

Guide to Operational Weather Radar Best Practices

Volume III: Weather Radar Procurement

2023 edition

WEATHER CLIMATE WATER



WORLD
METEOROLOGICAL
ORGANIZATION

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EXECUTIVE SUMMARY

The previous volumes of this *Guide to Operational Weather Radar Best Practices* (WMO-No. 1257) on weather radar network programme design and weather radar technology (Volumes I and II, respectively) provide background and other information relating to the organizational-wide impacts and considerations associated with procuring a weather radar.

However, radar procurement and establishing technical specifications are just the starting point. The previous volumes also describe the notional concepts that should be addressed before determining the requirements and specifications of the radar tender, including services and applications envisioned or expected to be supported. Technologies that support the robust operation and maintenance of the radar are recommended.

This Volume III of the *Guide to Operational Weather Radar Best Practices* (WMO-No. 1257) therefore presents an overview of the radar procurement process and provides examples of tenders of radar systems by WMO Members.

A successful radar implementation requires distinct overlapping phases covering:
(a) determining the requirements, technical specification, tendering and evaluation,
(b) installation, implementation and configuration and (c) operational support and maintenance. Each phase has a distinct identity, a distinct skill set and distinct team members. Interaction and information exchange among the teams are critical; otherwise, unnecessary gaps develop.

The present volume is aimed primarily at those responsible for managing the radar procurement process and writing procurement documents. Radar procurements are generational, and so there is likely little existing experience and expertise, particularly for first procurements. This volume should be used in conjunction with Volumes I and II. It presents the various components of a generic tender, describes different styles of tenders and summarizes examples.

1. INTRODUCTION

The process of procuring a radar is different compared to that for other observing systems. Radars are constantly evolving. They are not mass-produced items, and are made up of components (for example, civil works and environmental conditions) that may need to be tailored to local standards and configured to local environmental conditions (for example, scan strategies for local or regional weather systems, ground clutter, blockages and electromagnetic interference). Radar procurement is therefore a daunting task as there is a myriad of highly technical decisions to be made.

This volume of the *Guide to Operational Weather Radar Best Practices* (WMO-No. 1257), on weather radar procurement, outlines key considerations for the procurement process. It discusses radar requirements, radar project programme teams, tender issues and tender evaluation. It also provides examples of tender documents that have been previously established by WMO Members.

There is great variation in the example tenders, not only due to the differences in the technical requirements themselves, but also from the technical experience and knowledge available within the purchasing organization. Thus, the objectives, scope and constraints are distinct within each of the example tenders. The purpose of the present volume is to illustrate the various approaches that can be taken and describe how and why they might or might not be appropriate in various situations.

The first volume of the *Guide to Operational Weather Radar Best Practices* (WMO-No. 1257), on weather radar network programme design, provides a holistic perspective of the implications of establishing a radar programme. A radar will be a disruptive technology providing significant and impactful warning services. Volume I outlines the opportunities provided by, and the programmatic aspects of, introducing a weather radar into a meteorological service. These include identifying the intended service and applications, the weather environment, the observing requirements and the technical specifications leading to procurement. Volume I also identifies that efficiencies can be achieved with radar data-sharing and collaboration, and recognizes that maintenance and support are paramount.

The second volume on weather radar technology (*Guide to Operational Weather Radar Best Practices* (WMO-No. 1257), Volume II) overviews the critical weather radar technologies and terminologies for new procurement managers and teams to be aware of. It recommends consulting radar experts (for example, the WMO Commission for Observation, Infrastructure and Information Systems Joint Expert Team on Operational Weather Radar) to sort through the issues and technologies, particularly for those with no prior experience in weather radar technology.

In this guide, the term “project” refers to a limited time endeavour with well-defined scope and resources. The term “programme” refers to the ongoing operation and enhancement after the radar or radar network has been installed. Radars have a long life cycle (15–40 years). Their implementation affects the entire National Meteorological and Hydrological Service, and it is likely that the full benefits are realized only over an extended period of the order of several to many years. Therefore, the planning, design and development of the end-to-end radar programme is critical.

2. TECHNICAL RADAR CONSIDERATIONS

A weather radar uses the most complex weather observing technology. It is a powerful instrument (transmit peak powers of more than 10^5 W), yet, at the same time, a sensitive one (receive powers of 10^{-14} W). Such instruments are also constantly evolving, with rapid changes in technology (for example, in the telecommunications, miniaturization, processing, solid-state and digital technologies and software). This chapter gives some of the most important considerations (see also Volume I).

2.1 GENERAL CONSIDERATIONS

Weather radar technical specifications should start with service requirements (for example, detection range), weather (for example, thunderstorms) and application (for example, aviation wind shear or hydrology) considerations.

Staying current and up to date in highly specialized technologies is difficult. There are relatively few weather radar vendors. Support and maintenance of a radar are high priority in an operational radar programme and therefore the most critical requirements of the radar specification and procurement.

The ability and opportunity to collaborate and share data with other radar operators have a bearing on aspects such as siting, design of the radar network and the procurement strategy. Such collaboration and sharing can significantly reduce costs, as well as extend capabilities and service levels.

In the past, there were considerable differences in costs among the radar technologies (such as S band versus C band or klystron versus magnetron transmitter). However, the cost differences have significantly narrowed, affecting traditional trade-off analysis. For example, a klystron transmitter is roughly double the cost of a magnetron transmitter. But, experience indicates that the klystron transmitter's life expectancy is about three to four times longer than the magnetron transmitter's, precluding the need for radar outages to do the replacement and the effort to replace. Solid-state power amplifier transmitters are new to the market, but are stable, redundantly designed, and replacement can be done while the radar continues to operate.

The effectiveness of data processing to mitigate radar limitations such as estimating precipitation on the ground with vertical profile corrections, correcting for attenuation using dual-polarization self-consistency techniques, and range and velocity extension techniques all need to be considered.

