Response to RC1

The authors thank the reviewer for the time and consideration given this manuscript. We appreciate your overall view that the paper will benefit the community and are ahppy that the description

The reviewers comments have been listed below in **bold** and responded to individually (where needed) in *italics*.

General comments
The paper is well written and while the use of mobile x-band radars in this field is well known, this paper does a good job of highlighting the availability of this specific resource, and its use in several field campaigns. I believe the utility of the paper to the community would be enhanced by addressing the concerns described below.

Specific comments
Abstract.
13: The use of "prevalent" seems to overstate the use of X-band radars, particularly in relation to the QPE. Perhaps clarify that this is in the mobile / research campaign area.
Response: We agree with the reviewer and have replaced "prevalent" with "widely" in the abstract in addition to adding a follow-on sentience for clarification about the primary use in mobile applications. The revised section of the abstract is as follows:
"Abstract. In recent years, dual-polarisation Doppler X-band radars have become a widely used part of the atmospheric scientist's toolkit for examining cloud dynamics and microphysics and making quantitative precipitation estimates. This is especially true for research questions that require mobile radars."

1. Introduction
27: Again "ubiquitous" seems to overstate the use of x-band, particularly in relation to the QPE. It could perhaps be stated that this is the case for mobile applications but that this is not clear from this statement.
Response: As with the comment above, we agree with the reviewer and have made the clarification with the abstract as follows:
"Thus, small and or mobile dual-polarisation Doppler X-band radars have become popular tools for examining cloud microphysics and dynamics as well as making quantitative precipitation estimates (QPE) in mobile applications (Wurman et al. 1997; Matrosov et al. 2005; Wang and Chandrasekar, 2010)."

2. Technical 54 Summary of the NXPol 2.1 Operations
75: Table 1 – Is the power per channel or pre-split? Please include the radar sensitivity. Ideally both of the receiver and the radar system as a whole.
Response: We have now clarified in the table that this is pre-split and have added the information about the sensitivity of the radar to Table 1.

103: DOP has been calculated for other systems previously (as per the work of Gal- letti, Bebbington, Holt, etc.) Please clarify how the calculation of DOP in this case is "unique".

Response: We agree with the reviewer that the use of the word "unique" is over stated in this instance given the previous work. It was intended to mean that it was unique in comparison to other Meteor 50/60DX radars at the time it was purchased. The section of text has been revised as follows:
"In addition to the standard polarimetric variables provided by most operational dual-polarisation radars, NXPol also provides the of the degree of polarisation (DOP) of the backscattered signal."

Also, this capability seems interesting but is not mentioned further; for example, is it used in the field campaigns described? Is it found to be a useful parameter?
Response: DOP has been collected in the campaigns described within the paper but has only begun to be explored for its use in HCA due to its advantages over co-polar correlation coefficient for STAR mode radars. Currently we are not in the position to answer the question about its usefulness further or provide any further information. It is included here only to fully document the capability of the NXPol.

26: "They were also invaluable" – While it is clear how the data could be used in the aircraft case, it would be useful to describe how the data were used by forecasters - in what way were they invaluable?
Response: We agree with the reviewer that no reason for the vlaue of the quick-look images was originally given and have clarified the sentence as below:
"The quick-look images were also helpful to the NXPol's operators and forecasters at the Scottish Environmental Protection Agency and the U.K.'s Met Office during the six-month-long Radar Applications in Northern Scotland (RAINS) campaign in 2016 (Section 3.3) for assessing the impact that a radar in this location would have on observational quality in near-real-time conditions in comparison to existing observations."

2.2 Deployment Setup

41: The increased ease of health and safety could be mentioned at this point – consider a forward reference to section 2.3.
Response: We agree, and this has now been included.

65: "now" - when exactly is this?
Response: We agree with the reviewer that this usage of "now" makes no sense and have revised the sentence to the following:
"The RAINS project and on-going work at NFARR (where the NXPol will operate for several months at a time between campaign deployments) in particular demonstrate the need for this type of facility to support the radar in its long-term operations. "

2.3 Safety

02: It would be useful for others considering such a setup if some details of the contingency plan could be given – how is this issue addressed in practice?
Response: We feel this sentence was ambiguous and has now been removed and replaced with the following information:
"If the radar is unmanned, then access must be restricted to the distance at which public exposure limits ($10W/m^2$) are reached in the event the NXPol malfunctions and stops scanning but continues to transmit."

3. Example Deployments and Observations 3.1 COPE

Figure 5: c) Spokes can be seen in the figure but are not referred to – what is this source of this artefact in this parameter alone?

Response: The spokes are due a quality control filter on the calculation of Ah. This has been noted in the text.

Figure 5: d) the expanded colour bar label is difficult, if not impossible to read. Please revise.

Response: We have doubled the original size of the colour bar label text.

3.2 ICE-D

Figure 6: Figure appears to be reversed. Presumably the thick black lines represent geographical features (islands) rather than meteorological ones – not actually stated.

Response: This is now stated in the caption of the figure.

Is this data set publicly available? If so where? – If not please clarify the point being made in this and subsequent sections.

Response: Yes, this data is available on CEDA. Its location has now been included in the text.

3.3 Radar Applications in Northern Scotland (RAINS)

88: It is unclear what conclusion one is to draw from the QPE in this figure; other than that different algorithms give different results - can this be clarified?

Response: As the point of this paper is to show what types of research the NXPol can be used for, that is exactly the conclusion we want people to draw. Further results will be given in a publication focused on the results of the SEPA campaign.

It would be useful to state that one is making use of Kdp in the text rather than this having to be picked up from the figure label.

Response: We Agree and this has not been included in the main text.

Is a particular algorithm being used with the Kdp case?

Response: The KDP relation used is that of Diederich et al. 2015 using a = 16.9 and b = 0.801. This is stated in the text.

Does the use of Kdp improve comparison against ground truth?

Response: The answer to this question is part of on-going research and is beyond the scope of this paper. We intend this section to only depict an example of how the radar could be used to look at questions related to QPE rather than answering those questions.

Again – is this data set available?

