error estimates are requirements) and gaps in the data are permissible
- Some data assimilation systems prefer to use wind profiles or radial velocity fields; use of dual-polarization for hydrometeor type assimilation is emerging
- Radial velocity from all targets can be used for verification
- Radar data aloft can be used to initiate and for validation

Requirements for Climate

- Climate applications require continuous records of homogeneous products over broad areas and long periods of time and requires calibrated and homogenized products from regional and global networks of radars
- Hourly or daily average surface precipitation products are required
- Meta data is critical to track changes in the instruments, scanning procedures or calibration
- Radar can provide high resolution products (~1 km scale) to verify high resolution climate models,
- Low resolution products (~10+ km scale) merged with satellite products are required

Requirements for Environmental Monitoring

- There is a long history of the use of radar for bird migration monitoring; reflectivity, Doppler and dual-polarization radars can all contribute in identifying birds and their movement
- Mapping of the bird patterns requires low angle scanning; flux computation require vertical sweeps
- Avian hazard applications at airports require rapid scan and high resolution

Weather and Needs Analysis

Characteristics of the expected weather can modulate the technology discussion as well as the service level requirements. Quantifying these into climatological maps will aid in the network design.

- How intense and where are the heaviest rains or strongest winds, will it attenuate the signal totally or create ambiguities to prevent short velocity intervals to be used.
- How deep is the weather, or is it shallow? What are expected wind speeds?
- Where are the strongest winds?

- Where are the flash flood prone basins?
- What are the scale of the meteorological challenges? Is it hurricanes, freezing rain or thunderstorms that need to be monitored. What are the characteristics of the damaging weather, size, intensity, height, etc.
- Where are the major airports?

A useful concept is to combine the various factors into a single objective metric. There is no unique manner in which to combine the various factors but one approach is to categorize each factor into a common severity scale and then to weight them according to expert judgement. The factors could include population density, strong wind hazard, heavy rain hazard, basins prone to flooding, airport locations and even socio-economic factors. Fig. 16 shows such an example of the construction of a "needs index". There is subjectivity in this approach but it does provide an objective metric and sanity check on the network design.

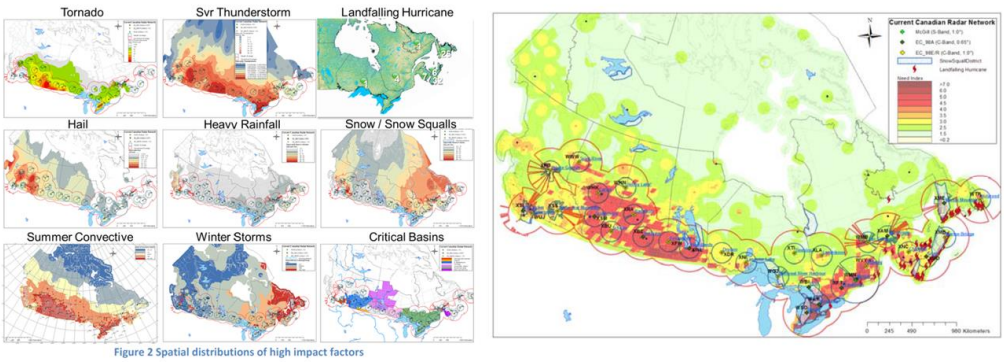

Figure 16: Weather climatology's of various hazardous (left) are categorized and then combined (equal weighting) to create an objective metric called the "needs index" (right) summarizing all the factors and identifies high risk areas (red areas). The large circles indicate reflectivity coverage (256km range) and the smaller circles indicate Doppler coverage (110km range). Comparison of the needs versus Doppler coverage is used as a rationale for additional Doppler range.

Operational Programme Design

The Radar Program

The radar implementation will affect and impacts the operational program in cross-cutting ways. This includes site maintenance, calibration, engineering, data processing, product interpretation, data management, message dissemination and outreach. Fig. 17 shows an idealized organizational structure. The strategic and tactical visions and capacities of each component will affect the program and must be considered when developing the Tender (also called Request for Proposal). This may lead to service and technological compromises. The process of the creation of the Tender will be an opportunity to build up the organization and develop consensus for an efficient operational radar network.

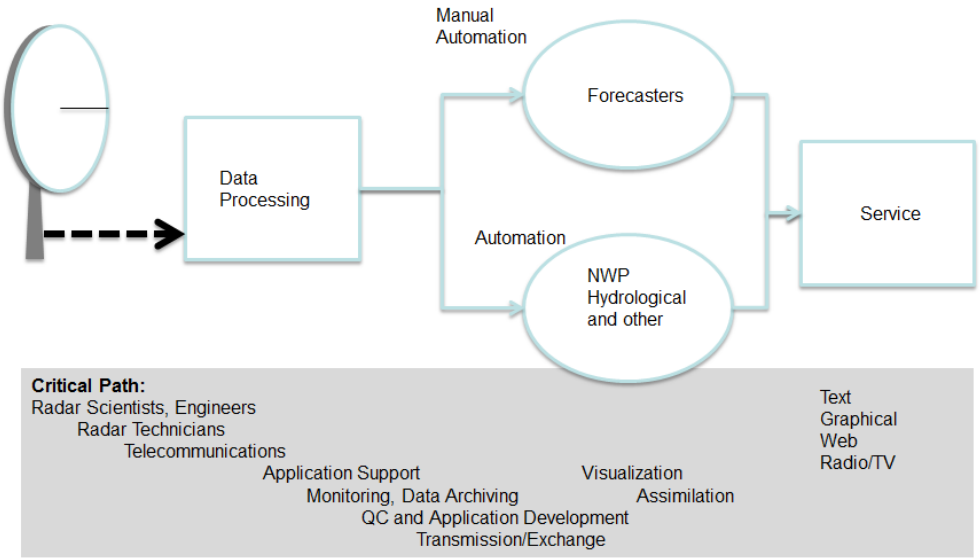

Figure 17: Implementing a radar affects every part of the organization and they are all critical to a successful radar implementation.

Radars are complex and involve many sub-systems, anyone of which can result in a non-functioning radar. In particular, support and maintenance is particularly important and requires advanced technical capabilities and capacity building. Fig. 18 shows the typical failure modes and provides an indication of the skills required to keep the radar operating.

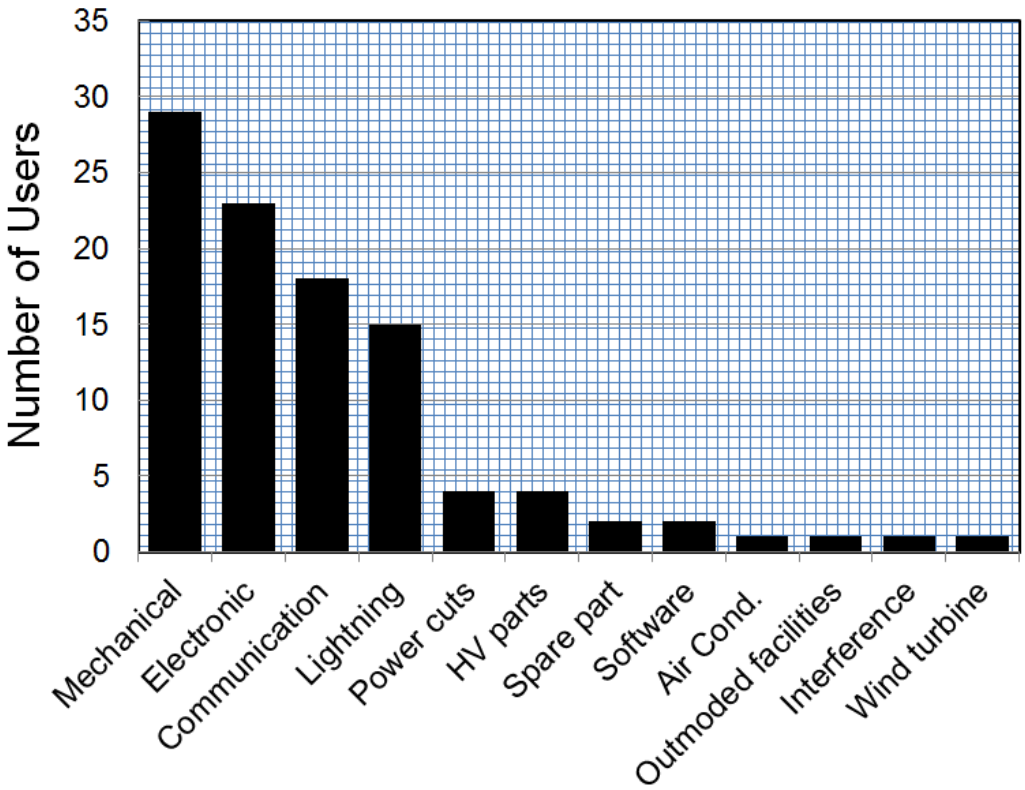

Figure 18: Failure modes of weather radars from the WMO Radar Survey (2010).

Radar and Radar Network Implementation

Overview

Once the high level service (what and where) and service levels that the radar is to provide has been determined, implementing a weather radar network consists of the following:

1. Establish the project team (project manager or lead, radar application and technology consultant including network designer, logistics consultant – see competencies)
2. Initial network design and technical considerations.
3. Prepare project plan, determine the application(s) requirements and the technology specification considering trade-offs. Establish the location(s)
4. Establish the budget and seek funding
5. Prepare procurement documents and go through procurement process.
6. Review Project Plan and prepare a implementation plan
7. Prepare site and site infrastructure.
8. Install the radar including frequency setting (project team changes from design to implementation team)

9. Configure, Data Processing, Quality Management, Product Generation. For radar network, a central processing facility is required.
10. Operations, calibration, monitoring and maintenance including sparing
11. Training – technical and meteorological
12. Sustainability – establish growth path for applications, including integration into forecast process, integration with other observations, future service enhancement and technology

The Project Team

The selection and design of a weather radar network requires a team with different skill sets. There needs to be an overall understanding of the application requirements and the technical and financial environments. There is a range of required competencies to design, operate a radar and radar network.

