Mobile radar fire plume project Western Australia

The logistics and science of collecting detailed radar data at prescribed fires

Peter May [1], Mika Peace[2], Alain Protat[2], Mark Curtis[2], Adrien Guyot[2,3], James Ashley[2], Afie Jazreen[4], Nathan Ramage[4], Agnes Kristina[5] and Pascal Mater[1]

[1] Monash University, [2] Bureau of Meteorology, [3] University of Queensland, [4] WA Department of Biodiversity, Conservation and Attractions, [5] WA Department of Fire and Emergency Services

Version	Release history	Date
1.0	Initial release of document	27/06/2024

Australian Government

Natural Hazards Research Australia receives grant funding from the Australian Government

We acknowledge the traditional custodians across all the lands on which we live and work, and we pay our respects to Elders both past, present and emerging. We recognise that these lands and waters have always been places of teaching, research and learning.

Publisher:
Natural Hazards Research Australia

ISBN: 978-1-923057-10-4

Report number: 30.2024

06/2024

Cover: Peter May, Monash University

Contents

Acknowledgements

This project has only been possible with the significant input and support from all of the partner agencies and the team of individuals involved.

Particular thanks to Natural Hazards Research Australia for the support for the workshop.

Department of Biodiversity, Conservation and Attractions (DBCA) supplied staff, housing and equipment to move and operate the radar.

Department of Fire and Emergency Services (DFES) supplied staff and funds to bring the radar to Western Australia.

Bureau of Meteorology (the Bureau) for their staff, travel and field support as well as arranging high-resolution Himawari data

NSW Rural Fire Service (NSW RFS), Country Fire Authority (CFA) Victoria, and CSIRO contributed to the workshop.

Executive summary

Mobile radar offers the promise of providing key decision support for meteorological hazards and evolving fire behaviour in and around fire grounds. In order to test the concept, a high-power mobile dual-polarimetric weather radar has been successfully deployed near several prescribed environmental burns in south-west Western Australia (WA) as part of a collaborative project between Monash University and state and federal agencies. The project aims were to demonstrate the feasibility of deploying a mobile dual polarisation radar near a fire and to capture data that is relevant to nowcasting of hazards and that can contribute to the development of improved tools for fire management.

The science aims of this project were:

- To demonstrate the ability to safely locate and operate the radar in (relatively) close proximity to fires.
- To demonstrate the diagnosis and detection of wind shifts using the 'clear air scatter' for nowcasting.
- To demonstrate the detection of ash and embers and discrimination from other airborne particles such as raindrops, using the dual polarisation data.
- To develop strategies for potential operational detection and monitoring of the development of precipitation and smoke/ash plumes.

The cooperative aims of this project were:

- To conduct a multi-agency field research project in south-west WA.
- To hold a multi-agency workshop to discuss the results of the field campaign.
- To provide a learning and development opportunity for field and technical operatives to work with leading scientists.
- To produce a report capturing and summarising the opportunities presented by mobile radar for understanding fire plume processes and ultimately mitigating impacts associated with fires.

It was possible to deploy the radar within a few kilometres of the firegrounds for all the potential cases we examined in south-west Western Australia, including for burns that were surveyed, but not sampled. The data collected clearly demonstrates the ability to measure detailed three-dimensional wind fields in the environment in and around fires and to obtain high-quality observations of smoke/ash plumes with two-minute time resolution and precipitation with a clear separation between precipitation, clouds, clear air and fire ash plumes.

This kind of data has clear potential applications for monitoring the changing wind fields around and within the fire. This may permit meteorologists and fire behaviour analysts to make timely decisions to mitigate risk. It can also inform research into developing predictive techniques for processes in fire plumes. The observations clearly showed the ability to observe wind circulations and map the ash plumes. Coupled fire models and predictive methods based on models are reliant on a small number of observations, so additional high-resolution data around fires will be invaluable in improving these methods. Improved predictions will support more accurate and targeted community messaging in a future climate where high-intensity fires are expected to become more frequent and impactful.

Data collected showed that even in these low-intensity fires, the local environmental winds were significantly modified. Further, the radar data shows the circulations within the fire plumes and the potential to detect hazardous winds as they develop.

The project has developed operating procedures and approaches for the safe location and operation of a mobile radar, as well as making recommendations on requirements for robust operational radar deployment practices.

End-user statement

James Ashley, Bureau of Meteorology

“The Mobile Radar Fire Plume project provided significant outcomes for Bureau staff to work closely with fire agencies, allowing us to build knowledge of how agencies manage fire and the fire ground, and strengthened relationships between the Bureau and the agencies.

“Working with scientists from Monash University and the Bureau of Meteorology helped meteorologists develop a deeper understanding of radar technology and radar interpretation, as well as a better understanding of fire and smoke plume dynamics. On top of this, participation in the workshop provided a rich opportunity to meet people from interstate agencies around Australia, researchers from the university sector and to discuss in detail the opportunities that this technology presents.

“Local involvement has provided significant benefits and as further research and operational uptake continues, the value of radar in examining fire plumes will expand to a wider cohort of practitioners across the country. As a result of this project, staff in the Bureau of Meteorology have not only increased their practical and scientific understanding of fires but have built relationships that are instrumental in improving our services to fire agencies.”