Response: Currently, this dataset may be requested from the author as it is still undergoing its primary analysis with SEPA. The dataset will become public on CEDA in the coming year when the first of 2 papers have been submitted. This has been clarified in the text.

Were any conclusions drawn regarding the benefits of the X-band data in this area?

Response: As the response to the comment above states, the goal of this manuscript is just to provide examples of how NXPol is used. It is not to describe results of specific studies. In addition, we are in the midst of finalising the analysis of the RAINS project but due to limits placed on us by SEPA, we are unable to say any more.

4. Ongoing Work at CFARR

Is this high quality dual wavelength data set available and if so, from where?

Response: Currently, this dataset may be requested from the author as it is still undergoing its primary analysis. The dataset will become public on CEDA in the next year. This has been clarified in the text.

It is unclear to the reader, what the benefit/use of the lower resolution, more attenuation prone X-band data is in this case. i.e. what is gained by this dual wavelength validation of the HCA?

Response: The benefits of dual-wavelength validation of the HCA are the constraints the multiple frequencies place on the scattering parameters. This has been clarified in the text.

The NCAS Mobile Dual-Polarisation Doppler X-Band Weather Radar (NXPol)

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Abstract. In recent years, dual-polarisation Doppler X-band radars have become a widely used part of the atmospheric scientist's toolkit for examining cloud dynamics and microphysics and making quantitative precipitation estimates. This is especially true for research questions that require mobile radars. Here we describe the National Centre for Atmospheric Science (NCAS) mobile X-band Dual-polarisation Doppler weather radar (NXPol) and the infrastructure used to deploy the radar and provide an overview of the technical specifications. It is the first radar of its kind in the United Kingdom. The NXPol is a Meteor 50DX manufactured by Selex-Gematronik (Selex ES GmbH), modified to operate with a larger 2.4 m diameter antenna that produces a 0.98° half-power beam width and without a radome. We provide an overview of the technical specifications of the NXPol with emphasis given to the description of the aspects of the infrastructure developed to deploy the radar as an autonomous observing facility in remote locations. To demonstrate the radar's capabilities, we also present examples of its use in three recent field campaigns and its ongoing observations at the National Facility for Atmospheric and Radio Research (NFARR).

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1 Introduction

Polarimetric radars are powerful tools for meteorological studies. The diverse quantities observed by polarimetric radars can provide significant insights into the evolution of clouds and precipitation (e.g. Fabry, 2015). Thus, small and or mobile dual-polarisation Doppler X-band radars have become popular tools for examining cloud microphysics and dynamics as well as making quantitative precipitation estimates (QPE) in mobile applications (Wurman et al. 1997; Matrosov et al. 2005; Wang and Chandrasekar, 2010). Currently, a significant number of such radars exist in the operational and research sectors to address a broad range of scientific goals pertaining to atmospheric physics and hydrometeorology (Maki et al. 2005; Bluestein et al. 2007; 2014; Kato, A. and Maki, 2009; Pazamny et al. 2013; Forget et al. 2016; Mishra et al. 2016; Antonini et al. 2017). Use of such radars notably includes recent field campaigns such as PECAN (Plains Elevated Convection At Night, Geerts et al., 2016), where a variety of mobile radars (both X-band and C-band) from multiple institutions were used collaboratively to achieve complex goals successfully. In the United States, where mobile research radars are more numerous, large multi-institution observational campaigns, similar to PECAN, occur several times a decade (e.g. the second Verification of the Origins of Rotation in Tornadoes Experiment (VORTEX-2), Wurman et al. (2012)). Mobile radars are also used as a teaching resource, for example, the University of Oklahoma SMART (Shared Mobile Atmospheric Research and Teaching) radar (Biggerstaff et al., 2005). Thus, it is difficult to understate the role of such instrumentation in hydrometeorology and atmospheric research.

Here we describe the NCAS Mobile X-band dual-polarisation Doppler weather radar (NXPol) shown in Figure 1 and the supporting infrastructure structure that has been developed to support the radar when on deployment. The NXPol is the first dual-polarisation mobile radar in the United Kingdom. The supporting infrastructure has been developed to create a robust facility that may be operated remotely with minimal staff. As such, the NXPol has developed into a semi-operational observing system facility that has the significant capabilities present in both traditional research radars used for intensive operational periods (IOPs) and radars operated as part of national networks. In addition to the technical description, examples of NXPol in 3 differing campaigns are shown, as well as an example of its ongoing use at the National Facility for Atmospheric Radar Research (NFARR) located at the Chilbolton Observatory. The NXPol is part of the pool of mobile instruments that make up the UK NCAS Atmospheric Measurement Facility (NCAS-AMF, https://www.ncas.ac.uk/index.php/en/about-amf) so it is available for use by the community according to the procedures set out by NCAS-AMF.

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Figure 1: Photograph of the NXPol collecting data at Burn Airfield near Selby, UK. Here the NXPol is deployed using only its trailer as a platform.

2 Technical Summary of the NXPol

The NXPol is a modified mobile Meteor 50DX (Selex ES GmbH) X-band, dual-polarisation, Doppler weather radar. The radar is a magnetron based system and operates at a nominal frequency of 9.375 GHz (~3.2 cm). A detailed description of the development of this class of Selex radars is given by Borgmann et al. (2007). The radar is capable of measuring areal precipitation, radial winds and properties of cloud and precipitation particles. It can also detect clear-air echoes, including biota, at close range by scanning at slower speeds and optimising the transmitter and receiver. Similar radars (including the newer Meteor 60DX) are utilised by national weather services and research centres throughout the world. Table 1 provides a summary of the technical characteristics of the NXPol.