2.2 USEFUL TERMINOLOGY

In the tender evaluation process, "state of the art" is not always sufficient for specifying performance requirements. However, the notions of "threshold" (minimum, not worth buying if performance is below it), "target" (expected performance) and "goal" (maximum, not worth buying if performance is above it because it would be too expensive) are useful terminologies to apply to requirements.

The term "operational" can be ambiguous with rapidly evolving technology. However, the notion of "technical readiness level" (see, for example, Héder, 2017) may be a useful concept, particularly if customized or optional requirements are specified.

2.3 KEY RADAR CHARACTERISTICS AND RADAR NETWORK DESIGN CONSIDERATIONS

The large number and range of potential applications of weather radars are a strength, but can also be a source of confusion. For example, a radar with poorly calibrated reflectivity (even by an order of magnitude) may still be used effectively for early warnings using spatial interpretation but will be totally unacceptable for precipitation estimation. Therefore, it is necessary to clarify the main applications of weather radars.

For applications where attenuation is an issue, such as quantitative precipitation estimation (QPE), dual-polarization capability plays a greater role at shorter wavelengths (C and X bands). Attenuation is less at S band. Therefore, attenuation correction techniques are necessary with short-wavelength radars for rainfall estimation. The trade-off is a maintenance/scientific (calibration and data processing) risk versus a technological risk.

Even for applications where attenuation is not an issue, long-wavelength radars also have a range-velocity advantage (the Doppler Dilemma – see Volume II). For the same maximum velocity, S-band radars have twice the maximum range or four times the areal coverage of C-band radars. Phase coding technology may mitigate the Doppler Dilemma and may be able to **retrieve** multiple-trip echoes. It is useful but not always reliable. However, phase coding should be applied to **correct** (identify and suppress) the data in the first trip for multiple-trip echoes.

High priority should be given to obtaining sufficient radar sensitivity for certain applications such as long-range detection of light precipitation ($<0.5 \text{ mm h}^{-1}$) or snow, detection of clear air echoes (insects), nowcasting the initiation of convection, and multiple-trip data quality and recovery.

The effectiveness of ground clutter rejection, multiple-trip echo correction and recovery is a function of the phase noise of the radar. Therefore, the phase noise performance of a radar system including commensurate signal and data algorithms cannot be overspecified. This favours coherent-on-transmit systems.

Doppler is useful at all ranges, as there is great variation in the Doppler radial velocity with height since the vertical shear of the wind is usually larger than the horizontal shear.

The smaller the beam width (for example, 0.65° versus the nominal 1.0°), the greater the quality due to beam filling and therefore the greater the “effective” range.

The Earth’s curvature is a major factor in designing a radar network. The farther the radar scans, the higher the measured radar information is above the Earth’s surface. At long range, extrapolation can be used to infer information and conditions at the ground, but may be unreliable. An assessment of the importance and impact of more accurate low-level scanning requires detailed analysis of the local weather and climatology associated with each of the envisaged applications. In cases where the existing network cannot readily meet such accuracy requirements, dense networks of (presumably cheaper) X-band radars have been proposed to avoid the need for extrapolation.

S-band radars are more expensive than C-band radars – the current capital cost difference is about 50% more. When performing cost-benefit analysis to decide on S versus C band, considerations include: (a) ongoing operational costs are more significant than initial capital costs, (b) in Doppler mode, S band provides four times the areal coverage of C band, (c) in polarization mode, there are more variables to calibrate, which is therefore a risk to data quality and (d) attenuation is much more significant at C band.

2.4 ASPECTS OTHER THAN THE RADAR ITSELF

Aspects of the procurement in addition to the radar systems include consideration of the following:

- Infrastructure and civil works;
- Project management;
- Warranty period, support and maintenance (possible access to the radar and site by the vendor);
- Type and level of staff training required (technical, configuration, software and application, meteorological);
- Responsibility for configuration, scan strategy and data quality;
- Development of the radar acceptance (factory and site) plan;
- Spares, life-cycle management and upgrade plan;
- Integration with WMO Members' infrastructure and networked products;
- Software/application development and human resources plan;
- Auxiliary meteorological sensors (on and off site).

Radars can potentially remain operational for 15–40 years or more. Therefore, radar procurements are generational events, and there is little expertise available to write requirements, technical specifications and procurement documents.

The greatest challenge when implementing a radar programme is thus the availability of highly qualified and knowledgeable personnel. Training and other capacity-development activities are critical, and should be included in the planning and budgeting of the radar procurement. This is an ongoing need as it takes time to realize the benefits and adapt to the capabilities of the new technology. It can be expected that at least 5 years will be necessary for engineers, technicians, meteorologists and scientists to become proficient. Therefore, after-sales and after-installation support for ongoing operation and configuration of the radar should be carefully considered.

Many radar failures are due to issues such as power quality, telecommunications, air conditioning and vandalism, rather than to the radar system itself. Use of uninterruptible power supplies to condition the power, particularly at remote sites and to allow for generators to start up, is recommended. Generators designed for a limited (typically a week) duration are recommended, as power outages are often a result of severe weather.

Lightning protection requirements and grounding standards vary considerably with location, and need careful attention.

3. DETERMINING RADAR REQUIREMENTS

User applications (for example, severe weather, hydrology and wind shear) and services (for example, warnings and coverage) should play the primary role in determining user requirements. The characteristics of the local and regional weather (for example, precipitation intensities, depth of the weather or wind strengths, tornadoes and typhoons) contribute to determining the technical specifications. Data processing accuracies and philosophical ideologies apply, regardless of the target technology network design, and budget has a major impact on the selection of radar technology.

Radar technology trade-offs are complex. They are even more confounding when the capital cost differences between S- and C-band radars are now much smaller, when operating cost differences between klystron and magnetron systems appear to be about the same over a radar life cycle and when programme application and development costs are considered. The comparison factors are heterogeneous, and it is recommended new radar buyers should seek expert advice.

X-band radars are beginning to be used much more in operational weather radar networks, mainly in specialized environments, such as complex terrain or urban environments. The concept of dense networks of short-range X-band networks is still emerging. Recent research experiences have demonstrated that dense networks can overcome attenuation and provide improved low-level coverage. Operational issues of optimal network design, including redundancy, number and location of radars, as well as operational support and maintenance processes and costs, are outstanding issues.