Introduction

The use of radar for research and potential operational applications in nowcasting of bushfire-related weather, fire spread and fire behaviour holds enormous potential to mitigate risks to life and property. The ability of operational weather radar to detect ash plumes from bushfires has long been recognised (Jones, 1950; Lhermitte, 1969; see McCarthy et al., 2018 for a complete review). However, the development of analysis methods is still in its infancy, with pioneering work undertaken by Melnikov et al. (2009). Innovative work in Australia using mobile radar has been led by The University of Queensland (UQ) with support for field work from the Queensland Fire and Emergency Services, the Victorian CFA, and the NSW RFS (e.g., McCarthy et al., 2018). A series of papers from that UQ research showed the feasibility of using a solid-state portable weather radar mounted on a trailer to monitor bushfire smoke plumes, including the capture of an intense bushfire producing a pyrocumulus cloud and showers downwind (McCarthy et al., 2018). McCarthy et al. (2020) combined the dual-pol observations from their radar and a machine-learning based unsupervised model to distinguish ash, rain and falling firebrands. In parallel, innovative research has also been conducted in the United States using operational weather radars to monitor fire progression (Lareau et al., 2021), to detect potentially hazardous wind shifts (Hermes et al., 1993) and fire-induced circulations (Lareau et al., 2018). More recently, Guyot et al. (2023) paved the way to a more generalised utilisation of operational weather radar data, by proposing a machine learning-based method to extract fire-related plumes and clouds from complex scenes involving other radar echoes. The potential for use of both fixed operational radars and mobile radars to monitor fire plumes was also recognised in the report prepared by the NSW Bushfire Inquiry following the 2019-2020 fire season [section 2.5.4.3 pg. 101].

This pilot project focuses on the deployment and use of a mobile radar system with very limited objectives. The Monash University portable weather radar (Selex Meteor 60DX)[1] is a commercial off-the-shelf system purchased by Monash in 2016. The Bureau of Meteorology is also exploring potential applications of mobile radar systems and recently purchased a similar radar to the radar used in this study. The Monash radar is far more sensitive (by ~ 20 dB) than the current and previously used UQ solid state radar developed by Furuno (WR2100), which is the only other portable weather radar that has been used to study ash plumes in Australia to date. The higher sensitivity should enhance the detection of clear air winds around the fire plumes and therefore improve the monitoring of the wind field in the vicinity of fires.

The science aims of this project were to:

- Demonstrate the ability to safely operate the radar in proximity to bushfires.
- Demonstrate the diagnosis and detection of wind shifts using the ‘clear air scatter' for nowcasting.

[1] SELEX Inc has since changed its name to Leonardo Inc.

- Demonstrate the detection of ash and embers and discrimination from other airborne particles such as raindrops, using the dual polarisation data.

The cooperative aims of this project were:

- To conduct a multi-agency field research project in southwest WA.
- To hold a multi-agency workshop to discuss the results of the field campaign.
- To provide a learning and development opportunity for field and technical operatives to work with leading scientists and for the scientists to learn more about operational needs and procedures from the DBCA and DFES staff.
- To produce a report capturing the opportunities presented by mobile radar for mitigating the impacts and risks of fires.

The science capabilities have the potential for use in nowcasting fire behaviour and risk after initial numerical weather model and diagnostic guidance (e.g. Tory et al, 2018; Tory and Kepert, 2020), noting that the technical and scientific development is beyond the scope of the current project. In addition, the extremely fine detail in the data collected will allow the study of fire behaviour and the development of local circulations such as the inflows into the ash columns and flows into the smoke plumes.

Following the analysis of the data collected during the project, we held a workshop at the Bushfire Centre of Excellence on 3 and 4 May 2023 to discuss the results and workshop key questions, such as a review of current work both in Australia and in the USA, potential operational uses and infrastructure needs and logistical and operational considerations with regard to deployment at controlled burns and bushfires.

The organisation of this report includes sections discussing background (2), the Monash radar system (3), a summary of the data collected (4), a discussion on logistics including lessons learnt (5) and options for the next phase of this work (6).

Background

Fixed radars

Australia has an expanding operational capability of fixed radar facilities around the country that is being modernised on a continuous basis. Many of these radars have dual-polarisation capability, enhancing their ability to discriminate ash plumes from other echoes such as precipitation, and supporting potential applications to monitor fire spread and behaviour. Any mobile radar-based analysis systems must be compatible with these operational radars. However, the Bureau's operational radars are not operated in a mode optimised for fire applications. Inevitably, fixed radar scanning strategies result from a trade-off with the radar settings optimized to meet multiple objectives. For example, the current Bureau radar scan rates are every five minutes, and the radar volumes extend to long range and high elevations to meet rainfall monitoring requirements, but they do not attempt to optimise clear air detection.

Fires are often long distances from the fixed radar location. This limits radar capability to resolve detail in the plume, as the spatial resolution decreases with range, being ~ 1 kilometre in width and height at a 50 kilometre range, and at increasing altitudes above the fire ground, so that the low-level circulations and fire structure are not resolved. Blockage of the beam in regions with significant topography further complicates the use of radar. However, operational radar data is used by the Bureau meteorologists and fire agency fire behaviour analysts (FBANs), albeit qualitatively. Enhanced use of the operational radar network using dedicated fire products and tools should be an integral part of any future development.