Like all standard mobile Meteor 50/60DX radars, NXPol is transportable. The radar is constructed on a wheeled platform that is approved for towing on roads in the European Union by a 4x4 vehicle and can also be lifted by a crane. This trailer includes a generator to provide necessary power and the communications infrastructure to operate and monitor the radar remotely for up to 24 hours. This mobility makes NXPol a highly versatile tool for studying a diverse array of atmospheric phenomenon across the globe. The main difference between NXPol and the standard mobile Meteor 50/60DX is that the NXPol has been fitted with a larger 2.4 m diameter antenna that produces a 0.98° half-power beam width. The NXPol is operated without a radome, which is beneficial for eliminating radome attenuation effects, but extra care is required during transport, and long-distance shipping may need the antenna and external waveguides to be removed. The decision to fit NXPol with a larger antenna was made to support the ability to make higher resolution observations of convective clouds. In comparison, the standard mobile Meteor 50/60DX has a 1.8m antenna that produces a 1.3° half-power beam width and is usually operated with a radome. In addition to its increased spatial resolution, NXPol is also advantageous for use in the observation of cloud evolution because of its rapid scanning capabilities; up to 36 $degs^{-1}$.

Table 1. Technical characteristics of the NXPol.

Parameter	Specifications
Frequency	9.375 GHz
Transmitter Type	Coaxial Magnetron
Pre-Split Peak Transmit Power	~75 kW (half to each channel)
Average Power	~80W
Dual-Polarisation Mode	Simultaneous H & V
Digital Receiver and Signal Processor	GDRX®4
Receiver Linearity	90 dB +/- 0.5 dB
Antenna Diameter	2.4m
Half Power Antenna Beam Width	0.98°
Antenna Gain	44dB
Minimum Discernible Signal (2μs pulse)	H: -118dBm V: -117dBm
Sensitivity (2μs pulse at 100km)	~-11dBZ
Radome	None
Elevation Scan Range	-1 to 181°
Azimuthal Scan Range	0 to 360°
Position Accuracy	±0.1°

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2.1 Operations

The NXPol can be operated via a remote computer (e.g. a laptop or server) that connects by wireless, ethernet or 3G to PCs onboard the NXPol's trailer unit. The operational software allows the user to set up the radar for deployment and schedule the scanning sequence. Ravis® is the maintenance and calibration software used for system diagnostics and testing, as well as real-time data visualisation. Ravis® includes an automatic sun tracking tool for alignment of the system. Rainbow®5 is the scan scheduling, data visualisation and analysis software, providing near real-time product and image generation. As shown in Table 2, the NXPol is highly configurable with regards to the pulse width, PRF and scan pattern and can be tailored to address the specific scientific question being examined. Bold values in Table 2 indicate the typical parameter settings used in the examples shown in Section 3. Signal retrieval, analysis and data storage are performed by the GDRX®4 digital receiver and signal processor.

Table 2. Parameter settings. Boldface indicates settings typically used for operations.

Parameter	Specifications
Pulse Width	0.5µs, 1µs, 2µs (**1µs**)
Pulse Repetition Frequency (PRF; Single or Dual Modes)	250-2000 Hz (**1000 Hz single-PRF mode, 1000Hz/800Hz dual-PRF mode)**
Dual PRF Mode	3/2, 4/3, 5/4 (**5/4)**
Unambiguous Velocity using single-PRF	±8m/s - ±16 m/s (**±8m/s**)
Unambiguous Velocity using dual-PRF	±8m/s - ±64 m/s (**±32m/s**)
Range Resolution	50m-300m (**150m**)
Maximum Range Gates	2000 (**2000)**
Maximum Operating Range	600 km (**150 km**)
Antenna Speeds	0 to 36° s^{-1} (~**13-24° s^{-1}**)

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Note that the NXPol operates only using the hybrid polarisation basis, also known as the simultaneous transmit and receive (STAR) mode (i.e. it splits the transmitted signal into two parts and simultaneously transmits and receives horizontal (H) and vertical (V) polarisations) (Chandrasekar and Bharadwaj, 2009). This mode operates under the assumption that the cross–polarisation signals are weak in comparison to the co-polar signals and are therefore negligible (Wang and Chandrasekar, 2006)). As the cross-polar signals are not measured, observations of the linear depolarisation ratio (LDR) are not available. The benefit of STAR mode is that the NXPol has a much simpler and robust hardware design because it avoids switching between H and V polarisation on a pulse-to-pulse basis (Doviak et al. 2000; Bringi and Chandrasekar 2001). STAR mode operations also lead to less noisy measurements of differential reflectivity (Z_{DR}) and other quantities while operating at rapid scan speeds.

The dual-polarisation capability of the NXPol allows for the retrieval of many additional geophysically-related variables. This additional information helps to provide insight into the size and shape of precipitation, enhanced target identification as well as the assessment of attenuation and propagation effects (Bringi and Chandrasekar, 2001; Kumjian 2013a;b;c; Fabry, 2015). The NXPol's polarimetric ability also enables many alternative methods for quantitative precipitation estimation, which are demonstrated in Section 3 (Deiderich et al. 2015; 2015). In addition to the standard polarimetric variables provided by most operational dual-polarisation radars, NXPol also provides the of the degree of polarisation (DOP) of the backscattered signal. DOP is a relatively unexplored variable with respect

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During operations, scan strategies are tailored to the application but typically sample a volume out to 150 km in range every 5 minutes. The typical volume includes ~10 PPI scans between 0.5° and 30° of elevation and a calibration scan at 90°. All data are recorded as moments in Selex's Rainbow®5 format (a flavour of XML). This format is easily utilised by common open-source analysis software packages (Heistermann et al. 2015) such as the LIDAR RADAR Open Software Environment (LROSE) that is provided by the Earth Observing Laboratory within the U.S.'s National Center for Atmospheric Research (NCAR) (Dixon et al. 2012; 2013), the Python Atmospheric Measurement Radiation (ARM) Climate Research Facility Radar Toolkit (PyART) (Helmus and Collis, 2016) and the Open Source Library for Weather Radar Data Processing (wradlib) (Heistermann et al. 2013). The NXPol has the capability of collecting raw IQ data for post-processing, but this is typically not done due to the size of the dataset.