The competencies include:

Project Leadership and Management	The organization must own the project and understanding of the overall goals and ability to lead, manage the end to end project is critical. The overall approach, the negotiations for and management of funds, the leadership of people and contracts is required. Many competencies may be provided in creative ways, by teams, by external consultants or others but project ownership must reside within the organization.
Scientific and meteorological	Strategic planning is required to specify the service, the service level, to design the radar network and applications. This is needed at the beginning of the project and could be provided by consultants working closely with the NMHS. Specific Competencies: 1. Understand organizations strategic plan and envisioned service and service levels, 2. Understanding of weather (climatology's of precipitation intensity, height of weather, characteristics of the severe weather) in the coverage area 3. Basic understanding of user or application requirements (bias, accuracy, data quality) 4. Basic understanding of radar technologies (attenuation, beam width, scan strategy, ground clutter mitigation) and trade-offs
Scientific - Engineering	Technical Support is required to convert the user specifications into technical specifications. This may be a team of people or provided with consultants working with NMHS and system designers – could be the same.

	1. Understand radar technology and trade-offs 2. Understand impact on service and application levels 3. Understand organizational competencies (project management, technical capacity) 4. Understand safety, licensing and construction practices
Technical – Support and Maintenance	Ongoing maintenance, calibration and support is required. This may be contracted out but could be fraught with problems (competency with radar may be difficult to find). 1. General knowledge and practice of occupational safety procedures when working with high power systems and heavy machinery. 2. General understanding of electronics (need to operate voltmeters, signal generators, oscilloscopes, spectrum analyzers) 3. Comfortable working with computers, setting up networks, backing up data and computers. 4. General knowledge of site maintenance (road repair, diesel and UPS power systems, air conditioners, heating systems) 5. Basic knowledge of high power systems, heavy machinery, electronic components at line replacement unit level, telecommunications 6. Diagnostic and analytical skills. 7. Quality Management culture. 8. Basic knowledge of radar applications.
Meteorological and/or Application Developer and Research	Role is to optimize use of radar data and integrate into forecast systems, training end-users. This may be a wide ranging group of people ("local guru") and could be developed over time. 1. Training and products may initially be done by radar manufacturer software. 2. Experience with technology will result in continual capacity building which is best done in-house. 3. Maturity with technology may result in increased or enhanced requirements and require changes in the radar or product generation configuration or in the data sharing. 4. Broad knowledge of radar applications; knowledge of cloud physics, meso-scale meteorology, precipitation measurements, hydrological application. 5. Application development is open ended – from commercial services, data exchange, software

	applications for radar, integrated observing system, forecasting, product improvement and enhancement

The Project Plan

The project plan is an internal document that should include a high level statement of the overall goal of the project, the scope and definition of the project, the objectives or deliverables and the schedule. This should be used as a vehicle to capture the issues and the discussions amongst all the internal stakeholders leading to realistic and implementable project.

The service level discussions, application requirements and organizational capabilities must be combined with technical radar knowledge and expertise into a network design and the Tender. So, the network design will evolve with the development of the project.

Radar Specifications

From a pragmatic perspective, where cost and supportability are key issues, it should be recognized that in this requirements or user based approach, the technology specifications and the structure of the Tender will be a compromise. There will be a feedback and perhaps modifications to the requirements, goals and objectives of the procurement and implementation. Any operating and supported radar will have significant benefits.

There are three main ways to specify a radar:

- Technical
- Feature/Functionality
- Performance

In the technical based approach, the Tender provides engineering type specifications for the radar components, such as the peak transmitter power or receiver sensitivity. It requires engineering knowledge and can be extremely detailed and the responsibility lies with the NMHS for the overall system performance. If over specified, it can restrict the bidders.

Feature or functionality based Tender is a high level approach that can require less technical knowledge of the radar system. This approach is useful particularly if interfacing with other systems. An example would be if the radar must deliver certain data formats for compatibility with downstream applications or that the radar system must do certain things like reporting potential faults and must have Built-in test equipment.

The performance based approach is a systems approach that follows from an user-centric approach and leaves the technical specifications to the manufacturer.

The Tender can be a combination of the three. Which approach one takes or emphasizes, depends on the available expertise and implicit circumstances. Contradictions in specifications need to be carefully considered and managed.

It is useful to specify mandatory and optional performance specifications. The optional performance may be on a progressive scale and there may be a performance limit beyond which it is wasteful to purchase. In most cases, the mandatory or threshold performance should be specified so that the minimum user requirements are met and that there are sufficient bids for a successful competitive bid process. The optional performance and cost will determine the successful bidder.

One crucial feature that is very difficult to evaluate is system reliability, robustness and long term maintenance performance. There are engineering techniques to estimate failure rates by aggregating statistics on a sub-component basis. However, they do not cover the interaction between sub-components which is most often the cause of the failures. The best way is perhaps to specify that references from existing customers should be provided.

From a technical perspective, radars can be primarily distinguished by wavelength, Doppler, dual-polarization features, transmitter power, receiver sensitivity and technology and beam width. Significant technology issues include sensitivity, ability to mitigate ground clutter, the trade-off between maximum range and maximum Doppler velocity and attenuation in heavy precipitation situations. Wavelength plays a significant role as well as signal and data processing techniques to mitigate the limitations. It is beyond the scope to describe all the technology issues but the Annexes (A and B) primer and discussion.

Radar Siting

The site selection and procurement is generally the responsibility of the NMHS. It will generally require getting land use permits. Lands may need to be purchased and environmental assessments may need to be conducted.

Most, but not all, weather radars have a long range surveillance role (>200km). The radar network design will provide a coarse location for the radar but the actual siting will require consideration of the local terrain. Using resources Google Earth and Digital Elevation Models (DEM), candidate sites can be identified to approximately 40km or better. Fig. 19 shows an example of using a DEM model to investigate blockage due to terrain. The figure shows a colour display of the distance or range to the terrain from a candidate site (specified by its geographical location and height including tower) as a function of azimuth and elevation angle. The upper most envelope is called the radar horizon and shows the lowest elevation angle above which the radar will have an unobstructed view and for general long range surveillance, the lower the better. However, for local applications (airport surveillance, mountainous valleys, hydrological basins), it may be acceptable that the long range coverage is blocked Note that local obstructions such as towers,

trees and other electromagnetic sources are not captured by the DEM and final site selection require site visits.

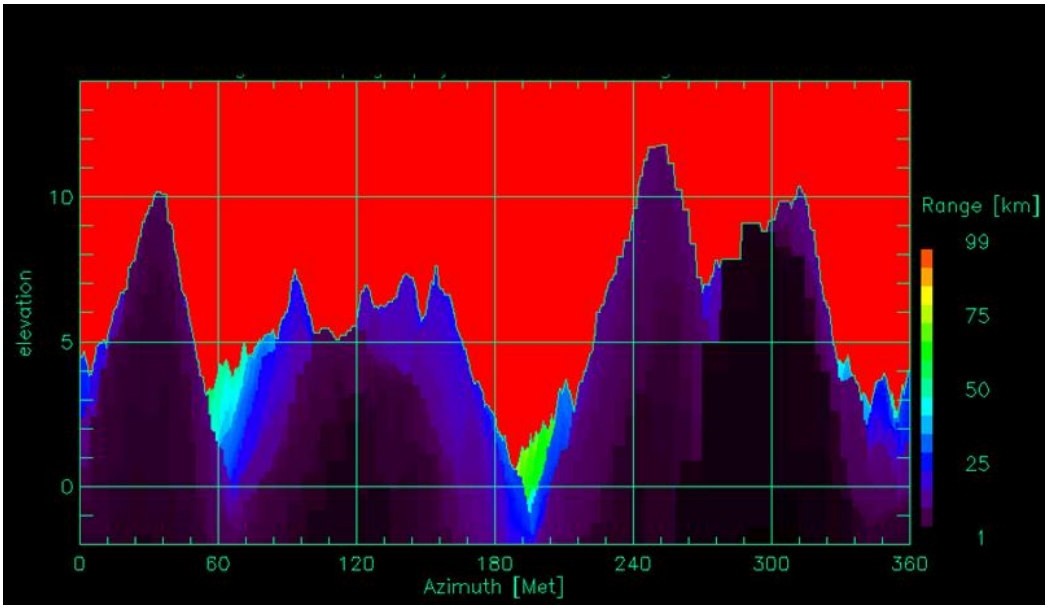

Figure 19: Digital Elevation Models (terrain database) or even commercial applications can be used to pre-select radar locations. In this figure, the radar horizon is displayed as elevation angle (taking into account the beam propagation through a standard atmosphere) a function of azimuth angle around the radar.

The selection of candidate sites should consider:

- Upstream location of high priority target areas (and out of the way of potential hazardous weather)
- Infrastructure (existing facilities, road, power, telecommunications, access)
- The actual location needs to consider local obstructions due to buildings, trees, towers and radio-frequency interference. Radars are often installed on towers to raise the antenna above the local trees or buildings. Tree growth should also be considered.
- Minimum elevation angles, radar side lobes and ground clutter rejection capability of the radar must be considered.
- Radars on top of high hills and towers may produce considerable unwanted clutter through the side lobes of the antenna.

The ideal set up is to locate the radar in the middle of a slight bowl (quarry or in a forest clearing) where the side lobes (and their multiple reflections) are absorbed by local obstructions (Fig. 20).

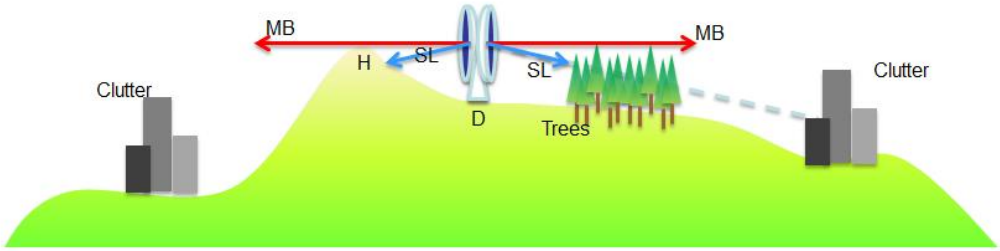

Figure 20: Hill or mountain tops (marked H) and tall towers are often chosen for radars for surveillance reasons but they are not always the best place. The side lobes (SL), which transmit less than 1 thousandths of the power of the main beam (MB), can create unwanted echoes from ground echoes ("Clutter"). Siting the radar in a slight depression (D) where the side lobes are absorbed by terrain (H) or trees (T) near the radar will remove a significant amount of clutter.