3.1 SOME IMPORTANT CONSIDERATIONS

3.1.1 Auxiliary data

A variety of sensors are often deployed to monitor the health of the radar system. Temperatures of various parts of the radar shelter and cabinets are needed to mitigate overheating issues. Webcams to monitor antennas aid in diagnosing antenna controller problems. Webcams can be used to monitor the environment (for example, radome icing) and also for site security.

A weather station with a precipitation gauge and wind information is useful to provide diagnostic information about the conditions at the radar site for data interpretation (for example, for dome wetting conditions).

For the adjustment of weather radar data for QPE, several automatic reporting rain gauges or disdrometers distributed in clutter-free locations (beyond about 30–40 km from the radar) are recommended.

3.1.2 Test equipment

Special test equipment should be available for radar technicians. Typical test equipment includes a multimeter, a signal generator, a radio-frequency (RF) power meter, a spectrum analyser, an oscilloscope, and other accessories such as test cables, RF attenuators and adapters. The test equipment should be purchased from the radar vendor for compatibility. Additional equipment may be recommended by the manufacturer and included as part of the tender.

3.1.3 Built-in test equipment

All operational weather radar systems require methods to continuously monitor the radar status. Most vendors include manual and automated procedures for testing, monitoring performance and calibration. An important tool in this regard is radar's intrinsic monitoring and fault

identification mechanism, built-in test equipment (BITE). The technical implementation of BITE varies depending on the radar model. Multiple radar characteristics can be monitored through BITE. It also has the capability to alarm radar operators if some of the parameters fall outside acceptable limits.

3.1.4 **Spares**

The high data availability requirement of a weather radar is for 24/7 operation without long breaks for time-consuming maintenance or failures in the system. To ensure high availability, it is good policy to store critical spare parts at the radar site or at the operator's warehouse, where they can be quickly deployed in case of failure. These spare parts can include critical parts of the radar transmitter, receiver, antenna drive system, electrical power and communication interfaces. The vendor will have a detailed list of recommended spare parts.

Some high-cost degradable parts (such as magnetron transmitters) may be stored and maintained by the vendor and shipped upon request. Less critical spare parts can be ordered on demand from the manufacturer. Many manufacturers offer service contracts or express spare part delivery services. Some manufacturers may offer to monitor the radar remotely and provide precautionary advice and service.

3.2 **CRITICAL PERFORMANCE SPECIFICATIONS**

Identification of "critical" performance requirements and levels for technology is an important component of a tender, particularly when the tender relies heavily on a "performance-based" approach. Determining what is good enough or best value for money, even though it may not be the best or most state-of-the-art solution, is a difficult aspect. The annex to this volume provides some detailed information and a discussion on radar performance metrics.

The joint WMO–International Organization for Standardization (ISO) standard (ISO 19926-1:2019) also offers some recommendations. See ISO (2019) and [Guide to Instruments and Methods of Observation](#) (WMO-No. 8), Volume III, Annex 7.A.

4. RADAR PROJECT PROGRAMME TEAMS

Volume I provides detail on the establishment of, and requirements for, multiple project programme teams. The present volume should be consulted regarding the various skills and personnel that might be involved in such teams. Multiple teams are identified to cover various stages or phases of the project from initial concept, establishing user requirements and translating to network design and technical specifications, to strategies and conducting the procurement, to installation of the radar(s), to operations and maintenance including training, development and integration into the forecast system.

Procurement of a radar system requires a team with diverse skills and knowledge, including on project management, data analysis, safety standards, radar technology and applications. See Volume I for a full discussion, but a summary is given here.

The requirements–technical specifications procurement team: A considerable amount of preliminary planning, meteorological and technological research and analysis must first be undertaken, starting with high-level strategic requirements. In addition, services must be well understood (see Volume I). These are then translated to a network design and technical specifications requiring support from radar experts for a variety of analyses. Hence, a broad set of skills and knowledge are required to create a project plan, assess risk, define scope and develop the tender. A tendering strategy is required to balance the various programme requirements. Radar technical specifications is only one component. External to the procurement, integration into the operational environment needs to be planned at this stage.

The implementation team: Once the tender has been issued, evaluated and awarded, project management and other skill sets are needed to plan for, manage and coordinate the installation and implementation phases. Once the radar is installed, the radar must be configured to match the application data quality requirements and to account for local issues (such as ground clutter and blockage). Coordination and interaction with the requirements team is needed to ensure the radar specifications are satisfied. Additionally, coordination with those responsible for the integration of the new radar into the operational telecommunications, data management and forecaster work environments is needed at this point. This includes initial technical and user training.

The operational support and maintenance team: After the initial warranty period, for the operation of the radar, the radar is often handed over to a maintenance and support team. As radar data and their application permeate through the organization, ongoing support by a variety of contributors is required, not just from a radar hardware team. Such support should include telecommunications, data management, software (for example, radar, application and forecaster workstation), radar and meteorological research and external user support. With the introduction of the radar, workflows for warning dissemination will evolve.

A successful radar procurement and implementation will require tight coordination among these teams and indeed the entire organization.

5. RADAR TENDERS

It is difficult to be prescriptive about the preparation of tenders. The varying nature of the requirements, funding plans, global trade rules and local procurement practices contribute significantly to how tenders are formulated. However, there are many elements that would be expected to be included in all cases. Chapter 7 presents several examples of radar tenders.

5.1 TENDER PROCESS ISSUES

There are many practical and process issues to consider in preparation for and during the development and establishment of a tender. These include local and national procurement practices, organization and/or government policies, trade agreements, legal obligations, funding and time schedule constraints, and technical constraints (including frequency allocation). Procurement specialists can assist in providing or obtaining that information.

5.2 TENDER ELEMENTS AND SCHEDULE

The table provides the various elements of the tender process with estimation of the timeline for each. The actual schedule is dependent on various constraints that might be applicable, often imposed by external factors (for example, product availability).