Once a volume is collected, the raw data are backed up locally and transferred to a central NCAS data storage facility if internet capacity allows as described in Section 2.2. In addition to storing the data for later analysis, Rainbow®5 generates several quick-look images in real-time (tailored to the application of the radar). The quick-look images are transferred to a central server where they are uploaded onto a web catalogue to disseminate the observations in near real-time and enable easy examination of past observations. Figure 2 depicts an example of a real-time image and corresponding catalogue page. Such near-real-time quick-look charts were crucial in the two field campaigns discussed later for changing scan patterns and directing aircraft. The quick-look images were also helpful to the NXPol's operators and forecasters at the Scottish Environmental Protection Agency and the U.K.'s Met Office during the six-month-long Radar Applications in Northern Scotland (RAINS) campaign in 2016 (Section 3.3) for assessing the impact that a radar in this location would have on observational quality in near-real-time conditions in comparison to existing observations.

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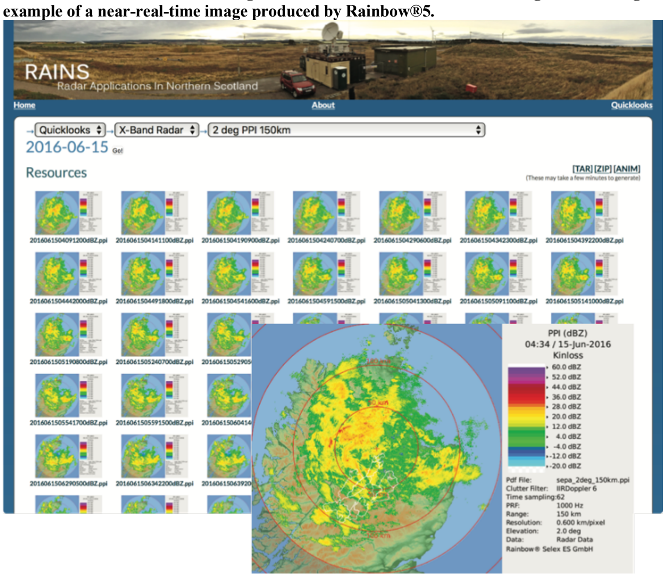
Figure 2. Example of the data catalogue used to monitor the NXPol observations in near-real time during the RAINS project described in Section 3.3. The background shows a collection of a set of images from a single day while the foreground highlights an example of a near-real-time image produced by Rainbow®5.



2.2 Deployment Setup

The operational requirements dictated by the strategic and project-specific scientific goals of the NXPol have led to the development of bespoke infrastructure to support the radar during operations. The primary requirements for deploying the NXPol radar are visibility, security, power and internet access. Considering these options, the NXPol may be deployed using solely its integrated trailer (as in Figure 1) or in conjunction with a platform structure as depicted in Figure 3. The platform setup is based on a similar scheme employed by Selex ES GmbH for the NXPol's deployment during the Single European Sky ATM (Air Traffic Management) Research (SESAR) campaign in 2015 at Braunschweig Airport near Hanover, Germany. The setup has the major advantage of lifting the radar off the ground to provide greater visibility. It also makes security and public safety issues (See Section 2.3) less problematic.

The platform consists of a 20-foot standard shipping container and a 20-foot office container set side by side along their long axis. To provide the necessary structural strength to support the weight of the NXPol, on top of each of the containers is a 20-foot platform container (also known as a 'flat rack'). Using standard shipping containers and platforms dramatically reduces engineering time and cost during deployments. Also, because of their global ubiquitousness, the elements needed to construct a similar platform can be sourced locally. This further reduces deployment costs. To provide safe access to the radar while it is on the platform, a staircase and railing are constructed from standard scaffolding materials as shown in Figure 3. Also attached to the platform structure are the various pieces of hardware that support a long-term autonomous deployment of the NXPol; lightning protection, a satellite internet connection, security camera and local weather station.

In addition to providing a platform for the NXPol, the office unit provides space for the additional IT infrastructure needed for NXPol's autonomous operation (described below). The office also provides a base of operations for staff while on site during remote fieldwork. The office is particularly useful during observational campaigns that involve the coordinated operation of the radar and an aircraft (such as the ICE-D campaign described in Section 3.2). During such campaigns, staff can monitor and direct the radar's observations in real-time and communicate with the aircraft to help target the observations.

Figure 3. NXPol deployed at Chilbolton Observatory, Hampshire, UK. Seen in the picture is the 20’ shipping container, 20’ office container, two 20’ platform containers and scaffolding used to construct a platform for the radar.

There is also the need in the scientific community for the collection of statistically meaningful observations over a wide range of synoptic conditions. This requirement has necessitated the move to semi-permanent, continuous and autonomous operations that last for many months. The RAINS project and on-going work at NFARR (where the NXPol will operate for several months at a time between campaign deployments) in particular demonstrate the need for this type of facility to support the radar in its long-term operations.

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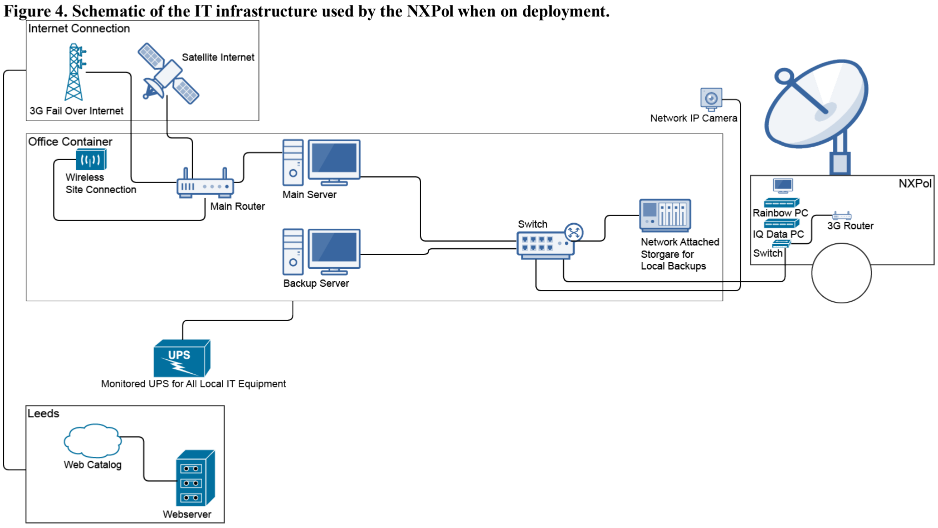
Table 3 summarises the operational requirements of the NXPol. Data and power availability vary depending on the deployment. Typically, when the NXPol is deployed for less than 24 hours, the onboard generator supplied by an 80 L fuel tank provides all electricity. An onboard 3G mobile data connection or satellite link provide internet connectivity. When the NXPol is deployed using the container platform, mains electricity is connected to the radar’s electrical grid and the onboard generator acts as a backup power supply that is automatically started upon loss of mains power. Additionally, the 3G mobile data connection is supplemented with a local area network connection or a satellite internet connection. This allows for more robust autonomous and remote operation of the system.