Radio Frequency and Interference Considerations

The ITU has responsibility for coordinating the use of the frequency spectrum on a global basis. S, C and X (and other bands) have been used for meteorological use as they are not so attenuated by gases in the atmosphere. However, local authorities can interpret the guidelines and agreements for co-habiting with other spectrum users (weather radars or otherwise). Weather radars use only about 1 MHz channels within the much broader frequency band and, so by judicious selection of the channel locations, radars can inter operate without mutual interference.

Given the proliferation of wireless technology for telecommunications, there is a constant threat to meteorological weather radars. The frequencies are selected for the same reason as that for meteorological applications. However, they use the entire frequency band and so can create interfering signals that cannot always be effectively eliminated (Saltikoff et al, 2016). Many of these technologies are un-licensed, can be trans-national and will be massively deployed with unpredictable and unknown performance. Vigilance in protecting the use of the spectrum for public safety and security is a constant concern. This can impact the selection requirement for the frequency band of the radar and radar network. The WMO has issued guidance statements on weather radars and use of the RF spectrum.

Wind Farms

Wind farms are both a source of clean energy but also for interference to weather radars. Preferred locations are on hill tops which are windy places but can also visible to the radar. In some instances, they compete for the same location. Unlike normal ground clutter, which are stationary targets, the turning turbine blades create signals that may confound the Doppler clutter filtering. In some cases, the wind turbines are already in existing ground clutter and pose no threat but in other cases they are isolated and create new sources of clutter. The WMO has issued guidance statements on the mutual co-existence of wind farms and weather radars.

Cost Considerations

One of the technical trade-offs for weather radars is the cost of the radar. The initial cost of the radar is only a part of the total budget. It should also include capacity building, life cycle management, ongoing application development and network management costs which are often limited. So, the Tender should focus on procuring radar systems that are of: (i) low maintenance, (ii) low infrastructure cost and (iii) low capital cost. To confound the financial analyses are strategic and tactical business decisions by the manufacturers.

In the following table, the costing issues are described and very rough order of magnitude estimates are provided to indicate where the project risks are.

Comment [PJ2]: To be completed after IPET-OWR survey.

Cost Items	Level of Effort (FTE and Time)	Comments	Rough Order of Magnitude ($USD)
		Does not include senior management (direction setting)	
Determine Requirements		Deliverable is a statement of NMHS service provision using radar, the role that radar would play. Interact with senior managers for strategic direction, users and managers for tactical direction. Delivered by a team of NMHS staff.	
Strategic Planning, Network design, Write, Issue and Evaluate Tender		Deliverable is a translation of user requirements into a high level strategic plan, low level technical plan including network design and an Tender. Delivered by a team of NMHS staff perhaps with consultation with experts. May involve dedicated procurement specialists.	
Siting, Licensing		Deliverable is site, land use permit, radio frequency licensing. Site surveys included. Delivered by land procurement department and project office for RF licensing.	
Site Preparation (site, road, shelters, telecommunications)		Deliverable is site ready for radar to be installed.	
Capital Cost of Radar		Cost of hardware.	
Spares		15-30% of capital cost.	

Training Technical and Meteorological Staff		Includes initial training for planners and configuration team, for technical staff (FAT and SAT), for product training for forecasters. Processing and analysis in local mesoscale meteorology case studies and forecaster training in future years. Quite open ended. Each training session is estimated at $100K and includes travel.	
Annual Maintenance		Power, heat and air conditioning, site maintenance, site travel, telecommunications, data archiving. Two annual visits included.	
Trouble Shooting		One time visits – expect 2 per year; does not include parts	
Data Processing		Includes software development to integrate into existing IT infrastructure, computers and data archiving. Quite open ended.	
Development and research		Both hardware and application development.	
System upgrades		Hardware and software replacements	

Radar Procurement

The Radar Market

There are a limited number of weather radar companies who have a mature signal, data and product processing for meteorological applications. There are several companies specializing in developing research radars who may venture into the provision of operational radars. Telecommunications companies use similar technology and may venture into the market.

There are many large multi-national electronic engineering systems company that build radars for military, aviation and other application areas that can credibly step into the weather radar market. They can produce radars of high quality and can integrate with existing signal, data and product processors or even develop them.

They tend to respond only to large procurements with detailed technical engineering specifications. Start-up costs and the establishment of long term support capability means that they normally respond to large multi-radar procurements.

It is viable to integrate sub-components and construct a radar "in-house". This may provide project flexibilities and cost savings. However, experienced engineering personnel were available and the organization was willing to accept the associated risks which include a high dependence on key personnel and the ability to capacity build and technology transfer to support personnel.

Another source of radars is the possibility that NMHS may decommission radars and make them available. They may still have value and be an inexpensive capital cost item and there have been success stories. However, the key issue is the after-sales support for these older systems, where to find parts, where to find expertise and capacity to maintain them.

Upgrading an existing radar is often a viable option. Studies exist that indicate that it is more cost effective to replace radars every 15 years or so than to upgrade. However, there are many NMHS' that operate radars for 25-40 years or longer. Doppler upgrades replace the transmitter, receiver and processing components for more stable components and advanced processing. Dual-polarization upgrades depend on the physical design of the waveguide and various joints. A popular solution is to put the receiver and processors on the back of the antenna.

Comment [PJ3]: Homework for IF OWR or for another document. Fin and Switzerland have done this and should get their studies.

Comment [PJ4]: Homework for IF OWR . e.g U.S., Canada, Cuba. N to discuss long term O&M strategie

The Request for Proposal

Overview

The procurement of a radar will have to follow local procurement processes and rules, trade agreements and treaties. Radars are not commodity items, with a limited market and standard procurement practices may ignore this. As radars are relatively large and unique procurements and have many components (land, construction, technology, service and support), different and more complex process may be invoked. Having a dedicated and experienced procurement person as part of the team may be warranted.

Informing the industry of the intent to procure radars is a good idea as the companies can assess it within their strategic and tactical plans, can give proper consideration to their capacity, perhaps provide an indication of budget and respond with an appropriate bid. This could be done formally via letters of intent directly to radar manufacturers or via the procurement department with a Request for Information or Announcement of Intent. This allows some formality in acquiring knowledge about the market, ability to assess the capabilities of each radar company, on how to separate roles and responsibilities and on structuring the Tender. Meetings could be arranged and each side could pose questions. Confidentiality agreements may be invoked. This has proved to be very valuable and can change the project and implementation plan.

Competitive or sole source bids can be prepared but generally the process is not that much different in terms of time, unless the latter approach precludes creating specifications.

There will some aspects of the radar implementation that will be the sole responsibility of the NMHS such as numbers and locations of radars, site selection and perhaps specific aspects of the technology (for continuity or life cycle management considerations). There are some roles and responsibilities that could either be that of the NMHS or the manufacturer such as site preparation and civil works. They will need resolution and be specific and clear. A NMHS project manager will be needed for logistics, coordination, scheduling, reporting and negotiation. However, the actual project management could be contracted to the radar company.

It is critical to consider "after tender" support, how to specify the level of service and who will do it. This includes monitoring, routine maintenance, trouble shooting and in some cases re-design. Support by the manufacturer may be difficult and/or expensive due to the global nature of the industry. If the manufacturer sub-contracts to a local company, it is unlikely that the support will have much experienced. In practice, many of these tasks are added on to the duties of existing technicians and engineers within the NMHS after training and experience. This ongoing support is crucial to a successful radar programme.

If many radars will be procured over time, the Tender should consider whether all the components be identical; whether the latest and better components will be acceptable; or, whether there will be a harmonization phase near the end to ensure that software and hardware updated to the same or the current version.

A related issue is the access to key personnel. Procuring a radar goes well beyond the installation milestone. It is also about building a relationship with the manufacturer for trouble shooting, upgrades and enhancements and accountability. Experience, expertise and capacity for long term support means the existence and access to key personnel.

Sample Tenders

Tenders are openly available documents once they have been issued. WMO has collated a number of them for reference (Annex C: Sample Tenders of this document). There are a variety of tenders from purchasing many radars, to single radars and to upgrading existing radars. Some emphasize project management, compatibility with existing software or data quality. Others adopt a technical, features or performance approaches.

Tender Evaluation

The evaluation criteria should require documented evidence of performance and not just statements repeating the requirement. This can take the form of engineering and climatology analysis for structural specifications, data analysis from similar radars for the radar technical specification, curriculum vitae of the key personnel that include their experience and qualifications for project

management and of key personnel and references for reliability, robustness or life cycle management performance.

A useful criteria is to use the concept of "Technical Readiness Levels (TRL)" to restrict the bids to existing proven systems or to open the bid to the latest innovations and prototypes. This may be used to restrict the bids to existing known radar manufacturers. On the other hand, if the goal is to foster the development of new local radar manufacturers, this may not be required.

A verification process is useful and should be stated in the Tender. This is the opportunity to clarify any ambiguity in the evaluation or even in the requirements. Verification could take the form of a physical or virtual visit to an existing radar or one in the factory, to validate the technical hardware performance (e.g. pointing angle, antenna acceleration, remote continuous operation for 1 week or more) and perhaps include data analyses for some evaluation criteria (e.g. polarization performance in drizzle or light rain). Many of these tests will be repeated at the Site Acceptance Test but it will be too late at the point if there are significant issues.

Post-Contract Award Activities

Once the evaluation is done and the contract is awarded, it is critical to conduct a review (s) of the procurement with internal stakeholders and with the manufacturer. This is a major milestone and detailed information of the technology and the manufacturer capacity is available for the first time. It is impossible to specify a radar system in an Tender sufficient to make detailed implementation plans.

- Did the award match or exceed the optional requirements and how does this impact the programme?
- Are the implicit assumptions in the Tender correct?
- Is there an understanding within the Tender bid and the Tender implementation team (may not be the same)?
- Are there additional requirements that are imposed within the contract?

A new project plan may need to be developed, certainly revised and an implementation plan created.

Civil Works Component

The decision is whether to include site preparation (clear lands, build roads, construct shelters, install power and telecommunications) as part of the procurement or whether this will be the responsibility of the NMHS and other contracts. The site procurement and preparation can take a year or much more.

Regardless, local sub-contracts will need to be issued for the site preparation as there are local building, electrical and telecommunication standards to follow. Coordination of construction of the site, installation of power, telecommunications, specification and installation of the radar tower and shelters need to be tightly scheduled.