5.3 RADAR SPECIFICATION STYLES

There are various ways to write radar tenders, and no attempt is made here to recommend a standardized approach. However, there are elements that all tenders should contain, including a set of specifications of technical requirements. The types of tenders can be roughly classified as “technical based”, “feature (or functionality) based” or “performance based”. Often, a combination of each of these approaches is used, depending on the function or feature specified.

Perhaps the most important aspect of writing the tender specifications is consideration of the evaluation of the submitted tenders and how to make a comparative assessment. “Value for money” is a difficult and subjective concept, and can be hard to quantify satisfactorily. Of particular importance is to be able to assess which features or functionality are considered mandatory or important, versus those that might be traded off to reduce costs.

5.3.1 Technical-based specifications

This is probably the most common way of writing radar tenders. It is the engineering perspective of a weather radar and is also the manner in which vendors characterize their radar models in “data sheets”. This is also the style available in some radar textbooks (for example, Rinehart, 2004).

In the ideal situation, the author of the tender would have knowledge about the technology. Pragmatically, the radar data sheet(s) can be used as a template. There is a tendency to write a technical specification that is a composite and to add specifications that are prototypical. Radars are expected to operate for more than 15 years, and specifying the latest technology protects the investment. This approach pushes the vendors to evolve their systems and to adopt the latest techniques. However, the specifications could be unrealistic, or the radar may not have a solid track record.

Project phase timelines

<i>Activity</i>	<i>Comments</i>	<i>Schedule</i>
Project team establishment	It can take considerable time to establish the project team, particularly when the required experience and expertise is not already available within the WMO Member.	Optimistically, it can take more than 6 months to assemble/build the project team.
Information gathering and proposal	This may be an ongoing activity of the project team and involves obtaining information relating to a range of different areas, including weather analyses, learning about weather radars and their benefits and limitations, budgetary information from vendors, preparing briefs and proposals for funding and award, among others. A formal request for information of pre-qualifying vendors is an option for gathering information before the final tender (see next activity).	Gathering information to create a detailed plan and budget, and to attain funding is significant work that could take more than 12 months.
Tender writing	This activity can overlap with the previous one. Creating the tender may include consultation with experts to define the requirements, scope and definition, interacting with vendors to understand their technology and their services and to acquire cost estimates for budgetary purposes. Evaluation criteria for the tender should be created at this stage.	Completing the written tender with all the relevant information and requirements could take as little as 3 months and up to 24–36 months, depending on the experience and expertise with the project team and on the complexity and scope of the plan.
Tender issuance, evaluation and award	Once the tender is made public, the vendors need time to prepare their responses. In some cases, they have to develop partnerships to meet the tender requirements. Then, the evaluations are done and the contract is awarded. It may be that briefs or approvals are still needed once the winning vendor has been identified.	Vendors require 90 d or so to respond, depending on the complexity of the requirements. Evaluations could take up to several months, including report writing and justifications. If the price is excessively overestimated, additional proposals for funding may be needed. There may be additional procurement or legal issues that could delay contract award for months or even years.
Radar installation	After receipt of order, it typically takes 12–18 months to install a single radar. There are often long lead times for some items or parts that could take 6 or more months to deliver. Siting activities, including land acquisition, environmental assessments and preparation can take considerable time. Specialist training of technical and meteorological personnel typically takes a few weeks.	Typically, installation occurs 12–18 months after receipt of order and subject to negotiation. Siting, acquisition and preparation can take 6–24 months, but can vary greatly.

In the technical-based specification approach, radar expertise is needed during the evaluation phase to assess different performance metrics or claims of performance. This provides more flexibility as all the bids could be compared but perhaps may not be as transparent.

5.3.2 **Feature-based specifications**

Another common way of specifying radar tender elements is from the user perspective (for example, technical, data, application and meteorological users), by specifying requirements

for particular features or functionality. This is particularly relevant for items like existing data formats, specific meteorological products, access to software or interfaces. Vague terms like “user friendly” or “comprehensive” are often used, but are difficult to evaluate.

5.3.3 **Performance-based specifications**

A performance-based specification is written from a “quality” perspective, in which the required performance levels for particular elements are specified. This might include for example, data quality, system availability, safety levels and range capability. For a radar, the use of this method of specification acknowledges and relies on the fact that the technical specifications are implicitly intertwined with the performance characteristics of radar systems through the radar equation (see Volume II for the radar equation). For example, pulse width, peak power and beam width all contribute to the sensitivity of the radar and data resolution.

Procurement specialists consider this a “fairer” approach to tendering, as it is effectively a technology-free method that requires an evidence-based approach to the tender submission and evaluation. While the performance-based requirements may, in the end, point to a particular type of technology or technological solution, this type of tender provides the vendors with the opportunity to modify their technical solutions to endeavour to meet the requirements, thus reducing the bias towards a particular vendor, product or solution within the tender. This method has the advantage of reducing the potential for contradictory specifications, which could confound the evaluation and lead to contractual issues.

An important aspect of this type of tender is to ensure the vendors submit adequate proof or evidence that their proposed solutions do indeed meet the performance requirements/levels.

5.3.4 **Directed procurement (sole source)**

“I want that” might sometimes seem like a reasonable approach and can save a lot of time, but it is highly subjective, totally non-competitive and not accepted by most procurement departments. A competitive tender process that allows multiple vendor submissions is always preferred and recommended.

6. RADAR TENDER EVALUATIONS

Evaluation is arguably the most critical part of the tender process and related documentation. The tender should include clear requirements along with any necessary explanation. Additionally, it should include criteria by which each specified requirement is or will be assessed. Often, technical data sheets or their restatement are provided by vendors as evidence of meeting the requirements of a technical specification. It is not recommended that these alone are accepted. The tender documents should request or require proof or evidence to be submitted or referenced for at least those requirements that are considered particularly important or critical.

In a performance-based tender in particular, the evaluation criteria should be evidence based and, where possible, based on the analysis of data. There should be independent proof(s) or measurement(s) demonstrating compliance. Measurements could be from an existing operational radar, or from factory or site acceptance testing.