Mobile radars

An additional plume monitoring capability is the use of mobile weather radars. Truck-mounted mobile systems typically operate at 3 centimetre (X-Band) wavelengths, a wavelength shorter than operational 5 and 10 centimetre (C- and S-Band) wavelength radars, allowing for similar detection capability from smaller size systems at the expense of higher attenuation of the signal, resulting in limited maximum range. Mobile radars have been widely used in the U.S. for the study of intense storm systems, with radars located very close to the system of interest (e.g. Bluestein, 2022). More recently, trailer-mounted systems such as the University of Queensland Furuno WR2100 radar have been used to observe fire plumes (McCarthy et al., 2018a) as well as 2.2 centimetre (Ka Band) radar observations in the USA (Aydell and Clements, 2021). The Monash radar built by Leonardo is a trailer-mounted commercial off-the-shelf system with dual-polarisation capability, while the UQ Furuno radar is an off-the-shelf radar system, mounted on a specifically designed trailer. They could both be integrated onto a small truck platform or equivalent. Table 1 shows some specifications of the two radar systems. Of particular note is the greater sensitivity of the Monash system, which is comparable to the Bureau's operational 5 and 10 centimetre wavelength radars. The greater sensitivity allows the detection of wider areas of clear air echoes and thus winds in the vicinity of fires as well as inside the ash clouds. To visualise this *Fig. 1* shows an example of reflectivity and Doppler velocity from a horizontal and a vertical scan during the deployment on 15 November 2022 along with panels where the data has been truncated to the sensitivity of the Furuno system. This shows the smaller, more agile system is likely to see the core structure but will miss the extended plume and much, but not all of the circulations surrounding the fire.

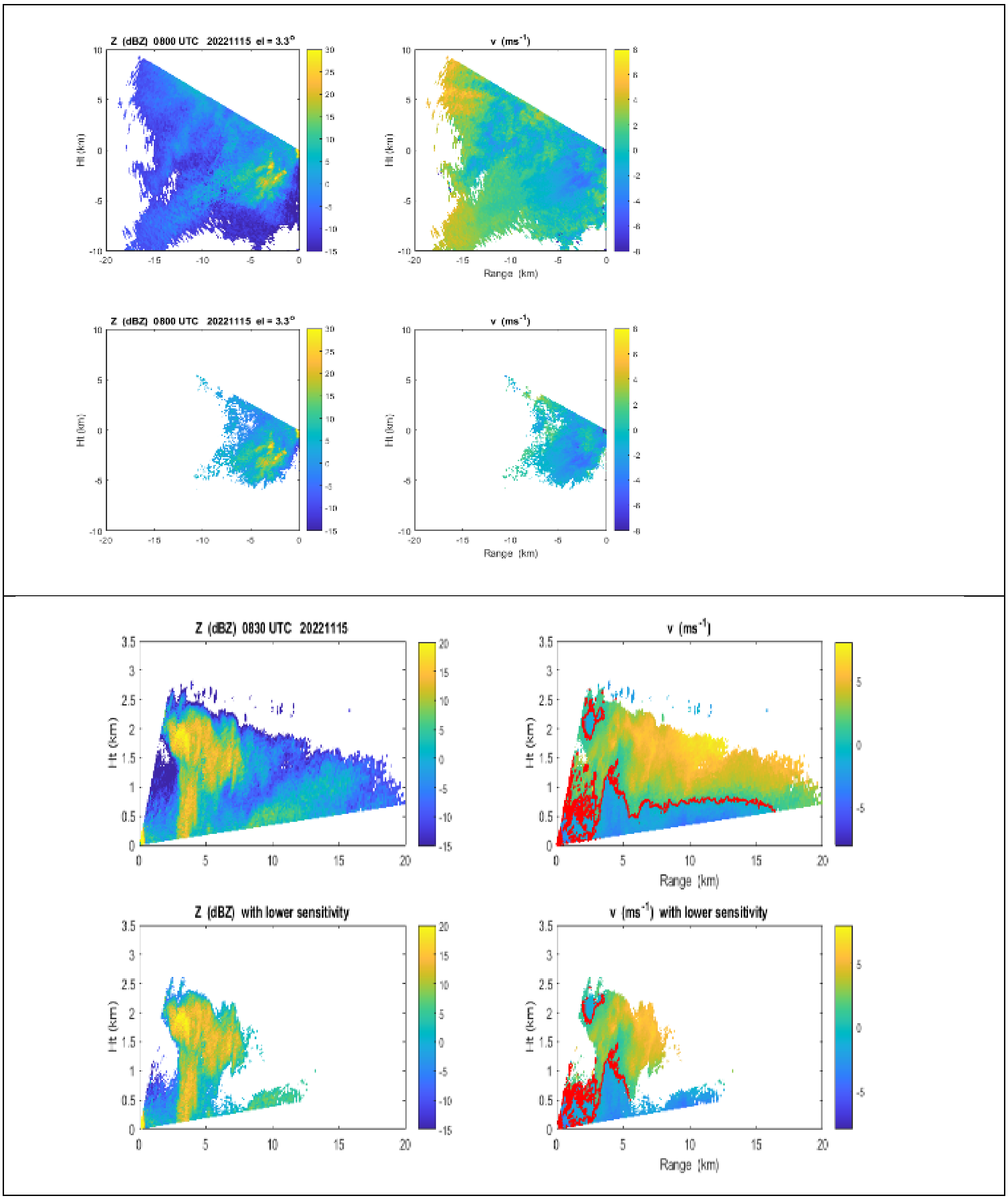

Figure 1: Panels show examples collected of horizontal (left) and vertical scans (right) around ash plumes on Nov 22, 2022. The top figures are the raw data while the lower panels are what the Furuno system would observe with its lower sensitivity.