Factory Acceptance:

Before the radar leaves the factory, it undergoes factory acceptance to determine whether the radar meets the Tender specification and evaluation criteria. Manufacturers may also have their own quality management processes and technical procedures which are often superior to that of the customer due to their expertise and experience. Not all manufacturers will have the complete radar installed at the factory or able to radiate. Some evaluation or acceptance criteria, system or end to end type requirements, may only be not be done during site

acceptance with weather. Hence, the evaluation criteria needs to be carefully considered and a combined factory and site acceptance plan should be formulated. In any case, the evaluation criteria must be stated to require verifiable documented evidence of performance. Using the intended data sampling and scan strategy would make the testing relevant to the envisioned operation of the radar.

Radar Installation

Installation of the antenna, the radome and the radar is generally organized by the radar manufacturer. Depending on site preparation and access issues, this can take two weeks or longer. Wind and weather can play a role as calm days are required to hoist the antenna and radome onto the tower.

Site Acceptance and Radar Configuration

The radar undergoes site acceptance and may repeat many of the same tests as in the factory acceptance.

The radar configuration can be done either by the manufacturer or by the NMHS after training. Configuration refers to setting up the radar for data sampling (number of samples, range and azimuth resolution), signal processing, scan strategies, setting up the ground clutter and other (EMI, Wind Farms) filters, data recording and calibration. Expertise and understanding of the trade-offs is required and the radar manufacturer can help but the responsibility of acceptable data quality lies with the NMHS user. Data and/or products need to be transmitted from the radar site to users or for downstream data processing and visualization.

Development and Training

Radar specific technical training, knowledge of radar products and capacity building is essential to the effective use of weather radars and networks.

Initial radar training is needed shortly (as soon as possible) after contract award for NMHS personnel to develop the concept of operations. This needs to created, as soon as possible, as the radar installation will have technical and capacity building requirements for other parts of the radar program and forecast system.

Radar specialists will need to know the capabilities the radar processing to remove ground echoes, produce end-user products and to determine which to produce and on what time schedule. The monitoring department may need to know how to exploit new diagnostic information that may be provided by built-in test equipment. Telecommunications will need to know file sizes for data or transmission capacity estimates and archiving. The forecast system will need to absorb and process the new data and products for inclusion in downstream applications or for visualization for the meteorologists or web pages. Adaptation to the radar data by downstream systems can take a long time. Appropriate training, data/product samples and case studies from other radars may accelerate these adjustments.

Technical radar hardware training is best done hands-on with an operating radar. This may be at the factory acceptance (depending on whether there will be a rotating and radiating radar system available) but certainly at the site acceptance phase.

Some generic training on the use of their radar products may be provided by the radar manufacturer. However, specific meso-scale meteorology training for early warning and nowcasting, relevant to the local area, requires time to acquire sufficient data and experience in preparation of forecasts and warnings as well as optimally configuring the radar to meet the needs of the NMHS. Given the capacity building and training required, this commissioning phase (site acceptance, configuration and parallel operations) could be extensive. External experts may be invited to conduct best practices and forecast training to accelerate the process. As knowledge in using the radar develops, the requirements evolve. A research and development program (from hardware to applications) is critical to sustainability of the radar network.

Radar Networking by Collaboration

Consideration should be given to developing collaborations for data sharing. Other agencies such as the hydrology, aviation, military or civil protection agencies may operate radars with weather capability. They may satisfy many of the requirements or enhance planned networks. Other NMHS' may cover border areas.

Collaboration and cooperation in sharing weather radar data and technical capacity amongst NMHS or other agencies could potentially result in considerable cost savings and therefore greater service levels. Increased coverage will provide longer lead times for early warnings and nowcasts, improved model performance through verification, validation and eventually data assimilation, redundancy in case of outages and result in efficient network design and use of resources.

Radars are a complex technology and building capacity for its support requires ongoing investment in people and expertise. Sharing of this expertise and capacity would greatly reduce the risk of the initial investment, improve service levels with greater availability and higher quality of data.

Weather radar networks may not be designed to include air traffic control and other radars, and there are challenges with merging inhomogeneous radars from antenna beam patterns to data access and format, but their inclusion can help fill gaps and increase low level coverage below 500 m or so. An example is the ASR9 Air Traffic Control radar that is designed to detect and track airplanes. It has a "fan" beam, 2° in azimuth and 6° in elevation and makes a complete rotation in 4 seconds. With integration of the data over 30 seconds, it is able to produce usable weather information for severe weather detection and warnings.

Quality Management and Availability

Sampling Requirements

Different applications have different signal, spatial and temporal sampling requirements. The Rolling Review of Requirements process maintains observations requirements. The nature of the weather, data sampling and signal processing govern the quality of the data but it is the data processing and application that determines the quality of the data can be tolerated.

The concept of quality is an fuzzy and a mixed concept. It has many meanings and metrics. In some cases, quality means frequent updates (<2 minutes) and to others it means (parameters with low variance and therefore slow updates. Lower data quality (data with higher variance) may be compensated at later stages of the processing through averaging or smoothing. It requires a thorough understanding of the user applications and available radar technology, an end to end view is needed and scientific expertise is required.

Operations

Modern radar system are generally very robust, reliable and designed to operate remotely and automatically via computer control. Most radars generally run a fixed schedule of 5, 10 or 15 minute that run continuously. In some systems, the schedule may be changed by an operator or the radar control program may reset the schedule automatically based on the data itself. This latter mode of operating radar requires sophisticated radar users.

Depending on the radar system, automatic on-site radar monitoring equipment (Built-In Test Equipment) will provide status information and can even shut the radar down automatically. Calibration scans for noise measurements or for the sun (for power calibration and pointing accuracy) may be configured to track the radar performance.

Modern radar systems are designed so that operators can access the radar computers and radar remotely. However, this requires good telecommunications to the site. Some radar systems can even be operated with “text messaging”.

An uninterruptible power supply (UPS) should be considered mandatory. Power at remote sites is not always of good quality and lightning may degrade the quality, so smoothing or conditioning the main power using a UPS will stabilize the power and reduce many outages and restarts due to surges in the power.

A generator (diesel or otherwise) is an option. They are sufficient to operate the radar for a few hours (depending on the size) and are good for temporary but short outages but not for long outages of the main power.

Calibration/Maintenance

Current radars are designed to operate automatically and they quite stable in terms of electronic performance. Receivers are quite linear and electronic single point calibrations can be efficiently and automatically done. Yearly checks by qualified personnel are recommended. The sun can be used to perform approximate routine calibration of pointing accuracy (elevation and azimuth) as well as power calibration (to a limited extent) and some dual-polarization parameters. This can be automated. Mean Doppler velocities are generally unbiased but limited velocity spread is critical to ground clutter filtering and can be checked using fixed ground echoes. Polarization parameters require light drizzle conditions and while the measurement could be automated, it requires require interpretation.

Depending on the telecommunications capacity and archiving procedures, general computer maintenance of disk space may need to be done.

Every few years, tree trimming (if permitted) may be required to reduce local obstructions. General site and road maintenance is expected.

Monitoring

Many current radar systems have Built-In Test Equipment to monitor key components of the radar (e.g. transmitter power, noise levels, frequency and many more parameters) and even the radar infrastructure (e.g. temperature, computer disk space). The information is generally small in size and can be transmitted out of the radar site on a schedule (e.g. minutely, hourly, daily) for remote monitoring of the radar. This information is valuable in the diagnosing of faults in the event of failure and can help plan and save unnecessary service visits to the radar site.

Developing specialized products based on the radar data for the technical diagnosis should be given consideration. Fig. 21 shows examples of data products that reveal hardware issues. Monitoring of the transmit-receiver switch via aggregation of radar data can prevent damage to the sensitive receiver and aid in the data quality. The distribution of reflectivity with range (Fig. 21, left; instantaneous or accumulated) can reveal Transmitter-Receiver switch failure. The top figure shows a good situation where the distribution of reflectivities is the same at all ranges in a uniform weather situation (stratiform precipitation). The bottom show the situation where the switch is slow to recover and the reflectivities near the radar (< 20km) are under-reported. Monitoring for antenna performance (comparing actual or read-back angles versus command angles) can allow for pro-active scheduling of these long lead-time repairs. This can improve radar availability and reduce repair expenses. The distribution of the difference between reported and commanded elevation angles (Fig. 21, middle) showing excellent (top), typical (middle) and poor (bottom) antenna pointing precision. All have slight biases. Precipitation accumulations (Fig. 21, right) very effectively reveal blockage issues, effective range and calibration biases. Blockage due to lightning rods/cables reduce the accumulation amounts in preferred azimuths.

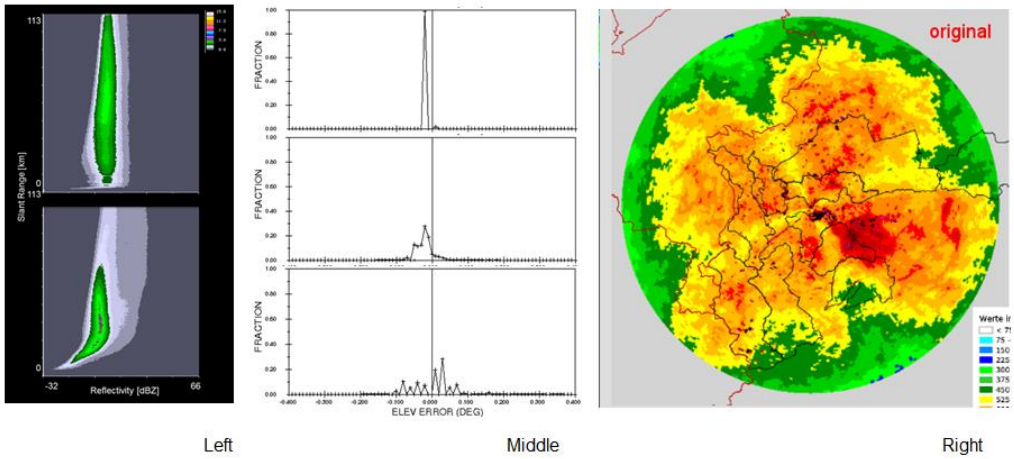

Figure 21: Examples of systematic monitoring of radar data to diagnose radar hardware issue. See text for details.

An automated weather station located at the weather site with wind and precipitation information (and icing information) would help the diagnosis of radome wetting or icing that will help interpret the radar data.