Often, the specification and evaluation are separated into mandatory (or minimum, “shall” type requirements) and optional (“should” type requirements) criteria. The optional criteria can usually be requested or offered to be submitted on a sliding scale, with greater value for better performance. The use of such a mechanism, such as a categorical scale, for example, “meets criteria” or “exceeds criteria”, or by capping the performance, can assist in managing and reducing the “overbuying” of technology (paying for something that may not be used). In this way, the evaluation can effectively be split into two criteria: mandatory and point rated. The relative weighting of the various metrics should be determined based on climatology (including analysis of the extremes and risks) and also the application(s) for which the radar technology is to be used.

Missing or duplicate requirements in a tender evaluation can potentially result in significant issues for the evaluation process. For example, proposals may offer unanticipated or unwanted technology or functionality.

Two of the most difficult requirements to assess and evaluate are the robustness and reliability criteria for components and systems infrastructure. While the engineering approach of estimating and aggregating the “mean time between failures” is often used, this is a theoretical design criteria and is usually not based on actual performance. Real statistical-based evidence is difficult to provide due to the long lifetimes of radar systems and their evolutionary and changing nature. In practice, references from other users are often required as part of tender specifications to assess the robustness and reliability of the system.

7. EXAMPLE RADAR PROCUREMENT TENDERS

This chapter provides examples from a range of different tender processes for weather radars that address a variety of different requirements, needs and scopes. The tenders have been established by WMO Members with existing radar programmes. The variable requirements specified are highly dependent on the expertise and capacity available, highlighting the importance of establishment of a project team as the first step in developing a radar programme, particularly for those WMO Members who are procuring their first radar. The examples assume procurement from an existing weather radar market and do not address procurement of customized radars.

The tenders are diverse and written in varying styles and formats. However, in all cases, performance specifications are provided for critical requirements. Together, the suite of tenders provides a valuable resource to a radar procurement project team, which could benefit from the study and analysis in the development and establishment of their own tenders. Radar tenders are generally publicly available.

A summary of some important aspects is provided below, and then each tender is analysed in more detail. Readers are encouraged to review the tenders to determine their relevance and applicability to their own tendering requirements.

Each tender presented is unique in its own way due to existing technology, resources (staff skills), network design, support, maintenance, siting, telecommunications, weather, applications, visualization and project management requirements.

Long-term maintenance is included as part of some of the contracts, reflecting the capacity and availability of local industry or proximity to the vendor. In one case, 20 years of support was requested.

Radar technology is only one part of the tender. Demonstration of quality project management, financial viability or qualifications of key personnel are also important requirements. In some cases, the main constraint is fitting the new technology into an existing infrastructure and an existing technical and/or meteorological and scientific culture. For new radar networks, this is not such a big issue, but it illustrates that the initial decision will have a significant impact for generations.

In all but two of the tenders presented below, the core radar technology is already determined (such as X, C or S bands, and magnetron or klystron). In one tender, C and S bands are required. They all have similar technical specifications components, but they differ in how they specify the data quality – some specify it at the hardware level, some at the data level. In one tender, performance is specified, and the onus is on the vendor for technology selection.

The evaluation criteria are as important as the specifications of requirements, particularly if data quality is a significant requirement. In many tenders, statements of performance appear to be acceptable, and in other tenders, documented evidence must be provided, though at the vendor's discretion. This requires radar expertise during evaluation. In one case, the nature of the documented evidence is specified in the tender, allowing for a uniform comparison metric. In this case, an objective evaluation criterion (point rating on a sliding scale) is developed and issued as part of the tender.

In all cases, networking the data and centralized processing is envisaged but not always a tender requirement. In one case, limited products are to be generated at the radar site for contingency purposes. In many cases, integration into existing data processing infrastructures is a requirement, even to the extent of integrating into competitor systems.

Two of the most important requirements are robustness and reliability. They are also the most difficult to specify and to assess at the time of tender evaluation, particularly if the radar model is new. Radars are always evolving, and the desire to procure current state-of-the-art technology to avoid obsolescence means that historical data are not always reliable. One tender specifies using consistency in manufacturing, performance data from recent radars and references from other

WMO Members as a proxy. Others specify extended periods of testing during factory and/or site acceptance or rely on the warranty. In the latter case, although the tender has already been awarded, for some applications, this can be too late, resulting in long periods of radar outage while waiting for repair or rectification.

In general terms, the tenders are written taking into consideration the existing strengths, limitations, capacity and resources. Those with in-house technical or engineering capacity write highly technical specifications. Those with strong application development backgrounds require the ability to develop and enhance the software. This highlights the importance of creating and building radar capacity and planning for a viable radar programme.

7.1 **X-BAND RADAR – TECHNICAL-BASED SPECIFICATION APPROACH (CANADA)**

The tender method used by Environment and Climate Change Canada is a typical example of a technical-based specification approach with mandatory and point-rated evaluations.

The primary requirement was for a radar system to facilitate snow fall research. The intent was to locate the radar where it could scan at low levels (tens of metres or less) above a compound of snow gauges (under test conditions, and including a high time resolution snow fall reference), to study the variability and also to develop algorithms to quantitatively retrieve snow fall intensity from the radar. High spatial resolution was required to bridge the gap between point measurements by gauges and volume measurements (kilometre square data) from operational radars.

There was no requirement for long-range operational surveillance, but the radar had to be sensitive enough to detect snow to a range of about 40 km, have dual polarization for rain-snow discrimination and transportability to support experiments at different sites with different precipitation climates over the period of several years. Therefore, the Doppler Dilemma did not play a significant role in the specifications.

Doppler was requested to mitigate ground clutter, and high-range resolution was required to limit smearing of the ground clutter. Due to proximity to the test site, spatial resolution was not a primary concern, but a narrow beam (1° for X band is considered narrow) would provide greater gain and hence sensitivity. An operational C-band radar, located about 30–40 km away, would provide surveillance capability and observations at a second frequency to investigate multifrequency approaches to snow fall retrieval. Being a research radar, many operational features were not considered – such as data formats, product generation software or visualization.