Dual-polarisation radars utilise both horizontal and vertical polarisations (wave orientation) and this provides significant additional information over conventional single-polarisation radars, including the ability to separate ash particles from other echo sources (McCarthy et al., 2020). This is done by calculating the ratio of the reflectivity of the two polarisations (Z_{DR}) and the cross-correlation of the returned signals (ρHV(0)). The dual-polarisation variables, their physical interpretation and typical ranges of values are summarised in Appendix 1. As seen in Table 1, the specific advantage of the lower sensitivity radars such as the Furuno system is their smaller size and weight, allowing for an easier integration on truly mobile platforms (such as a truck) and therefore simpler logistics to deploy in the field and potentially to access sites that are impossible for larger systems. The other advantage of low-power systems is simpler safety management related to radiation. The Monash radar requires a 100 metre exclusion zone, while the Furuno radar is mounted high on its trailer and therefore does not require an extensive exclusion zone. Note that the radiation issue is also mitigated if the Monash radar antenna is physically raised during deployment.

Table 1. Radar characteristics of the Furuno WR2100 and the Leonardo 60DX.

	FurunoWR2100 +trailer X-band (3 cm) Radar	Leonardo Meteor 60DX X-band (3 cm) Radar
Beamwidth	2.7^o	1.3^o
Range resolution	100 m	150 m (90 m)
Peak Power	100 W (pulse compression)	75 kW
Minimum detection limit at 5 km	-4 dBZ	-20 dBZ
Weight	2.5 t	3.5 t
Height	2.5 m in transit 4 m (deployed)	3 m
RADHAZ: exclusion zone in non-sector blanked areas	6 m	100 m

Operational fixed radars are generally sensitive radars and have a definite role in bushfire monitoring. They are used extensively in forecasting operations to qualitatively monitor fire plumes. They have demonstrated an ability to both track ash plumes and more recently in research, the use of the reflectivity (Z) and the differential reflectivity (Z_{DR}) texture fields for the determination of ash characteristics and the separation of ash from precipitation (Guyot et al., 2023). There is early work on a potential capability to monitor surface fire spread, which is highly complementary to satellite-based hotspot detection (Fig. 3 taken from Lareau et al., 2022), but this needs to be tested on a much larger variety of fire cases with more complex wind fields and fire front propagation.

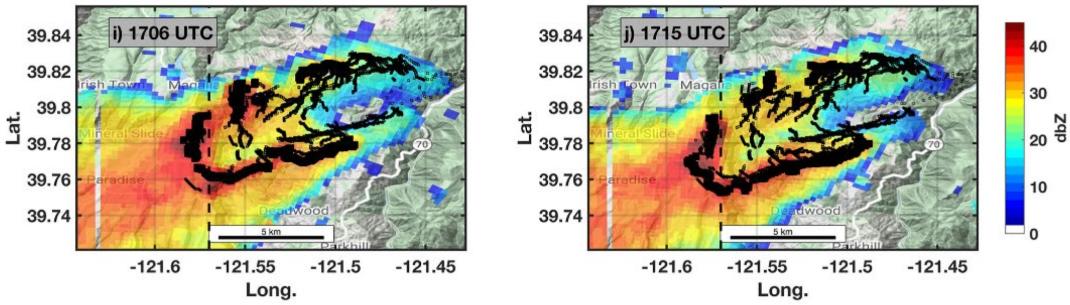

Figure 2. Two snapshots of Radar-derived fire progression during the early growth of the Camp Fire from 1500 to 1832 UTC. Each panel shows the radar reflectivity (shaded), the current fire perimeter estimates (solid black squares), previous perimeter points (small black squares), and a meridian indicating the eastern edge of the town of Paradise, CA. Taken from Lareau et al. (2022).

Operational radars have been used qualitatively during major fire events in most Australian states. Operational forecasting teams in severe weather and decision support have worked alongside FBANs and fire agency intelligence teams during multiple events, using radar data in real time to:

- assess plume growth and extent as indicators of changes in intensity in surface fire intensity and rate of spread
- take estimates of plume elevation to assess plume height and the likelihood of pyro-convective cloud
- monitor wind changes on Doppler radar to provide accurate timing messages on imminent shifts in wind direction to crews on fire grounds.