Table 3. Operational conditions and logistical requirements of the NXPol.

Conditions	Specifications
Max Operational Wind Speed without Radome	56 mph (90km/h)
Electrical Supply	3-phase 32A Service or Onboard Diesel Generator
Power Consumption	8kW (average), 12kW (max)
Operating Temperatures	-10C to 35C
Total Weight, Nose weight	2800kg, 120kg
Width (without supports, with supports)	2.550m, 3.560m
Height (0 degs, 90 degs)	3.995m, 4.250m
Max drive Speed	50mph (80km/h)

The IT infrastructure needed for the NXPol's autonomous operation includes a server that provides a gateway for communicating with the radar and data backup. Figure 4 summarises the IT strategy. In addition to communications, the infrastructure includes a local weather station to primarily monitor wind speeds, a video camera to monitor the radar's movement and an Uninterruptible Power Supply (UPS) for the server. Data production is on the order of between 5 and 9 Gb per day. During long-term remote operations the data can be backed-up using a commercial satellite internet system if available, although it may be cost-prohibitive if there is not an unmetered period (typically in the early hours of the morning local time). The onboard 3G connection provides redundancy and/or remote control, if local signal strength permits, but it is not practical to backup bulk data via this route. If near-real-time remote raw data access is required, a suitable Internet connection is necessary. Quick-look charts as shown in Figure 2 use considerably less data and are therefore logistically simpler, potentially allowing selective download of raw data over a lower-bandwidth connection. Data are backed-up locally to a Network Attached Storage (NAS) system in the office container in medium- to long-term deployments.

Figure 4. Schematic of the IT infrastructure used by the NXPol when on deployment.



2.3 Safety

An important consideration when deploying the NXPol radar is the protection of both operators and the public from exposure to transmissions. The location of the deployment site is determined in conjunction with the required safety distance specified by a radiation exposure assessment. The International Commission on Non-Ionizing Radiation Protection (INCIRP) specifies that the maximum continuous exposure to radiation at frequencies between 2 GHz and 300 GHz should not exceed $10Wm^{-2}$ in areas where the general population has access and 50 Wm^{-2} for occupational exposure, averaged over a period of 6 minutes (Ahlbom et al. 1998). When deployed on the ground, a safety barrier must be constructed or measures put in place to prevent access within the distance which the exposure threshold would be exceeded as determined by the radiation assessment (e.g. if the radar dish stops scanning). When NXPol is situated on a platform and is scanning and operating as scheduled, there is no risk to people (including those with implanted medical devices) on the ground 15m from the radar and, hence, this is another benefit of this method of deployment. If the radar is unmanned on the platform, then access must be restricted to the distance at which public exposure limits ($10W/m^2$) are reached in the event the NXPol malfunctions and stops scanning but continues to transmit.

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The second major safety consideration is the operation of the system in high winds. Without a radome the maximum operational wind speed is 56mph. The weather station continuously monitors the wind speed and notifies operators via text and email alerts when a set threshold (typically below the 56mph maximum limit to allow for gusts) is exceeded. Operators closely monitor the conditions during forecasted events and, in the case of significant winds, interrupt the scan schedule to move the antenna into the vertical position (which provides the least wind resistance) and activate the locking stow pin to prevent movement. In addition to winds, NXPol's temperature must be monitored carefully to avoid operations below -10C and above 35C as there is no radome to provide a conditioned environment for the transmitter and receiver equipment boxes located behind the antenna. This operational range also limits the regions where the NXPol may be deployed.

3 Example Deployments and Observations

Below, four examples of the use of NXPol are given. Descriptions are provided to highlight the utilisation of the radar to achieve the scientific aims of each project.

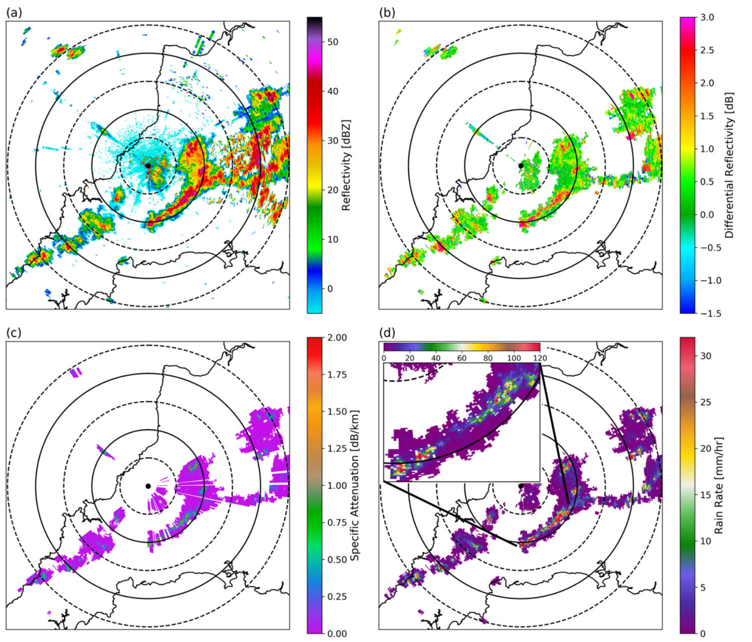
3.1 COPE

NXPol was utilised for the first time in the COnvective Precipitation Experiment (COPE) held in the vicinity of Davidstow, Cornwall during July and August, 2013. Three aircraft, including the Facility for Airborne Atmospheric Measurement (FAAM) BAe-146 aircraft, and other ground-based instruments were also deployed; see Leon at al., (2015). The principal aim of the project was to understand the physical processes involved in the production of heavy convective precipitation that could result in flash flooding. Ultimately, predictions of heavy precipitation and potential flash floods by Numerical Weather Prediction (NWP) models will be improved as a result of the new knowledge and understanding of physical processes. Several flash flooding events have previously occurred in the region, the most notable in recent years being the Boscastle flood of 2004 (Golding et al. 2005). The role of the radar was to determine (a) the altitude of the first echoes; (b) the rate of development of the reflectivity echoes; (c) the spatial and temporal distribution of the main echoes; (d) the particle types from dual-polarisation parameters (e.g. warm rain or graupel), and (e) the maximum intensity of the precipitation.