Environment and Climate Change Canada operations had been using signal processors from the same vendor for many years. Given their critical function, a research group was asked to procure and evaluate processors from other vendors to reduce risk and dependencies. The specifications did not consider solid-state or pulse compression technology, although they were not excluded from bidding.

This specification was also used to procure a radar system to be deployed during planned operational radar outages.

7.2 **DUAL-POLARIZATION UPGRADE – TECHNICAL APPROACH (CANADA)**

This tender call by Environment and Climate Change Canada specified a single unit with an option to purchase nine additional units. The tender was written in a technical-based specification approach.

The objective of this tender was to upgrade custom-built radars from Doppler to dual-polarization capability. The unique aspect of the specification was that the opening for the waveguide through the pedestal was small and physically could not support dual waveguides. Unless the entire antenna and pedestal were to be replaced (an expensive proposition), the only feasible solution was for the receiving electronics to be mounted on the back of the antenna. While a prototype existed, the original company was no longer in business, so an open tender was issued.

7.3 **NEW DUAL-POLARIZATION RADAR – PERFORMANCE SPECIFICATION APPROACH (CANADA)**

This is an example of an Environment and Climate Change Canada tender for a large number (20) of new operational radars. Existing conventional C-band radars that were approximately 35–40 years old were to be replaced. The network design (pre-Doppler) assumed that the maximum range of the radar was 256 km. An ultra-long-range scan of 500 km (lowest scan only) was used in primarily coastal regions but also elsewhere. The weather application requirements were broad and included large, tall extratropical coastal storms or hurricanes, shallow lake effect snows, mountainous terrain and summer convective weather. The most significant constraint was that no new sites could be established. The original siting resulted in gaps in the Doppler coverage.

The procurement approach began with a requirements/needs analysis. It concluded that Doppler coverage of the gaps was needed, that dual-polarization attenuation techniques at C band were sufficiently advanced for operational applications and that a mixed network of S and C bands was affordable. The latter was based on a pre-tender survey of cost estimates from vendors and operational maintenance and support projections. A mixed network was considered supportable if there were a critical number of each type of system and that the variations of radar components were minimized (for example, the same signal processors were used). Consultation with other WMO Members supported the concept of a mixed network.

A request for information was issued by the procurement department, which started the formal procurement process. The in-house analysis was provided. Vendors had the option of requesting a meeting that was chaired by the procurement department. An independent fairness monitor was retained to oversee that the procurement process was equitable and met the procurement rules. The vendors were offered the opportunity to propose the network design. The procurement process began with the request for information followed by subsequent discussions internally and with vendors, which were considered confidential.

Subsequently, based on the vendor responses and budget estimates, a tender was released around 6 months later. There were several unique aspects to the tender. It was a performance-based tender where the radar technology, including wavelength, was not specified. Due to the large number of radars and expected long implementation period, project management by the vendor, and the experience, expertise and qualifications of key personnel were also mandatory requirements. A great weight was given to small beam widths and solid-state transmitters as options.

The tender specified a common evaluation metric, and the vendor had to provide documented evidence (data analysis) of compliance. Consistency in manufacturing, robustness and reliability were evaluated by requesting performance data from three systems. The requirement for low operating costs was difficult to state explicitly, and evaluation was done through references.

With this performance-based tender, the radar expertise was expressed in the specification of critical criteria and the relative weighting. The evaluation was straightforward, transparent and objective.

7.4 **S-BAND KLYSTRON NETWORK (REPUBLIC OF KOREA)**

This is an example of the procurement of a radar network with requirements for centralized radar management, data collection and processing including compositing, by the Korea Meteorological Administration. The vendor had to submit documented evidence of performance and was asked to submit data and product samples. It was left to the vendor to determine how it would provide the evidence, and so radar experts were required at evaluation time to resolve the different metrics. After radar installation on site, 4 weeks of testing and then 2 weeks of site acceptance were required to assure reliability. During site acceptance, the radar configuration and system performance would be optimized.

After all radars were installed, there was a requirement to harmonize all the radars' hardware and configuration. Technical requirements were specified, and also the overall accuracy of various radar variables. It was left to the vendor to propose the verification method. An external calibration (corner reflector) system was required.

This bid provided comprehensive lists, including models, of test equipment, spares and accessories required for support and maintenance of the radar network. The tenders were evaluated on a pre-published point-rated system with expert evaluation of each criterion with an 80:20 split for technical expertise versus cost.

7.5 **NEW C-BAND DUAL-POLARIZATION MAGNETRON (SWITZERLAND)**

This is an example of a Federal Office of Meteorology and Climatology tender, where C-band magnetron radars for mountainous terrain were required. The responsibility for the site preparation lay with another federal department, and access to the site was by cable car or helicopter. Support for the maintenance (not described in the tender) at the radar sites was contracted out.

The tender required the vendor to provide a centralized computer system for network data processing. Integration of previously developed in-house data processing algorithms (specific to mountainous terrain), extensive algorithm and software training, and the abilities to modify and add to the data algorithms by in-house experts were required. This included the possibility of processing other kinds of data (for example, satellite, surface and numerical weather prediction data) with the radar data. The forecaster would view these products in the NinJo workstation (Joe and Falla, 2004), and the tender called for custom compatible data formats. With a firm concept of ongoing research, a radar simulator was specified so that development and testing would occur on a separate processing system without disrupting the operational system.

The tender preferred a solution where the receiver was mounted on the antenna, as the buyer considered the dual-polarization rotary joint to be expensive and fragile, although it would accept proposals for all solutions. Relative, not absolute, power calibration capability was specified.

The tender had an aggressive timeline and an extensive test plan. Contract negotiations began around 5 months after initial posting of the tender. There was an opportunity for presentation (by invitation) and revision of the tender after initial submission. The tender had a multiphase approach to implementation and installation.

One of the first deliverables was the centralized computing system in less than a year. Factory, installation and site adaptation acceptances included 2 week, 3 week and 6 month test periods, respectively. After installation of the final radar, an additional 4 months for a functionality verification period was specified. With such a plan, the full-time availability of radar staff and experts was needed during initial implementation. A 20 year support period for the radar technology was required.