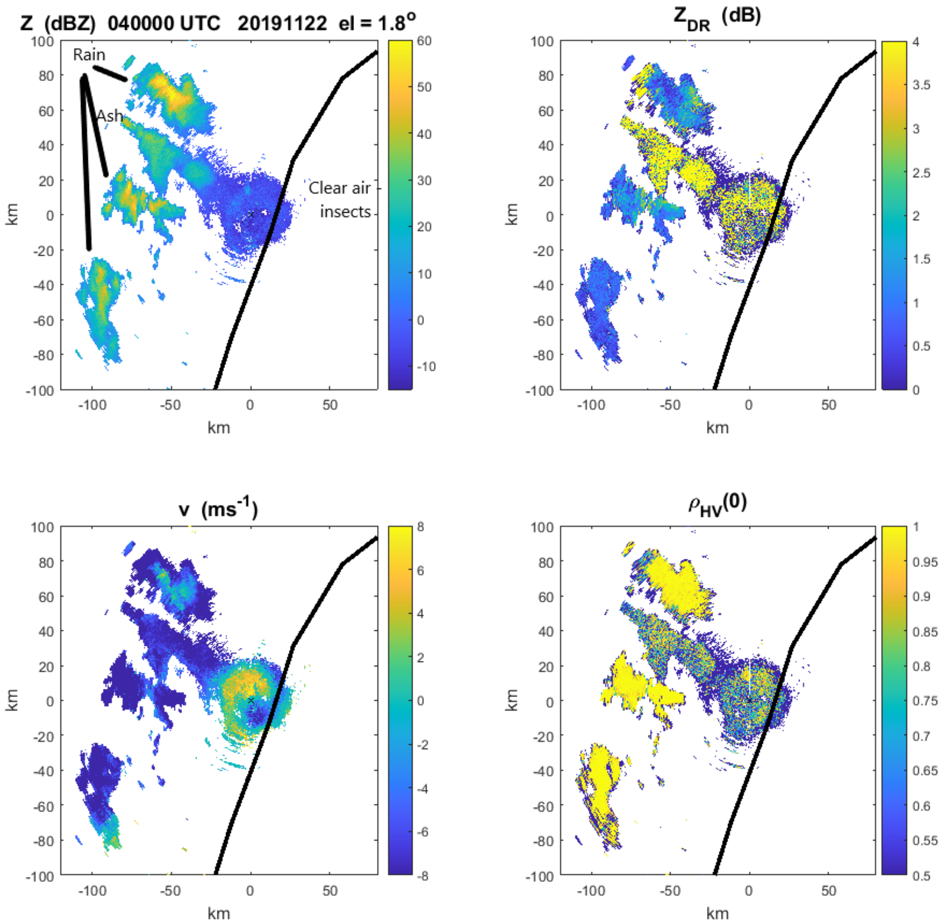

Figure 3: An example of operational Bureau radar data collected with the Terrey Hills radar during the 2019 bushfires near Sydney. These show rain showers and ash plumes as well as clear air signals close to the radar.

Fig. 3 shows an example taken from the Black Summer fires in the Blue Mountains using the Terrey Hills radar in Sydney. The research visualisations show features not routinely analysed and monitored in real time. The radar data, along with the texture of the radar variables can highlight the ash plume area and provide early detection of rapid plume and pyro-convective cloud development as demonstrated by Guyot et al (2023). This, along with US work on fire spread, highlights the capability for real time fire plume monitoring as well as the wider environment including any rain areas.

Thus, the use of operational radars is recommended, but there are limitations related to range and topography. These radars are often a large distance from the fireground – greater than 50 km. Australian operational radars have at best a beamwidth of ~ 1° in azimuth and height, and this means that the radar volumes are spread over a disk with ~ 1 kilometre diameter at 50 kilometre range and ~ 2 kilometre at 100 kilometre distances. Further, the radar beams' height above the ground increases with range (Fig. 4a) providing a coarse and incomplete view of the fire plumes and no near-surface information. However, when a radar is located near the features of interest, the resolution is far higher and the beam locations are much closer to the ground, as can be seen in Fig. 4b for a typical low level scan angle. To further illustrate this, Fig. 4c shows a vertical cross-section of radar reflectivity from one of the cases collected in May 2022 along with a comparison of what a cross-section from an operational radar would look like at ranges around 50 and 100 kilometre. This clearly shows the dramatic loss of detail. Along with losing the low-level structure, the plume echoes are smeared in the vertical, so plume height will be overestimated. The sensitivity also decreases with range so that sampling the downwind plume is lost.Thus, mobile radars deployed at ranges of 5 -10 kilometre from a fire provide the opportunity to provide far more detailed observations of plume structure including potentially the presence of near-surface vortices (McCarthy et al., 2018). In fact, mobile radars have been a key (and routine) tool for the study of tornadoes in the US for three decades (Bluestein, 2022) and more recently have been deployed to bushfire-. Further, sensitive radars such as the Leonardo 60DX will also measure clear air scatter, allowing the measurement of wind fields and wind shifts in the vicinity of the fire, which can be critical to firefighter safety. In summer months, these radars will typically see clear air out to ranges of ~ 15-20 kilometre or further.