NXPol collected data during 16 IOPs covering a variety of synoptic and microphysical conditions including heavy precipitation from shallow clouds (warm rain only) and several cases of deep convection along semi-organised convective lines with similarities to the Boscastle event. An example of the convective clouds that formed along a convergence line (at 20 km range between S and SE) and observed elsewhere on 3 August, 2013 is shown in Figure 5. Note that Figure 5 and all following figures were created using software developed in NCAS that is based on the Py-ART software suite (Helmus and Colis, 2016). The rainfall rates (Figure 5d) were derived from the unfiltered and uncorrected calibrated horizontal reflectivity (Z_H, Figure 5a) by first applying a second trip filter and a fuzzy logic clutter filter as described by Dufton and Collier (2015). In addition to these corrections, a correction for partial beam blocking and attenuation (A_H) have also been applied. From this corrected Z_H, rainfall rate was retrieved using the Marshall-Palmer relation ($R(Z)=aZ^b$, with a=200 and b=1.6 as is used by the UK Met Office) to derive rain rate for their operational network of C-band radars (Marshall and Palmer, 1948). For access to the observations made with the NXPol during COPE, please see the

Centre for Environmental Data Analysis (CEDA) archive for the campaign at http://data.ceda.ac.uk/badc/microscope/data/ncas-mobile-xband-radar/version-2/ (Blyth et al., 2013).

Figure 5. Example of observations made by NXPol (located at the centre black dot) at 0.5° elevation on 3 August 2013 at 1332 UTC showing: a) calibrated but unfiltered and uncorrected horizontal reflectivity (Shown as to display the importance and impact of the data processing) , b) calibrated, filtered and corrected differential reflectivity, c) specific horizontal attenuation (A_H) and d) rainfall rates derived using the Marshall-Palmer relation ($R(Z)=aZ^b$, with a=200 and b=1.6. The missing spokes of data in A_H are caused by quality control settings in the processing routine that reject radials that do not meet certain threshholds. The sub-panel in d) shows an expanded section of the line of intense rainfall (>120mm/hr in some pixels; please note the expanded colorbar to the top of the sub-panel) to the southeast of the radar. Range rings are drawn every 10km.



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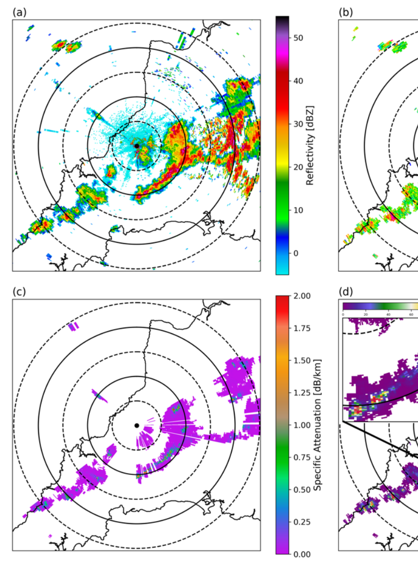
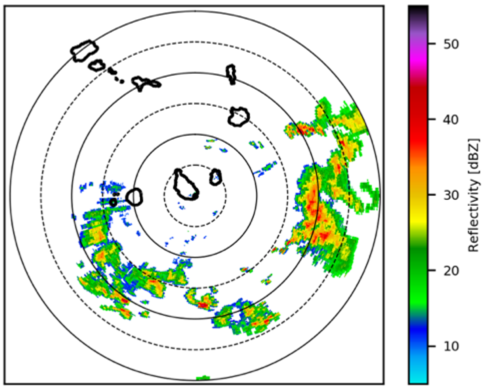


3.2 ICE-D

NXPol was deployed at Praia, Cape Verde (14°55′N 23°31′W) during July and August 2015 in the UK's Ice in Clouds Experiment-Dust (ICE-D). The goal of ICE-D was to determine how desert dust affects primary nucleation of ice particles in convective and layer clouds and the subsequent development of precipitation and glaciation of the clouds. In addition to NXPol, the FAAM BAe-146 research aircraft and the University of Manchester ground-based aerosol laboratory were deployed. All data from this campaign may be found on CEDA at http://catalogue.ceda.ac.uk/uuid/55b5d76a7edb42e39933c1edc37f7b90.

The main objective of NXPol was to provide the spatial and temporal distribution of the clouds, to identify suitable cloud regions for the aircraft to sample and to provide coordinated observations of the development of precipitation within about 100 km of the island. Two modes of data collection were implemented dependent on the synoptic conditions and location of cloud development. In "surveillance mode", NXPol was configured to maximise its observable range. In this mode, observations were made out to 300 km at several low elevations. An example surveillance mode PPI observed on 23 August 2015 using the surveillance mode is given in Figure 6. Use of the radar in this mode was found to be invaluable for near-term mission planning and directing the use of the FAAM once it was airborne. For suitable clouds at closer range, NXPol operated in "data-collection mode", providing higher spatial and temporal resolution observations; volumes of 12 elevations from 0.5 up to 12 degrees were collected out to a range of 150 km similar to COPE.

Figure 6. Example of a surveillance mode PPI observed by NXPol at 2119UTC on 23 August 2015 while on the ICE-D deployment in Praia, Cape Verde. Range rings are drawn every 50km. The thick black outlines are the islands of Cape Verde.