7.6 **RADAR UPGRADE OR REPLACEMENT – TECHNICAL APPROACH (SWEDEN)**

The Swedish Meteorological and Hydrological Institute tender called for the modernization of 12 existing radars to be operated remotely. This was a joint procurement with two different government departments – each owning their own radars. The unique aspect of this proposal was the option to offer new or upgrades to the current radars/network. The tender had an effective formal style that allowed these two seemingly diverse requirements to be simply stated. A table listed the buyer furnished equipment as “shall be used” or “may be used”. The vendor was provided with detailed information about the characteristics of the current radars, for example, the quality of the transmitter, antenna and radome.

The tender provided an itemized list of deliverables and payments (as a percentage of total cost), and a draft contract was provided. Various levels and kinds of training were specified and classified by personnel as verification, management, integration, maintenance, system administration, and research and forecasters, through the different phases of the project, such as construction, verification and acceptance. Radar system components may be developed (versus using existing components) to meet the technical specification, but must be approved by the buyer. The tender specified maintenance services were to be provided, but that secure remote access would be the responsibility of the buyer. The statement of work included two handbooks on safety with more than 450 pages.

The data from the 12 radars would be shared and the data processing design allowed for both departments to generate their own products. During the transition to the new radars, it was required that the new data processing system could process data from the current radars. ODIM_H5 format was a requirement for data exchange (see *Guide to Operational Weather Radar Best Practices* (WMO-No. 1257), Volume VII).

The timeline from contract award to the operational test was 19 months. Verification of performance and acceptance tests were to be proposed by the vendor and should be to the satisfaction of the buyer.

7.7 **ADDING A NEW RADAR TO THE NETWORK – EXTENSIVE EXPERIENCE IN INSTALLATION (FINLAND)**

In this Finnish Meteorological Institute procurement, an additional new radar with an option for two more was to be added to an existing network of radars. The existing radars were from two different manufacturers but used the same software. The buyer had considerable experience in the installation of radars and would be responsible for site preparation and installation. The tender requested a description and costing for installation by the vendor for only the first radar, as an option.

If the decision by the vendor was to install the radar itself, the vendor was required to provide instruction and supervision at the site. Installation was to be issued as a separate contract. Fifty days were allotted for bid submission, and installation of the first system was specified to be within around 7 months after bid submission. The tender specified training, but as an option. If required, training would be a separate contract.

Antenna performance was a particular concern (side lobes and spillover of radiation), and the buyer reserved the right to discuss and negotiate design trade-offs including lower gain (sensitivity). Quality was based on the hardware performance specifications and on statements of compliance.

Technical evaluation of the tenders was conducted on a limited number of critical radar features, which were eight hardware performance and 10 system features, and contributed to 35% of the bid evaluation. Part of the costing evaluation was based on the cost increase for additional sparing, additional maintenance training and learning the new system, life-cycle operations cost, hardware and software. The additional effort to learn and operate the new system was estimated to be 5.3 staff per year or US\$ 330 000 (assuming US\$ 62 000 for 1 full-time equivalent human

staff resource per year). Software operations and maintenance was estimated to be US\$ 165 000, for a total cost increase of about US\$ 500 000. The calculation was aggregated over 10 years, which is a conservative estimate of the lifetime of the radar. Installation and training was not part of the cost evaluation.

7.8 INFRASTRUCTURE AND NON-RADAR DATA (TÜRKIYE)

In this Turkish State Meteorological Service tender, six new C-band dual-polarization turnkey radar systems were required, as well as two disdrometers per radar. Functionality was required to automatically adjust the reflectivity–rainfall relationship at various timescales (hourly, daily, monthly, yearly and all) using the disdrometers. The technical specifications were comprehensive and included detailed specifications on the infrastructure requirements such as grounding, tower construction techniques, uninterruptible power supplies and external generators.

The vendor was requested to prepare the site (including conducting a geotechnical survey), arrange for power and construct the infrastructure. Dual telecommunication systems (128 kbits s⁻¹) were specified, with the primary system being satellite based and the backup terrestrial based. The buyer would provide access to the satellite telecommunications, but the vendor would be responsible for the routers. Raw data were to be transmitted from the radar site. But four basic products were to be generated at, and transmitted from, the radar site. Automatic switching of the data transmission and a commensurate switch in the radar scanning modes were required. Two redundant uninterruptible power supplies, “as-built” documentation and drawings, and extensive training were specified.

The vendor was required to ensure the systems were compatible with the existing data processing and visualization system. There were extensive software requirements to allow display and interaction with non-radar data such as surface observations, satellite and lightning data.

7.9 STANDING OFFER (AUSTRALIA)

The purpose of this Bureau of Meteorology procurement was to establish an ongoing contract of standing offer valid for 4 years, with the possibility of three extensions each of 2 year duration, for C- and S-band radars in a mixed network. The pricing option requirements were for an option procuring up to five radars per year and an option for more. The actual number of C- or S-band radars was not explicitly stated. The tender (S band versus C band) could be awarded to separate vendors. The buyer has considerable expertise in designing, modifying and constructing radars. The buyer has experience with operating a mixed network of C- and S-band radars with magnetron and klystron transmitters and radars with varying beam widths.

The procurement was done in two phases. A request for proposal was initially issued followed by an invitation to respond to a request for tender. The request for proposal identified there were no vendors offering >2° beam width radars, and this was subsequently removed. The tender requested costing for C- and S-band 1° dual-polarization Doppler radars. The buyer was experienced in data processing and planned to use its existing systems, so this was not part of the tender. Comprehensive technical specifications (essential, very important, important, desirable and response) were evaluated against criteria of “exceeds requirements”, “fully complies”, “partially complies” and “does not comply”. The contract of standing offer(s) would be based on the buyer’s assessment of best value for money, which was defined as “a comprehensive assessment involving a comparative analysis of the relevant financial and non-financial costs and benefits of the tender”. The buyer indicated that it would not be bound by the lowest priced tender. A draft deed was provided as part of the tender.