Radar Network Monitoring

In spite of all the efforts, absolute calibration is still a challenge due to the number of sub-systems. Applications have been develop to perform inter-radar calibration within a network. Assuming that the reflectivity statistics of neighbouring radars are the same, pair-wise biases can be estimated. If the biases exceed a threshold (generally around 1-2 dB), technical assessment of the source of the biases are investigated and adjustments are made. Fig. 22 shows an example of a network monitoring application show intra-network biases over 30 days within the U.S. – Canadian weather radar network. Less than 1 to 1.5 dB difference is common. One particular radar is low (green, CXX) and one is slightly high (XNC) and may require attention. It is updated ten minutes for a thirty day average.

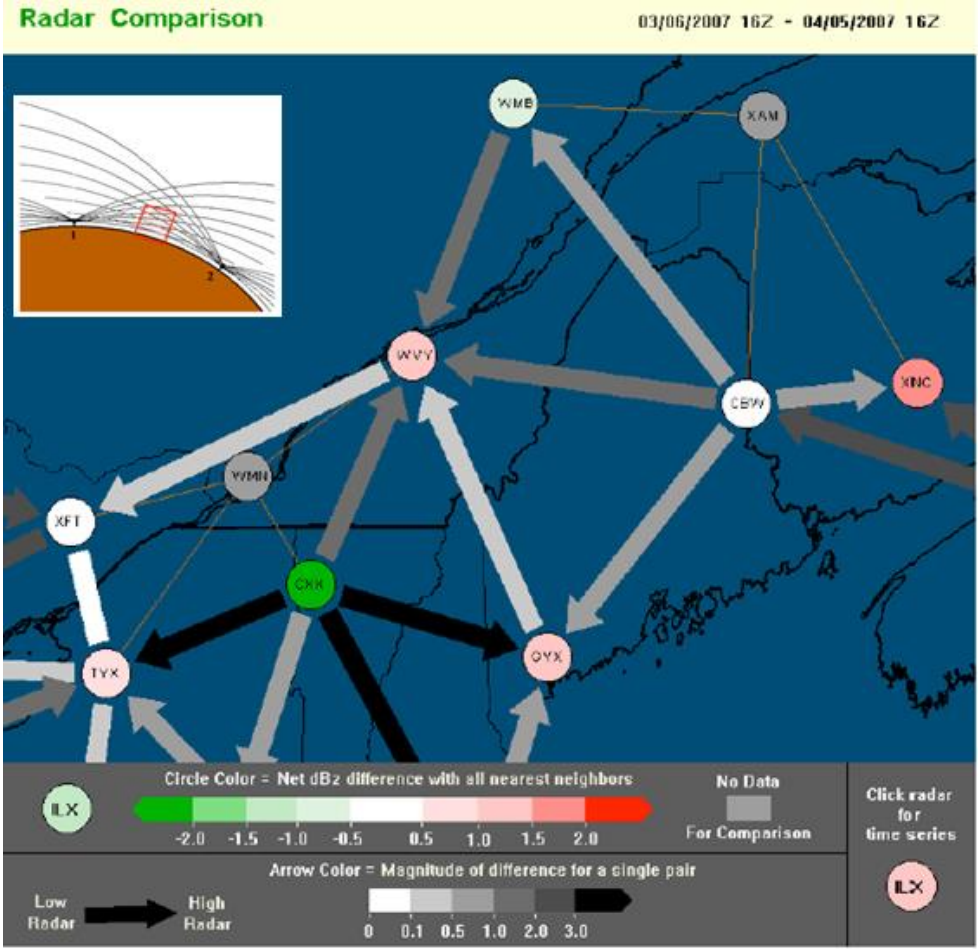

Figure 22: An example of a real-time assessment of the relative reflectivity biases. The inset figure shows where the location of the data which is used for the inter-comparison.

Data Processing

Radar and Radar Network Processing Requirements

Weather radars detect everything in its beam and the atmosphere can change the radar beam path and cause mirage effects. Fig. 23 shows that external targets and atmospheric conditions affect the radar data. The weather radar can detect or blocked by various types of static ground clutter (mountains, buildings, trees, wind farms), moving targets (insects, birds, planes, cars, trains) and other sources of electro-magnetic energy (radio local area networks, sun, other radars). Also, the pencil beam of the radar spreads with range which smooths the data. Due to the curvature of the Earth, the beam increases in height with range and so it may partially (beam not completely filled) or completely scan over (overshooting) the falling precipitation. If the precipitation is heavy, the radar signal may be partially or totally attenuated. The atmosphere can change the beam propagation path and be

reflected from the ground and produce mirage like effects. The + or – signs in the figure indicate whether the radar reflectivity is augmented or diminished by the feature. Traditionally, forecasters have been trained to interpret the radar products for these artefacts for the provision of early warnings. For quantitative applications and automated detection of hazardous thunderstorms, even perfectly calibrated radars need automatic quality control of the radar data to mitigate these issues. Hence, processing for data quality and applications is an explicit part of the radar network system design.

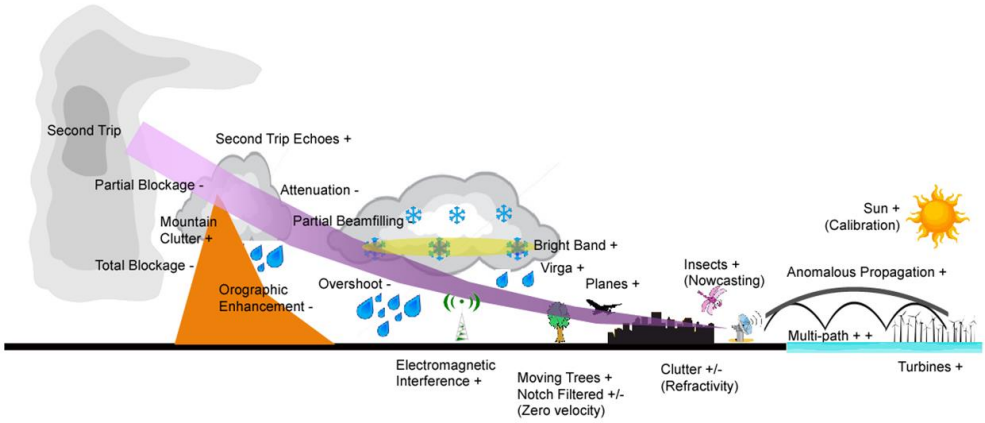

Figure 23: The weather radar is affected by the environment and by physics. See text for details.

For quantitative applications, the radar data must be converted into precipitation intensity, precipitation type, wind speed and direction. For severe weather applications, pattern recognition techniques are used to identify the location and intensity of thunderstorms. For hydrological applications, integration, sub-setting, target identification and conversion to precipitation intensity are required. This is a substantial challenge due to the accuracies required.

Data, Transmission and Visualization

This processing may occur at the radar site with commercial radar processing systems. If there is sufficient bandwidth, the data may be transmitted to a central site where this occurs. Typical dual-polarization volume scan radar data files is typically around 10 Mbytes in size (depending on number of parameters and size of parameters collected). This assumes 20% compression ratio. The data is collected every 5 or 10 minutes. So, the minimum bandwidth to transmit the data is about 8 Mbits per second. An order of magnitude more of bandwidth is actually required for timeliness and processing considerations.

If there is insufficient bandwidth for the data, products can be created at the radar site with perhaps reduced resolution for transmission to end users or the central

processing facility. Products (image or data-like products) are typically 20-50Kbytes in size and so have much reduced bandwidth requirements.

For forecasters, visualization capabilities are critical. Geo-location and integration with other data sets (satellite, lightning, surface data), are needed to form an accurate and consistent picture for effective weather warnings.

Archiving and Retrieval

Archiving of the radar data should be considered. The value of the archive increases with time as it enables high resolution climate applications, provides underlying data for quality management analysis for radar support and network design. Radars are replaced every 15 or more years and this sets the retention time for the data to have a single life cycle of information. As with all data archiving systems, commensurate retrieval systems much be developed as well. Archival of long term data radar data sets is normally the responsibility of the NMHS.

Glossary and Acronyms

RADAR	Radio Detection And Ranging
LIDAR	Light Detection and Ranging
WSR88D	Weather Surveillance Radar 1988 Doppler also known as NEXRAD (United States)
NEXRAD	Next Generation Radar (United States)
TDWR	Terminal Doppler Weather Radar (Wind shear radar)
ASR9	Aeronautical Surveillance Radar 9 (Air Traffic radar)
DEM	Digital Elevation Model (Terrain Height data(
ADM Aeolous	Atmospheric Dynamics Mission - European Space Agency Mission for lidar wind measurements from space. Aeolus is "keeper of the winds" from Greek mythology.
RFP	Request for Proposal or Tender
GOS	Global Observing System
GCOS	Global Climate Observing System
WIGOS	WMO Integrated Observing System
WMO	World Meteorological Organization
RRR	Rolling Review of Requirements
CIMO	Commission of Instruments, Methods and Observations
IMO	Instruments, Methods and Observations
NMHS	National Meteorological and Hydrological Services
WRDB	WMO Weather Radar Database

Resources

Who to call for help?

There are several resources available and include: WIGOS RRR, CIMO Guide, CIMO IMO Reports, Training Workshops, other NMHS's, conferences and trade shows.

GOS RRR	The WMO Global Observing System maintains a table of the observational requirements that is constantly being reviewed called the Rolling Review of Requirements. This can aid in specifying the minimum observing or sampling requirements.
CIMO Guide	CIMO maintains an overview of radar technology and applications as part of the CIMO guide.
IMO Reports	In the past, various activities and workshops were published as reports. In particular, the training and maintenance guide is a valuable resource.
WRDB	The Turkish Met Service maintains an on-line database of weather radars. This is most useful to be informed of the current status of operational weather radars.
NMHS	Consultation with other NMHS or consultants could provide aid in understanding but also in the design and/or procurement of weather radars. The Observation Department at WMO could aid in making linkages. Visits are invaluable to see the complete spectrum of issues.
Trade Shows at Conferences	Conferences tend to be for the advanced user. However, manufacturers often exhibit at conferences and trade shows.