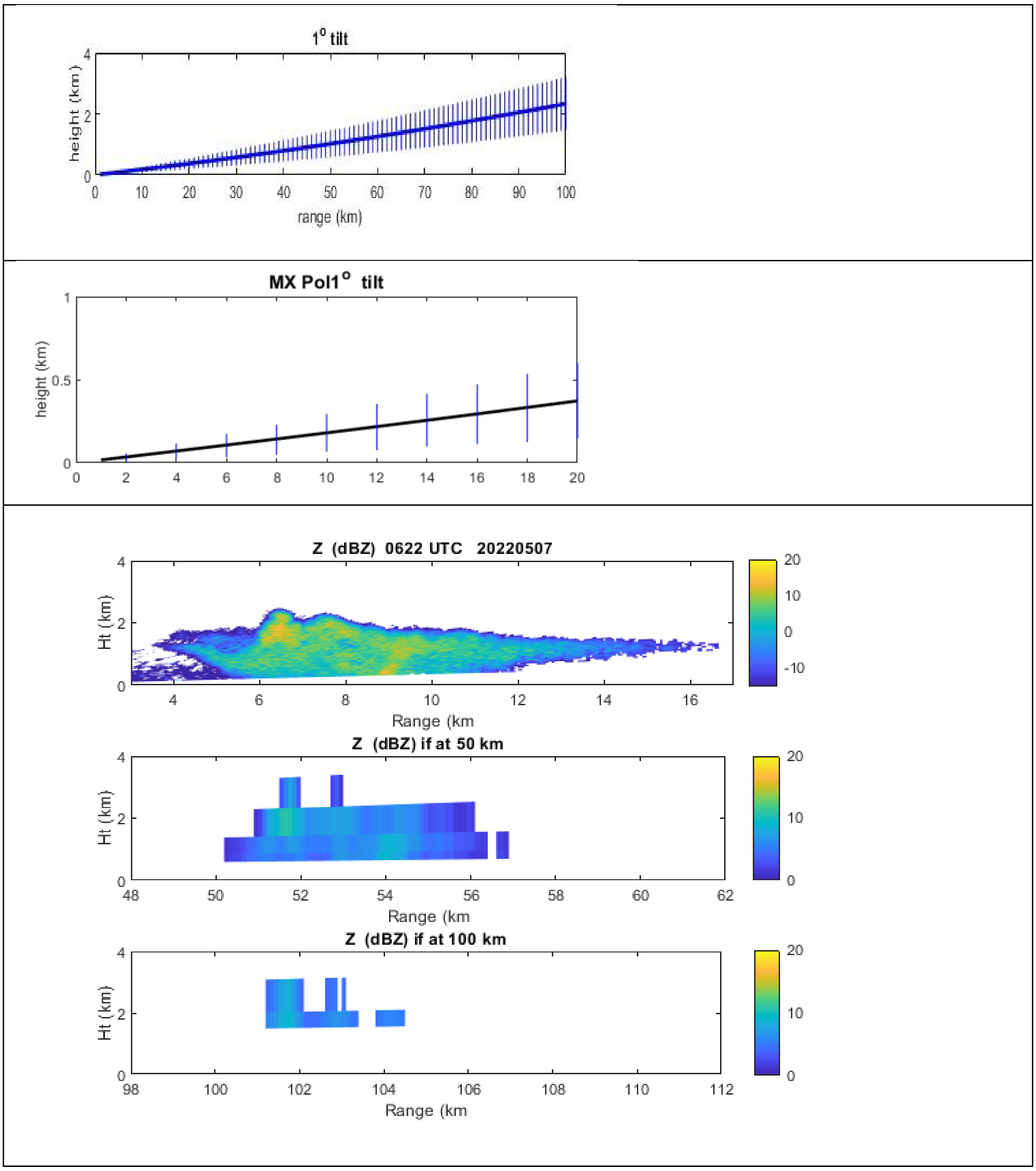

Figure 4: An illustration of the height and size of a radar beam with a 1° beamwidth similar to Bureau operational radars out to a range of 100 km. (b) A similar plot zoomed into a maximum range of 20 km, but for a 1.3o beamwidth similar to the Monash radar and (c) An example of a vertical scan through an ash column and plume collected on7 May 2022 (top) along with a calculation of what a radar with similar sensitivity to a Bureau operational radar would observe at a distance of approximately 50 kilometre (middle) and 100 kilometre (lower panel) where the beam height is well above the ground and the vertical resolution and sensitivity for a given reflectivity is reduced.

Monash radar and its capability

The Monash radar is a trailer-mounted Leonardo 60DX (formally SELEX) 3 centimetre wavelength system. It has a peak transmitter power of 75 kW and can transmit between 0.3 and 2.5 µsec length pulses, with a pulse repetition frequency of 1000 Hz at the longer pulse length. A pulse length of 1 µsec was used for all observations collected during this project. To compare the radar sensitivity to the Bureau's operational systems we need to use the radar equation. The radar equation for scatter from small particles (compared to the radar wavelength) is given by equation (1):

$$P_r = \frac{P_t G_t G_r c\tau (\theta_{HPBW} 2)\pi^3 |K|^2}{512\,\lambda^2}\left(\frac{Z}{R^2}\right) \qquad (1)$$

Where the terms are: *G* the antenna gain, *ϑ* the radar beamwidth, R the range, λ the radar wavelength and *K* is the refractive index of the scatterers. The Monash radar has a similar beamwidth to the Bureau's operational radars and the smaller transmitter power is approximately made up for by the smaller wavelength so that the sensitivity is similar to that of the Bureau's operational radars. This means it is capable of seeing (biological) clear air scatter for the measurement of wind shifts.

Figure 5. The field team from the left, Nathan Ramage (DBCA), Pascal Mater (Monash University) and Mark Curtis (the Bureau) for the first campaign with the radar and the truck used to tow it in the background.

The radar is 3 metres tall, and weight is approximately 3 tonnes. For the field experiments, the trailer was towed using a 4WD 3 or 4 tonne truck (Fig. 5). Once at site, installation of the radar took approximately 45 minutes before operations began. This included unhitching the trailer and levelling the radar. Ideally, the radar requires a clear view of the sun to calculate its orientation. Routine pack up of the radar took ~ 30 minutes, although this could be much faster in an emergency. The primary safety concern with the radar operation is the (microwave) radiation hazard from the beam. The minimum safe distance in front of the transmitting radar was 100 metre. This risk was mitigated by limiting transmission to a fixed sector and all personnel and the public were excluded from that area. This was marked with flags and the operation was continuously monitored. The radar includes a kill switch in the event the transmission area was being encroached on.

Research findings

Summary of the experimental data collected and some illustrative examples

Field experiments were undertaken 3-9 May and 9-13 November 2022. During these periods, data was collected from four environmental burns and on one day we sampled a wide area of convective rain that also included an example of a very small local ash plume. The details of the burns are summarised in Table 2.