3.3 Radar Applications in Northern Scotland (RAINS)

COPE and ICE-D are examples of the use of the NXPol for traditional IOP based operations. This section highlights the use of the NXPol for semi-permanent operations. Previous studies have shown the value of operating a mobile polarimetric X-band radar in coastal regions to fill gaps in the coverage of national operational radar networks (Matrosov et al. 2005). Matrosov et al. (2005) found that the NOAA X-band radar (9.34 Hz, 30kW peak power) was effective in covering an area up to 40–50 km in radius offshore adjacent to a region that is prone to flooding during wintertime land landfalling Pacific storms. More recently, the Collaborative Adaptive Sensing of the Atmosphere (CASA) Engineering Research Center's X-band dual-polarisation radar network has shown the utility of short-range radars at making high-resolution observations of rainfall that are close to the ground over a variety of conditions (Wang and Chandrasekar, 2010).

During the RAINS campaign, the NXPol was installed at Army Base 39 Engineer Regiment, Kinloss, northeast Scotland from January 2016 to August 2016. This deployment was a joint project between NCAS, the Scottish Environment Protection Agency (SEPA), the University of Leeds and the UK Met Office with the goal of examining the value of additional and higher-resolution radar observations in this region for creating more accurate QPE and flood forecasts. Beyond just improving radar coverage in Northern Scotland, the data collected from the NXPol is also being used to examine the specific improvements in QPE that dual-polarisation observations can provide hydrological models in this region, which is characterised by low melting levels (i.e. low bright bands) and mountainous terrain.

In Figure 7 we show an example of two differing QPEs during a typical precipitation event during the deployment. The observations and the two rainfall rate retrievals are shown here to highlight the potential differences in rainfall rate methods that are being explored as part of RAINS. In particular we highlight the difference between the rainfall rate calculated using the Marshall-Palmer relation ($R(Z)=aZ^b$, with a=200 and b=1.6) which is used by the UK Met Office and rainfall rates calculated using the $R(Z_H,K_{DP})$. The $R(Z_H,K_{DP})$ is described in Diederich et al. (2015b) and here we use a = 16.9 and b = 0.801. The entire RAINS dataset may be requested from the author as it is still undergoing primary analysis with SEPA and has not been released publically. Once this analysis has been concluded the dataset will be available on CEDA.

As part of the work in RAINS, a set of software tools was created to convert NXPol data into the Met Office NIMROD format using a combination of gridding software (Py-ART or LROSE) and bespoke scripts developed by NCAS. Many UK agencies (i.e. the Environment Agency and SEPA) use this format in their modelling and analysis tools such as HyRAD, developed by the UK's Centre for Ecology and Hydrology (CEH). These scripts may be requested from the authors.

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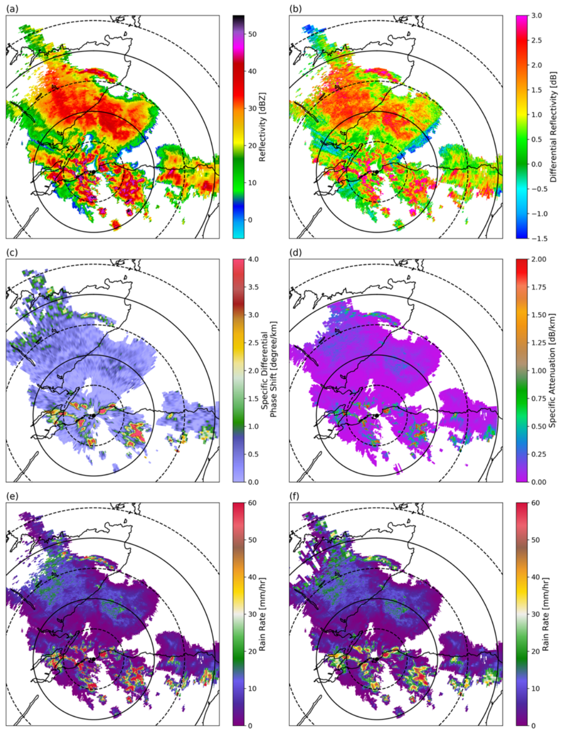
Figure 7. Observations and derived rainfall rates from the RAINS campaign on 20 July 2016 at 0409 UTC at 1.5° elevation: NXPol is located at the black dot and range rings are drawn every 25km. (a) calibrated, corrected and filtered Z_H classified as precipitation echoes; (b), (c) and (d) calibrated, corrected and filtered Z_{DR}, K_{DP}, and $A_{H,}$ (e) rainfall rate calculated using the Marshall-Palmer relation ($R(Z)=aZ^b$, with a=200 and b=1.6) and (f) rainfall rates calculated using $R(Z_H,K_{DP})$. NXPol is located at the black dot and range rings are drawn every 25km.



4 Ongoing Work at NFARR

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In between major field deployments, the NXPol makes continuous observations at the National Facility for Atmospheric Radar Research (NFARR), located near Chilbolton in Hampshire, UK. This enables NXPol to work in coordination with the other state-of-the-art radar facilities located at the observatory to make novel observations of high impact wintertime storms and summertime convective events using an array of ground-based remote sensing and in situ observations. The goal of this work is to improve flood forecasting in the UK by using these novel observations to drive the development of physical parameterisations in high-resolution numerical weather prediction models.

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Most significantly, this work includes NXPol making coincidental RHI scans of frontal events with the Chilbolton Advanced Meteorological Radar (CAMRa), which is the largest steerable meteorological radar in the world. CAMRa operates at S-band (~3 GHz), and its 25m antenna creates a beam width of only 0.25°. This results in the ability to make high-resolution observations at far ranges (i.e. at 100 km from the dish, the resolution of a 0.25° beam is 0.4 km). Like the NXPol, CAMRa has dual-polarisation and Doppler capabilities. For a full description of CAMRa, please see Goddard et al. (1984). An example of coincidental observations from CAMRa and the NXPol on January 12th, 2017 at 13:36 UTC are shown in Figure 8. Currently, observations from both radars may be requested from the authors as they still undergoing its primary analysis. The datasets will also become public on CEDA by 2020 after the 2 year embargo period for this campaign is over.