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Annex A: A Radar Primer

The basic weather radars works by sending pulses of energy by a rotating antenna (in all directions) into the atmosphere. The antenna is generally parabolic producing a pencil beam of the order of 1° in azimuth and elevation. Phased array, flat panel antenna are emerging. The pulse is reflected by various targets and the minute energy that is reflected is received by the radar. These signals are then sorted by time, location and processed (averaged and filtered to improved detection and quality) to produce polar coordinate radar data as a function of where it is pointing (in terms of azimuth and elevation angles, range and time). Attributes of the data depends on the radar hardware and may include reflectivity, Doppler and dual-polarization information. This radar data is remapped to geographical coordinates and further processed to remove artefacts, converted to precipitation rate and to various products for severe weather diagnosis. Fig. 24 shows a schematic illustrating how a radar operates. The options for various components are discussed here.

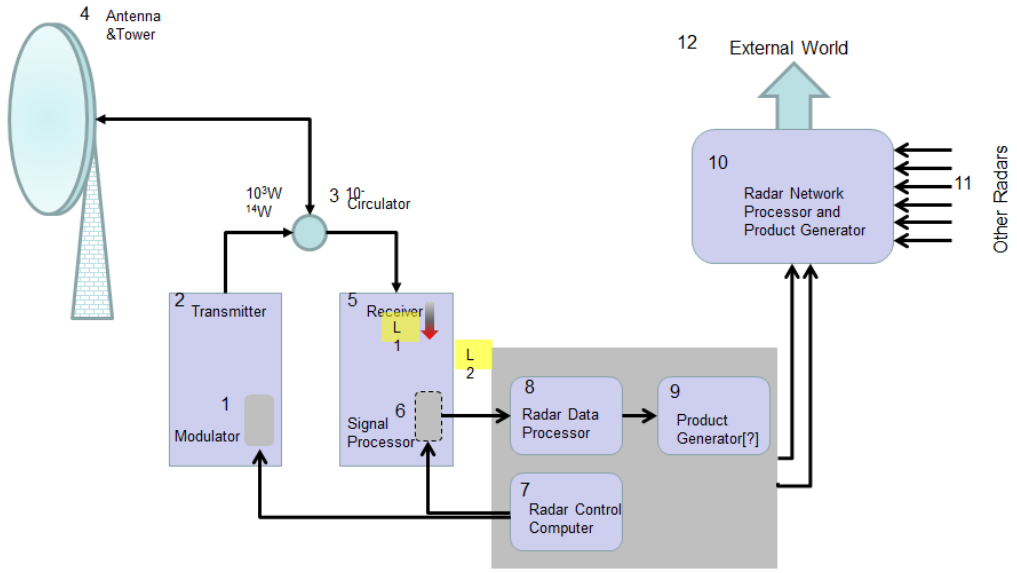


Figure 24: The schematics shows a block diagram of a radar system.

When the radars are networked, the radar data is transmitted to a central processing facility to generate products with greater spatial extent.

The weather radar is a very sensitive instrument and so it can detect targets very far away. At long ranges, the curvature of the Earth becomes a significant factor. At long ranges (e.g. 200km), a radar beam initially pointed at the horizon will no longer be skimming the surface of the Earth but be several kilometres above the ground and extrapolation of the information to the ground is required. Fig. 25 shows graphs of critical concepts of Doppler weather radars.

In fig 25a, the shaded coloured polygons represent the height and the depth of 1°, 0.65^o and a 6° degree beam width radars, with the bottom of the beam at 0° elevation and located at 0 km, 300km and 150 km range, respectively. Precipitation and winds significantly evolve in the lowest few hundred meters of the atmosphere (grey box) and are barely observed at about 100km. Inclusion of even 6° fan beam radars (red polygons) can produce useful data though at shorter ranges. The depth of the beam at 20 km range is equivalent to that at 115km or 190km, range for the 1° and 0.65^o beam width radars, respectively. It is evident that Earth curvature effects are significant at the distances that radar can observe. At far ranges, a radar beam that is pointed horizontally is significantly above the Earth's surface.

Fig. 25b illustrates the Doppler Dilemma, which is a trade-off of maximum range vs maximum velocity and is highly wavelength dependent. The limits are within the velocity and range requirements for weather surveillance and therefore poses a dilemma for a radar network designer.

Fig. 25c shows that a broadening and rising beam smooths, but also partially fills the radar volume, resulting in an under-reporting of the reflectivity with range.

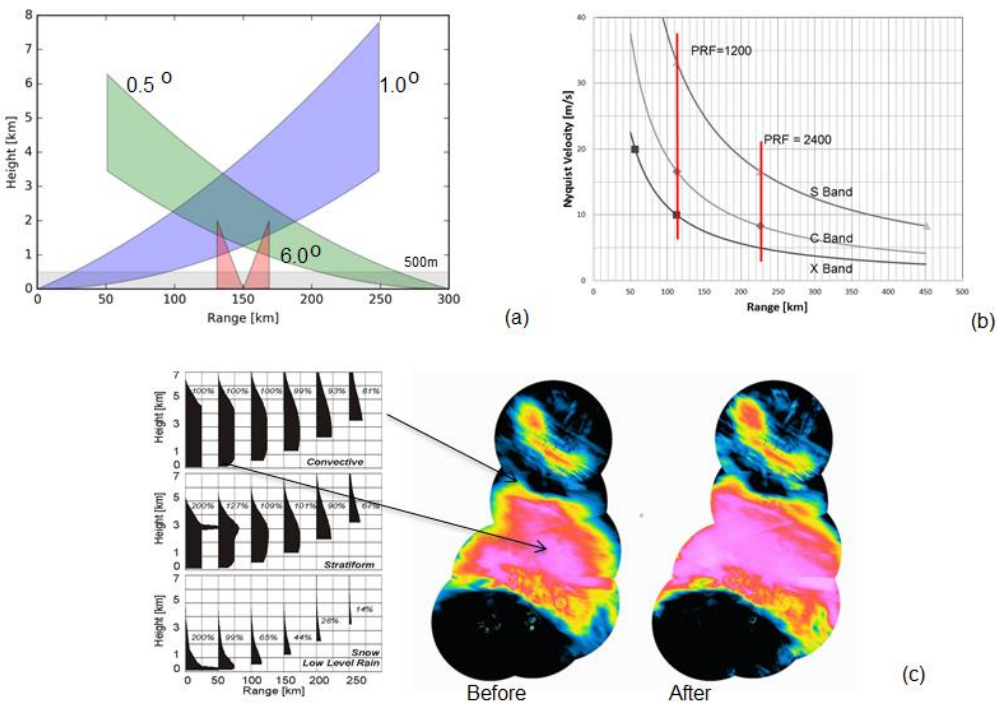


Figure 25: Technical considerations for radar network design. See text for details. Note that for (c), the profile at zero range is treated as the truth for the profiles at longer range.

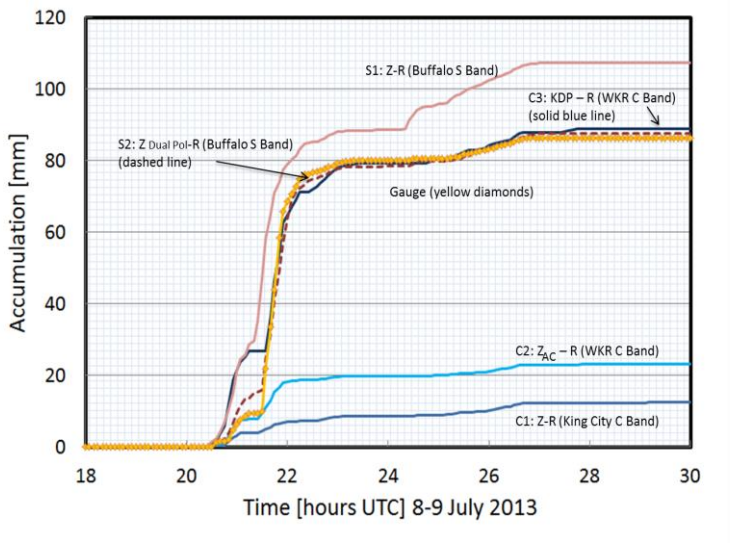
The weather radar, not just sees only precipitation, but sees all targets in its view. For precipitation-only or hydrological applications, removal of or compensation for these non-precipitating targets must be done.

Annex B: Radar Technology

Radar scientists, engineers and manufacturers attempt to improve the technology to overcome the limitations but also to improve the performance, reliability and robustness of the radar and radar network.

The Transmitter Sub-System	
Wavelength	The radar transmitter generates high peak power energy in the microwave region based on impulses from the modulator. Microwave energy is conducted via waveguides. Operational radars operate at 3 primary frequency bands (2 to 4 GHz, 4 to 8 GHz and 8 to 12 GHz) and are designated S, C and X bands, respectively. The corresponding wavelengths are nominally 10, 5 and 3 cm, respectively. This has a significant impact on the radar capabilities – Doppler Dilemma, attenuation, sensitivity, beam width. Transmitters are specific to each frequency and pragmatically, transmitters are limited in the amount of peak power that can be transmitted at each frequency. S band transmitters generally transmit more power than C or X band transmitters and this reduces the impact of frequency on sensitivity[1]. Also, radar operators generally reduce the transmit peak power to reduce failures and increase availability.
Attenuation	As the radar propagates through heavy precipitation, there is a gradual loss of signal intensity due to extinction. The smaller the wavelength, the greater the attenuation. The signal can be totally lost depending on the location of the heavy echoes. Polarization techniques are available to recover the signal if it is not totally lost. Fig. 26 shows a meteogram of accumulated rain from a gauge (yellow line with symbols) from a heavy flooding case. The bottom (C1) and top (S1) lines are accumulations based on traditional reflectivity-rain rate from a C-Band (40 km from gauge site) and a S-Band (100 km from gauge site) radars. The C2 line is a Z_{DR}-only attenuation correction, C3 uses a KDP technique from the C Band radar and S2 uses the dual-pol technique from the S-Band radar. The improved Buffalo S- Band results are attributed to removing the hail bias using the dual-pol particle classification technique. This illustrates the impact of dual-polarization to quality control the data for attenuation and for echo type to improve quantitative use of radar, particularly at C Band.

[1] At first glance, the radar equation indicates that shorter wavelengths are more sensitive radars but the power transmitter limitations confound this notion.