At the start of the project, tests were conducted to determine an optimal radar scanning strategy. The challenge was to capture the three-dimensional structure of fire plumes at the highest possible temporal and vertical resolution. The final selected radar scanning strategy included a mixture of two modes. There were (1) sector volumes where the antenna was rotated horizontally within a sector of azimuth angles covering the fire and its near environment at a sequence of elevations to build up a three-dimensional image of the fire plumes. This was augmented by (2) the use of manually selected vertical ('RHI' or range-height-indicator) scans to provide the detailed vertical structure at fixed azimuth angles through the most active areas of the plume. Overall, using ~6 elevations for the sector scans and two RHIs per volume, we were able to achieve a high-resolution 3D sampling of the fire plumes in about two minutes. The data collected were augmented by the deployment of an Australian Warning System (AWS) near the radar for three of the fire cases and the supply of rapid update (2.5 minutes) Himawari 8 data from the Japanese Meteorological Agency.

The radar data is supported with post-fire analysis. For example, Fig. 7 shows Hoffman with low burn success in forest and Fig. 8 shows Walpole
with high burn success in heath vegetation, derived from 10 metre resolution Copernicus Sentinel 2 imagery.

Table 2. Description of the various field sites and conditions during which data were acquired.

May 2022	15 November 2022	7 May 2022	6 May 2022	5 May 2022	Date	N/A					Distance from fire edge
Manjimup A/P	Arklow	Walpole	Hoffman	Collie (Boonering)	Location	Mainly storms	Mainly across	Mainly across	Overhead	Mainly across	Plume orientation
N/A	Forest (Jarrah North West)	Coastal Shrubland	Forest (Jarrah North West)	Forest (Jarrah North East)	Vegetation type	Sector volumes	Sector volumes	Sector violumes	RHI	Sector volumes	Primary radar mode
N/A	9	7	14	6-7	Approx Fuel age						Hours of data
Rain case	Moderate (Cell 3 and 4)	High	Low	Moderate	Burn success	2.5 min Himawari	2.5 min Himawari AWS	2.5 min Himawari	2.5 min Himawari AWS	2.5 min Himawari AWS	Additional data

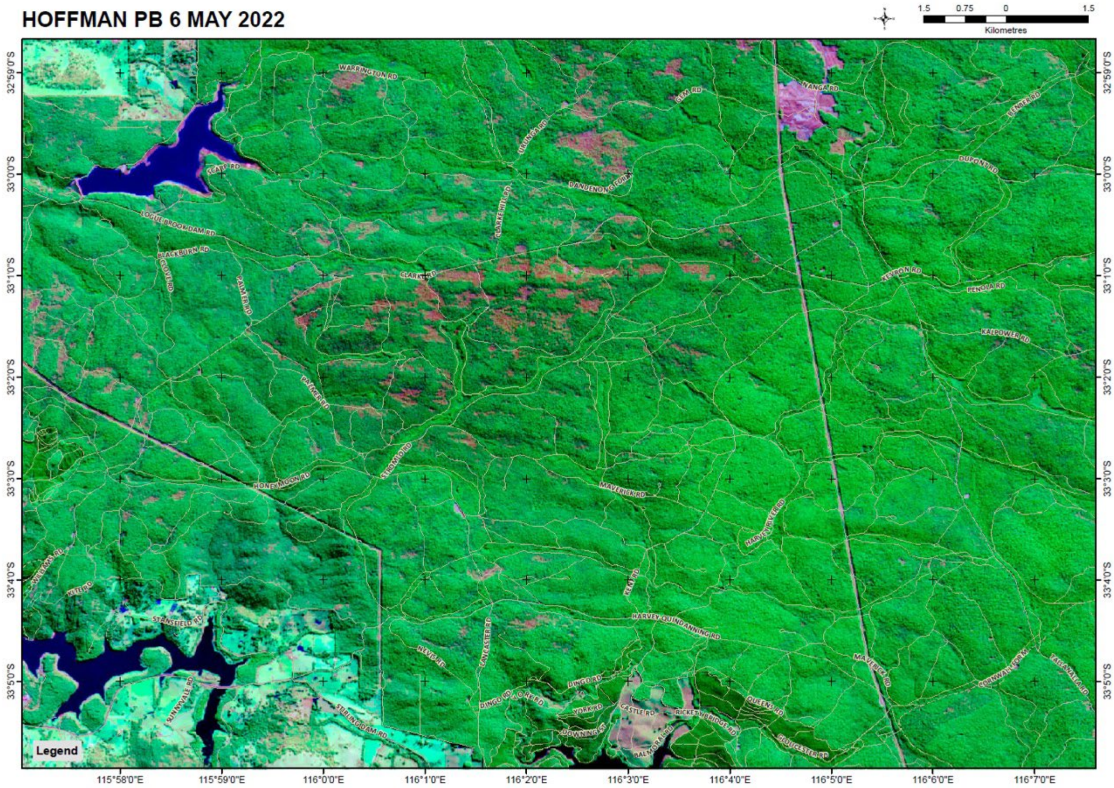

Figure 6: Satellite mapping showing limited burn coverage (light brown area) for the Hoffman fire (6/5/2022)