7.10 HIGH-LEVEL SPECIFICATIONS (DENMARK)

Three C-band dual-polarization radars were required in this Danish Meteorological Institute tender. In contrast to the other tenders, the technical specifications were written in a high-level manner (for example, “antenna should be suitable for dual-polarization radar”), with open-ended performance criteria (such as “the more symmetrical beam pattern the better”).

The quality evaluation was on a scale of 1–5, corresponding to very insufficient, insufficient, sufficient, good and very good. High-priority requirements were identified and received double value. This form of tender required extensive radar expertise during evaluation. Cost evaluation included radar and installation costs, hourly rates for on-site services expected to be 100 h over 4 years and for hotline services expected to be 240 h over 4 years. Consideration was given in the case of outliers in pricing. Quality and cost were evaluated with equal weighting.

ANNEX. RADAR PERFORMANCE METRICS

The table in this annex lists some essential performance metrics for a weather radar system. These metrics play a crucial role in a radar tender.

Table of radar performance metrics

<i>Performance metric</i>	<i>Value</i>	<i>Description</i>	<i>Comments</i>
Sensitivity	As best as possible; minimum -5 dBZ* at 50 km, which is equivalent to 7 dBZ at 200 km	Light rain is about 18 dBZ (0.5 mm h^{-1}) and snow can be as low as -10 dBZ. Insects useful for nowcasting are between -20 and $+15$ dBZ. Hail can be about 60 dBZ. The sensitivity falls off with range as the square of the inverse of range.	The radar equation links all the radar parameters (e.g. transmit power, pulse length, antenna gain, system losses, beam width and data sampling) affecting sensitivity. So, this requirement de facto specifies many technical parameters with a single specification. A data sampling strategy (e.g. pulse width, number of samples and range resolution) should be specified to have evaluable values.
Maximum range/ maximum velocity	250 km and 36 m s^{-1}	The Doppler Dilemma is a trade-off of maximum unambiguous range (single) and velocity. Techniques are available to extend the velocity and range.	This is a key specification to determine the radar wavelength. There are various techniques available. Dual pulse repetition frequency techniques can be used to extend the velocity, and phase coding can be used to extend the range. The latter requires good phase stability. Sensitivity needs to be re-visited for a second trip. Must specify a data sampling strategy and velocity error rate ($<1\%$).
Phase noise	Less than 0.5°	This determines the ability to remove ground clutter, to recover second-trip echo using phase coding techniques.	Well-maintained magnetrons can achieve as low as 0.1° , but require good workmanship and good stable local oscillators. This is standard (or better) with coherent (klystron, solid-state) systems. The smaller the better. Critical if using phase coding for second-trip recovery.

<i>Performance metric</i>	<i>Value</i>	<i>Description</i>	<i>Comments</i>
Differential reflectivity (Z_{DR})	Zero bias in drizzle or vertically pointing	Z_{DR} is the ratio of two powers and a check of the polarization quality is that it should be 0 when looking at spherical particles.	This is an overall check of the polarization quality, which is affected by the antenna quality, cross-polarization isolation, rotary joint, power splitter, etc.
Z_{DR} variation in azimuth	Variation (maximum – minimum difference) of the mean Z_{DR} over 360° azimuth should be less than 0.2 dB	The radar infrastructure (e.g. lightning rods, tower and radome) can affect the data through blockage or scattering. Measuring Z_{DR} as a function of angle and elevation in light precipitation (drizzle) will reveal this bias. This must be corrected through data processing.	This is an overall check of the radar infrastructure design. Lightning rods and air conditioners should be angled or located in such a way as not to affect the data.
Co-polar correlation coefficient ρ_{HV}	The median value should peak at greater than 0.995	The correlation of co-polar correlation is a quality indicator for polarization radars.	This is an integrated measure of the quality of the antenna, the cross-polarization isolation, the power splitter, etc.
Range side lobes for pulse compression radars	Range side lobes should be more than 60 dB down	Pulse compression radars synthesize a pulse in the signal processor. Different frequency modulations can be employed to control the side lobes.	This is important for weather with high reflectivity gradients such as thunderstorms and typhoons.
Near-in minimum detectable signal of a pulse compression radar		Pulse compression radars use low power and long pulse widths and allow for use of solid-state transmitters (although it can be done with magnetrons and klystrons). The result is a long blind zone that is filled by data from short pulse(s).	This is new technology. The solution is to send a traditional short pulse right after the long pulse to fill the gap but with lower sensitivity data (e.g. the minimum detectable signal is –3 dBZ in the short pulse observation range of 7 km). It is less sensitive to clear air/insect echoes in the immediate vicinity of the radar.
Consistency	Performance of more than three radars should meet the critical performance metrics	When deploying a radar network, consistency among the radars is critical.	This is a check that manufacturing and workmanship is acceptable. The performance data could come from different contracts.

<i>Performance metric</i>	<i>Value</i>	<i>Description</i>	<i>Comments</i>
Robustness and reliability	References from users on robustness and reliability	Engineering processes are available to aggregate mean time between failures of individual components but are not very informative. References may be anecdotal in nature, requiring interpretation.	A reliable operating radar is the most critical aspect of the specification; however, it is difficult to evaluate because many of the causes are not radar related but are infrastructure related such as power outages, air-conditioning failure and telecommunications problems.
Beam width	1° or smaller for C and S bands; 2.7° or smaller for X band	Smaller beam widths extend the range for quantitative precipitation estimation and increase the data quality due to beam filling. They also allow for lower scanning to see low-level weather.	Vendors have ad hoc standardized to 1° beam widths. Changes in dish size need to be commensurate with possible pedestal change. A new proposal to use a frequency in between the traditional C and S bands and using S-band dishes would result in smaller beam widths and with associated issues (e.g. range, velocity and attenuation).

* See the *Guide to Operational Weather Radar Best Practices* (WMO-No. 1257), Volume II, for a definition of the radar reflectivity factor and its log form dBZ.

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