	 **Figure 26: An example of the impact of attenuation correction and hydrometeor classification on quantitative use of radars with dual-polarization capability and its particular impact with shorter wavelength radars.**
Coherent vs non-coherent transmitters	There are two categories of transmitter. Coherent transmitters are high quality, stable in frequency, phase and phase jitter (also called phase noise) and inherently have Doppler capability. These are klystrons, travelling wave tubes and solid state type transmitters. Low phase jitter is required to filter out the most significant clutter. Non-coherent transmitters, which are basically, magnetron systems, drift in frequency, have random transmit phase, require frequency control management, require phase monitoring of the transmit pulse to provide Doppler capability. They are smaller, cheaper and meet most weather radar requirements.
High Power Magnetron (non-coherent)	The classic transmitter type is the co-axial magnetron. It is a power oscillator and the phase of each pulse is random (incoherent). For Doppler capability, the phase of the received signal is processed with respect to that of the most recent transmitted pulse and it is often called a “coherent on receive” radar.
High Power Klystron (coherent)	The klystron is a power amplifier and it amplifies a low power input signal and the phase of each pulse is the same (coherent transmitter). This is called a “coherent on transmit” radar. Echoes from the previous transmitted pulse can appear as data – thereby creating ambiguity in interpretation. To separate the first trip and subsequent trip echoes, the pulse can be phase modulated

	or coded. In this case, a phase shifter is required (not shown in the Fig. 24).
Low Power transmitters (coherent)	These are coherent type devices such as klystrons (low power versions), travelling wave tubes or solid state and are generally low power. Some solid state transmitters are implemented with numerous power modules to increase the total transmitted power and meet the sensitivity requirements. The modules are redundant and hot-swappable which creates a very high availability radar system design. Solid state transmitters are relatively new but they are inherently stable, robust and reliable. For operational weather radars, these low power system require pulse compression to meet detection requirements (range resolution and sensitivity). Non-linear frequency modulation are employed to manage range side-lobe artefacts.
The Doppler Dilemma	
Doppler	Weather radar measure the difference in phases from pairs of pulses instead of the frequency shift within a pulse due to lack of technology to measure the true Doppler shifts at high frequencies (~5Ghz). Virtually all commercially available radars have Doppler capability.
Maximum Range vs Maximum Velocity	For Doppler, relatively high number of pulses need to be transmitted in short period of time (typically 1000 pulses per second). This is called the Pulse Repetition Frequency (PRF). This creates a trade-off between maximum Doppler velocity and maximum range. This trade-off is known as the Doppler Dilemma (Fig. 25) as these maxima are within the weather surveillance requirements. Ranges of more than 250km and greater than 36 m/s are operationally required for weather surveillance. The range requirement may decrease with specific applications (e.g. aviation terminal operations for detection of wind shear). These limits are also called the first trip, unambiguous or Nyquist limits. Radar wavelength and network radar designs plays a significant role in resolving this classic problem. Consideration of requirements, range and velocity extension techniques need to be considered when resolving this Dilemma For non-Doppler operations (reflectivity or dual-polarization), low PRF can be utilized to extend the range but the velocity limits will generally be too low to be easily usable.
Range Extension	Configuring the radar with limited Nyquist range results, in a data quality issue, where echoes beyond the maximum range can still be detected by the radar and may appear or overlap with echoes within the Nyquist range. These echoes are called multi-trip

	echoes. Continuity and Doppler techniques have been developed to locate these echoes correctly using Doppler. Continuity techniques utilize data taken a low and high PRF or high and low maximum range, respectively and can often (but not all the time) locate echoes in the right location if they are isolated or sometimes locate echoes when they overlap (effectively isolated due to echo power difference). Doppler techniques rely on statistics. Several pulses are processed to estimate the mean phase or Doppler velocity. • In a non-coherent radar, echoes received from the previous transmitted pulse appears as noise since their phases are random with respect to the most recent transmitted pulse. If the processing is done with the previous pulse, then echoes in the second trip can be recovered. In this kind of radar, the transmitted phases are random and hence the phases of each transmit pulse must be measured. • In a coherent system, the transmitted phases are the same and so the phase must be modulated to produce a pseudo-random effect. In fact, sophisticated modulation schemes have been developed to recover multiple trips. • The technique are superior to continuity techniques. • The phase noise is the limiting factor in the technique and so coherent systems have greater multiple trip recovery capability due to the lower phase noise. • This is one of the few instances where there is no trade-off except in terms of computational complexity which is not a significant issue. It cleans up the first trip due to second trip echo interference. This is nice additional feature to extend the range of the radar for an upgrade to an existing radar but should not be specified as the solution to meet the maximum range requirements for a new radar as the data in the extended range is not always recovered.
Velocity Extension	Velocities that are beyond the Nyquist velocity are aliased or folded back into primary interval. Velocity extension techniques rely on continuity or on combining estimates from two or more measurements taken with different Nyquist velocities. Continuity techniques, manual or automatic, rely on interpreting two dimensional patterns of Doppler velocity. If the echo distribution is incomplete, interpretation may be ambiguous. Multiple Pulse Repetition Frequency (PRF) or Pulse Repetition Time (PRT) techniques rely on Doppler velocity differences to determine the true velocity to a larger interval, called the Extended Nyquist velocity. The technique relies on assuming that the

	velocity estimates are from the same true velocity which may not be the case in hazardous high wind shear areas. The dual PRF technique relies on data taken on adjacent radials and the dual PRT technique relies on data taken on the same radial but with alternation long and short pulse intervals. The latter technique has poorer clutter rejection capability.
Dual Polarization	
Polarization Radar	Polarization capability provides information about the shape of the target. This can be used to identify different types of hydrometeors and targets. Hence, it can be used to improve the quality of the radar data for quantitative precipitation estimation and data assimilation. There are several kinds of polarization radar: linear or circular (elliptical), dual-transmitter and single transmitter types. Traditional weather radars transmit and receive horizontally polarized pulses. There are radar with vertically transmitted pulses but the echo returned from horizontally polarized pulses reflecting from horizontally oriented large raindrops is stronger. Dual-transmitter radars send alternating pulses of horizontal then vertical polarization and there're are two receivers to measure the returned signals. However, this requires a high speed high power switch or two transmitters. A robust and reliable high speed switch has proven to be elusive for operations. Most operational dual-polarization radars have one transmitter and two receivers and the feed horn is set to transmit a pulse that is linear but is oriented at 45° so there are equal power in the horizontal and vertical.[2] The system receives both horizontal and vertical polarization information. This is known as the hybrid system and has proven to be pragmatic solution. Since, the transmit pulse is mixed, the complete scattering matrix cannot be determined bust is sufficient for hail and rain detection. The Linear Depolarization Ratio (which indicates how much power is leaked over to the other channel) which provides a clear signature of the melting layer is not retrievable. There are radars that measure LDR but at the expense of other polarization data moments. LDR requires that the reflectivity is above 30 dB above the noise level as LDR is about a thousand

[2] Circular polarization, often used in air traffic radars, is similar but where the horizontal and vertical powers are equal but there is a constant phase shift of $\pi/2$ radians between the two powers. The polarization is either called right or left hand circular depending on the convention.

	times lower in power than the total power.
Particle Classification	A simplistic overview of hydrometeor classification using dual-polarization parameters (Fig. 27). Z_H is reflectivity and is roughly proportional to particle size. Z (all power measurements) is proportional to ND^6, where N is the number concentration and D is the diameter, and so is strongly indicative of the largest particles in the sampling volume. Z_{DR} is differential reflectivity (ratio of Z_{VV} to Z_{HH}) is indicative of a distribution of particles with congruent shape and orientation (elongation in horizontal or vertical). ρ_{HV} is the correlation of the horizontal and vertical signals and so tumbling or poorly defined shapes yield low values. Congruent shapes yield high values. K_{DP} is the specific differential phase change (of the horizontal vertical signal) and similar to Z_{DR}. Smaller wavelength radars are more sensitive to attenuation and particle shape.

Parameter	Comment	Particle Type						
		Drizzle	Moderate Rain	Heavy Rain	Ice Crystals	Snow Aggregates	Graupel	Large Hail
Z_H		low	med	high	low	med	med-high	high
Z_{DR}		zero	zero	positive	zero	positive	zero – postivie	neg
ρ_{HV}		one	one	med	mod	low	low	mod
k_{DP}		zero	med positive	high positive	low positive	med positive	+/- low zero	+/- med zero

Figure 27: A simplistic version of a dual-polarization interpretation of hydrometeor type.

Implementation	Dual-polarization can be implemented with the receiver mounted on the antenna. This is particularly useful for upgrades or retrofits where there are constrictions precluding two waveguides. Reliability of good data quality relies on good temperature control of the electronics. It can also be implemented in shelters with two waveguides through the rotary joint.
The Antenna Sub-System	

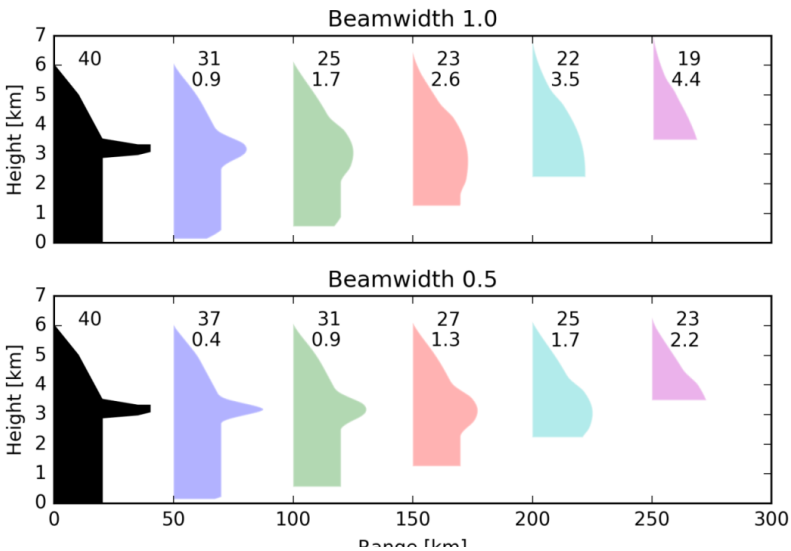
The Feed Horn and Parabolic Dish	The energy from the transmitter is transmitted via waveguides to the feed horn which then illuminates a parabolic antenna to form a pencil beam. Most commonly for operational radars, the feed horn is located approximately at the focal point of a parabolic antenna. The feed horn is held in place by struts that affect the energy distribution in the beam in a minor but discernible way. It can be moved along the axis of the antenna or it can have be shaped or tapered to alter the illumination. This affects the beam width, the side lobe locations and intensity in limited ways.
Beam width	The combination of the wavelength and the antenna size linearly determines the width of the beam. The larger the wavelength, the larger the antenna size to have the same beam width and vice versa. While, it is common to have a 1° beam width in weather radars; there is nothing special about 1° except that it is a nice number. Narrow beams have higher gain resulting in greater sensitivity and also greater range for hydrological QPE applications (without advanced algorithms) due to beam filling and lower scan angles (Fig. 28). Narrow beam radars can provide estimates of precipitation to farther ranges due to (i) increase sensitivity, (ii) lack of smoothing and (iii) beam filling. The figures shows a 90 day accumulation of precipitation. The radar on the left has a 1° beam and the one of the right has a 0.65^o beam. On the left, there is a fall-off with range at about 80 km range and about 100km on the right. Typically, 1° radars are effective to a range of 80 to 100km but this is dependent on the vertical extent of the weather. 