As part of the ongoing research with NXPol, the use of hydrometeor classification algorithms (HCAs; also referred to as particle identification or PID) to explore cloud microphysics is being pursued. Such an HCA has been initially implemented for the NXPol using the framework provided by LROSE (Dixon et al. 2012). The HCA is a fuzzy logic approach, and the membership functions are based largely on the work of Dolan and Rutledge (2009) and Thompson et al. (2014). An example result of the HCA applied to NXPol and CAMRa observations from May 17th, 2017 at 12:24 UTC is shown in Figure 9. The NXPol's HCA results are part of on-going research and have not yet been fully validated. As such, Figure 9 is shown only to demonstrate the type of on-going investigations enabled by the NXPol's observations. Nevertheless, the comparison shows good qualitative agreement between the algorithms applied to the two radars. Future work will include validation with in situ observations made with FAAM. We hope that the use of multiple frequencies will help constrain and reduce uncertainty associated scattering parameters within the retrieval.

Figure 8. Coincident RHIs of Z_H (a and b) and Z_{DR} (c and d) from the NXPol (a and c) and CAMRa (b and d) on 12 January 2017 at 13:36 UTC.

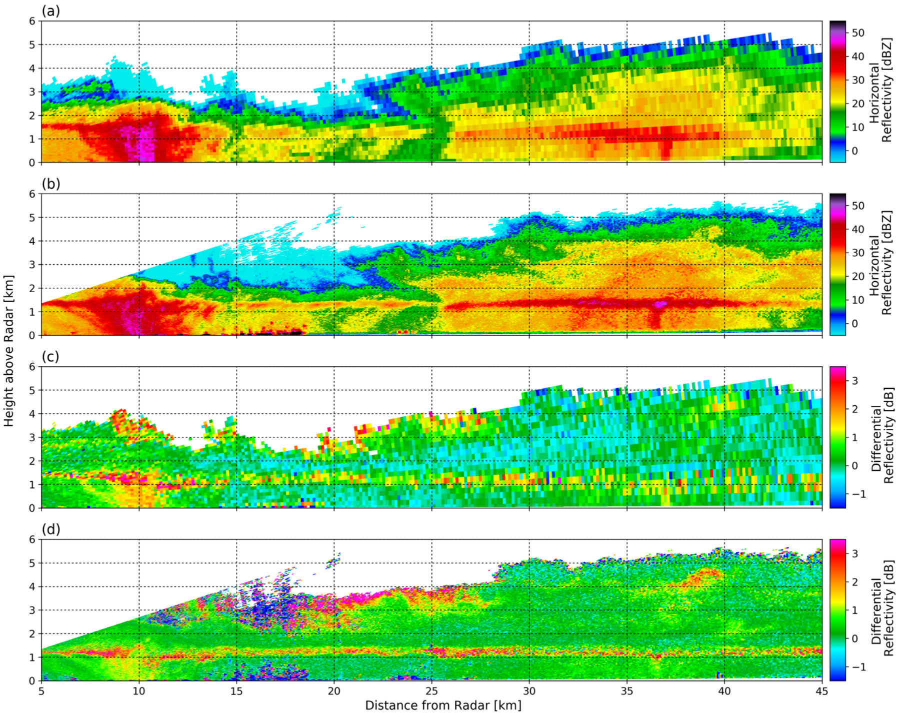
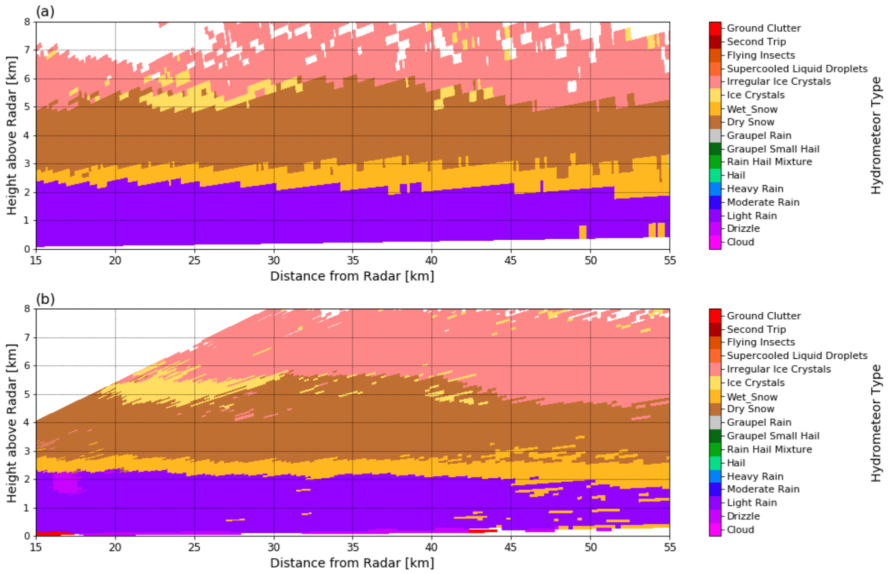


Figure 9. Coincident RHIs from the NXPol (a) and CAMRa (b) on 17 May 2017 at 12:24 UTC with the HCA applied to both.



5 Summary

Here we have summarised the key technical characteristics of the NXPol and the infrastructure used to deploy the system autonomously at remote locations. We have also shown examples of its successful use in four differing scientific campaigns. As is shown in the examples, the NXPol is a highly capable and flexible instrument for use in examining the microphysics of clouds and producing QPE. As described in Section 4, in between bespoke deployments to remote locations, the NXPol will be located at NFARR to make continuous observations in conjunction with other instruments at this site. The NCAS and Leeds University Radar Group welcomes any collaborations that utilise the NXPol and its observations.

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For further information on the use of the NXPol including instrument access policies, data format, NXPol specific analysis software and availability, please see the NXPol instrument homepage at: https://www.ncas.ac.uk/index.php/en/about-amf/263-amf-main-category/amf-x-band-radar/1098-x-band-radar-overview.

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