	Figure 28: Narrow beam radars can provide better estimates of precipitation to farther ranges. Beam smoothing and Earth curvature effects as a function or range are illustrated for a 1° and a 0.5° beam. A theoretical beam profile for stratiform precipitation is shown at zero range (The scale of reflectivity is 1dB per kilometer.). The beam is smoothed and rises with range. The numbers indicate the maximum reflectivity and the depth of the beam in kilometers.
Pedestal	The antenna is mounted to a pedestal and is capable of rotating in azimuth and elevation. Most radars operate with rapid changes in azimuth and slow changes in elevation. Elevation movement may be limited by the design of the antenna counter-weight structure or by specification. It is highly desirable that the antenna could point vertically in order to perform dual-polarization calibration.
Phased Array	Phased array antenna are emerging. This consists of a flat panel antenna with an array of active radiating elements. By electronically shifting the phases of the radiating elements, a beam can be formed and steered and typically provide about +/- 60° coverage. However, the electronic steering may only be in one plane, vertical or horizontal, requiring mechanical rotation in azimuth or tilting in elevation to provide three dimensional coverage, respectively. Some systems can electronically scan in both directions precluding the need for mechanical scanning but would require three panels to view all directions. For weather applications, the great advantage is that it reduces the mechanical demands on the antenna sub-system. It also opens up the possibility of adaptive rapid scan, multi-target (including non-weather) detection applications. Off bore-sight beam shapes may not be circular or uniform which will impact polarization variables.
Radome	Radomes are generally made of composite materials. They are installed to reduce the wind stress on the gears and motors driving the antenna. Radomes have hydrophobic coating to facilitate shedding of water that may strike the radome with an overhead storm. Wet radomes reduce the power transmitted particularly at short wavelengths. The radomes are generally constructed of pseudo-random panels in order not to affect (create biases) the polarization data.
Lightning, Safety Lights and Tower Structure	Tall structures require lightning protection, lights to indicate obstruction hazards to aircraft. Care is needed to avoid creating artefacts due to electrical cables running down the sides of the radome.

	Also, location of railings or other structures that may obstruct the beam may also create artefacts.
Modulation	
Modulator	The modulator generates impulses that trigger the release of energy by the transmitter.
Pulse	Operational weather radars operate by sending short pulses (0.3 to 2.0 μs, typically) into the atmosphere and listening for the return echoes. The width of the pulse determines the range resolution. The pulse moves at the speed of light and so the range to the target is determined by the time it takes for the pulse to travel to the target and back. The maximum range (also called the first trip) is determined by the time between transmitted pulses. The radar determines the time of the echo relative to the time of the most recently transmitted pulse. Radars can be set to measure virtually any maximum range but there are velocity and scan cycle time trade-offs. This is the traditional modulation scheme for operational weather radars.
FMCW	Frequency Modulated Continuous Wave transmits continuously and the frequency is varied (modulated) in a known fashion. Both the power and frequency of the returned signal is measured and the frequency is related to time and hence range. High range resolution can be achieved (with high frequency quantization or resolution) but only short maximum range. This kind of radar is not used operationally.
Pulse Compression	This kind of radar is a combination of a pulse and a FMCW radar. A long low power pulse is transmitted (e.g., 50 or 100 μs) that is changes in frequency (or modulated). It is used with low power transmitters such as solid state. The entire pulse is used to compute the energy from the target, whilst the frequency is used to determine the range to the target. The ratio of the physical pulse length to that of the resolution is called the compression ratio. Side lobe probes in range are created but can be mitigated through non-linear frequency modulation through signal processing. There is a data gap from radar to the first range bin (40 km+) as the radar cannot receive and transmit at the same time. To mitigate this, a short pulse(s) is transmitted to fill in this gap. This is an emerging area for weather radars. There is a significant sensitivity difference and also the potential for data discontinuities due to pulse calibration differences.
Processing	
Signal and Data Processors	The signal processor samples the “signal”, organizes them into range bins, averages, filters and processes in different ways into “data”, which are called moments (e.g. reflectivity, radial velocity, differential reflectivity, etc.). The sampled signals are called time series data or In phase-Quadrature (IQ) data or Level 1 data. The moments are called moment data, base data or Level 2 data. The “signal processor” is essentially one half of the brain of the

	radar. It can also perform quality control functions to remove noise and to remove ground clutter via “algorithms”. Signal processors used to be implemented in special high speed electronics but common desktop computers are sufficiently fast to perform this function.
Data Processor	The moment data is then collected and collated by a “data processor” that assembles, attaches metadata and creates data volumes. Quality control and application algorithms (e.g. convert reflectivity to rain rate), product generation and data management can also be implemented here. In some cases, output from the data processor can be used to modify the signal processing algorithms. Signal and data processors may now be implemented on the same general purpose computers.
Radar Control	A third processing system controls the radar sub-systems – the radar configuration setting, the sampling and scan strategies, antenna control and system monitoring.
Built-in Test Equipment (BITE)	Many modern radar systems have equipment and procedures for monitoring and calibration as part of the radar system. A stream of data reporting on the status of the radar can be generated in real-time (order of minutes) or daily.
The Receiver	
Calibration	For the support and maintenance, calibration refers primarily to checking that the receiver is functioning correctly. This is done by injecting power into the receiver from a signal generator (presumably well calibrated itself) and recording the output. The receiver will have a minimum value that it can report and this is noise level. Modern receivers are quite linear and some manufacturers require only a single test value. Modern receivers are also quite stable and require calibration on a semi-annual basis or less. Note: calibration for end-users often refer to converting the radar data to precipitation rate at the surface, after removing the artefacts and adjusting for evolution of the precipitation between the point of measurement (aloft) and the surface. This difference in terminology creates confusion.
Dynamic Range	Weather echoes strengths span a considerable range of intensities from -20 dBZ to 75 dBZ for very light snow/clear air to hail echoes, respectively. So the receiver must have a dynamic range of 95 dBZ to accurately capture the full range. In the past, receivers had logarithmic responses to meet this requirement. Linear receivers are required for Doppler measurements. They have limited dynamic range and modern receivers have essentially two front ends with overlapping ranges and overall dynamic ranges of more than 110 dB can be achieved.

Critical Performance System Parameters[3]	
Accuracy	This refers to bias and variance. Bias is the difference of the estimated mean and the true mean. Variance is the square of the deviation of the value from the mean or the spread of the measurements.
Sampling, Scan Strategy and Bias Correction	Note: • A sampling strategy for performance evaluation should be specified due to dependencies amongst the various radar configuration options • Specifying a scan strategy should be specified for pedestal servo tuning performance testing (though this is not indicated here as a critical performance parameter) • Absolute calibration of reflectivity is difficult and bias correction using gauges or other means is common
Minimum Detectable Signal (MDS)	This is an overall system reflectivity performance parameter (along with dynamic range). It takes into account the transmitter power, antenna gain, receiver sensitivity and signal processing. A typical sampling strategy should be specified. The variance is controlled by averaging – the more samples the lower the variance. The bias is controlled by calibration – sometimes done empirically. There are various ways in which to specify the minimum detectable signal. From a user perspective, specifying it as a reflectivity value at a certain range provides relevancy; for example, -8dBZ at 50 km. The value can be reported or transformed to other ranges (e.g. 1km or 256km) using the radar equation. $P = C\frac{Z}{r^2}, \quad C \text{ is the radar constant}, r \text{ is range and } Z \text{ is reflectivity}; dBZ = 10\log Z$ Eighteen dBZ is approximately 0.5 mm/h rain rate[4]. If the requirement is to detect rain out to 256 km, the MDS should be at least 18 dBZ at 256 km. This translates to 4 dBZ at 50km. 50 km is often used as it is the “sweet spot” for radar-gauge comparisons. It is far enough to avoid ground clutter (general) and the beam is not too high.
Phase Noise or Stability or Jitter	This is a performance parameter for Doppler capability. It is a measure of the purity of the phase from pulse to pulse. Coherent transmitter have the best performance but good co-axial magnetron systems are more than adequate in modern radars. However, even loose connectors can create phase noise. So this is

[3] See sample Tender’s for specifications and evaluation criteria

[4] This is derived fromthe Z-R relationship of Marshall and Gunn (1952), erroneously called the Marshall-Palmer relationship, $Z=200R^{1.6}$, w here R is rain rate in mm/h and Z is reflectivity in mm^6m^{-3}

	a test of the overall system quality including transmitter, the stable and coherent oscillators, frequency control as well as workmanship. Mean Doppler velocity can be estimated with even if the phase noise is high as long as the signal is very strong. But ground echo removal using Doppler filtering, range extension using phase coding, estimation of spectral width and recovery of radial velocity of weak signals would be compromised.
Differential Reflectivity	This is an macro performance parameter for dual-polarization capability. This is the ratio of the co and cross polar reflectivity values and should be zero when the antenna is pointed vertically as all the hydrometeors statistically have a symmetric shape. Alternatively, if the precipitation is drizzle or very light rain with spherical drops, then it should also be zero.
Correlation	This is a micro performance parameter for dual-polarization capability. It is the correlation of the cross-polar time series data. Distribution of hydrometeors with consistent vertical and horizontal backscatter have very high correlation.

Annex C: Sample Tenders

Canada – Replacement	20 radars are replaced with new ones at about 4-7 radars per year with sparse coverage (~400km spacing)
Canada – Upgrade	10 radars are upgraded to dual-pol

Comment [PJ5]: Homework for IF OWR.

This section to be completed after RFP's are collated.