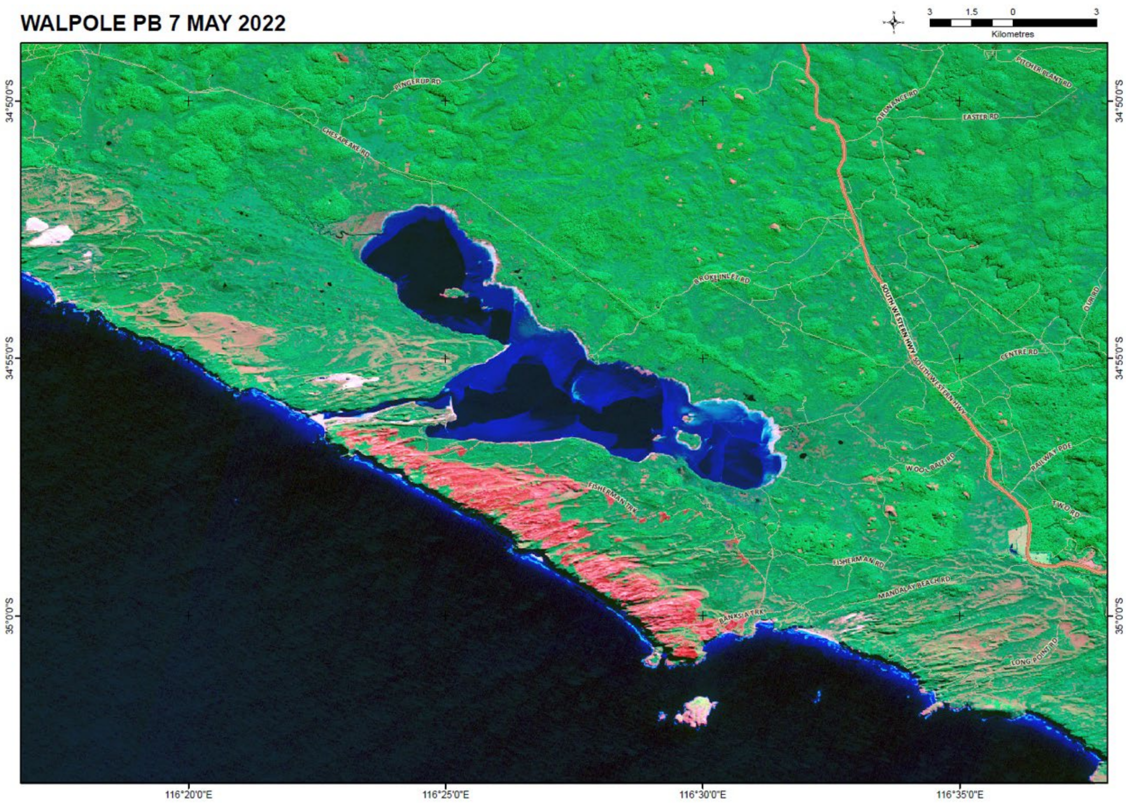

Figure 7: As for Figure 6, but for the Walpole fire on 7/5/2022 with high success (red area).

Useful data was collected on each of the target fires. To illustrate some of the radar capabilities some snapshots of the data are shown in Figures 8-12.

Fig. 8 from 5 May 2022 shows an example of the real time reflectivity data on site, resolving the five lines of the incendiary release. There is nearby clutter and echoes off trees on a ridge at the edge scan. Given the terrain of the fires and trees, some clutter is inevitable in the data and would need to be filtered by real time processing using existing radar quality control techniques. The lower part of Fig. 8a shows an RHI scan with the plume extending more than 20 kilometre from the burn site, despite the relatively low intensity of the burn. As can be seen from the figure, a very high vertical resolution of the fire plume can be achieved using vertical scans.

Fig. 9 shows data from an RHI scan over one of the more intense spots of the Walpole burn on 7 May 2022. The reflectivity shows the plume extending up to 2.5 kilometre height, which was well above the inversion height, but at this intensity, there was little transfer of ash into the free troposphere and the plume settled down to near the top of the boundary layer downwind. This example also includes the Doppler velocity showing the inflow into the plume at low levels and the upper-level divergence into the downwind plume. This illustrates the level of fine detail available in the radar data that will be an important capability for the use of the radar for verifying fire simulation models and improving understanding of the development of fire circulations including vortices. It also provides valuable information about the magnitude of the wind speeds in and near a plume, data that is difficult to sample through other methods. Animations of the radar imagery clearly show the internal structure and circulations around the plumes. There was a clear 'buoyant bubble' structure and evolution in the plumes and this data demonstrates an ability to provide valuable information on the dynamics of the fire plumes which can support robust testing of our fire models and assess potential risks from wind outflows.

Fig. 10 shows a sample of the observations from Manjimup airport during the passage of rain showers. This clearly illustrates some of the capabilities of the dual-polarisation radar to determine target types. From reflectivity alone, the nature of the radar targets is not definitive. However the use of the Z_{DR} and ρHV(0) clearly shows the various echo types with the (biological) clear air echoes with high values of Z_{DR} and the smoke with very low values of ρHV(0) separated from rain (high ρHV(0), low Z_{DR}). This capability can be systematically exploited, both for precipitation and for ash cloud characterisation (Wen et al., 2015; 2016; McCarthy et al., 2020).

Fig. 11 shows observations from an RHI scan at 0830 UTC, 15 November 2022 as a sea breeze interacted with the fire plume, a situation that has produced hazardous conditions in the field for firefighters at other fires. The reflectivity clearly shows the rising core above the fire and the ash plume moving downstream. The combination of the Z_{DR} and ρHV(0) fields shows the clear air on the radar side of the fire while downstream there is a plume of ash moving away. The highest density and size of the particles is between 1 and 2 kilometre above the ground but the combination shows that the area below the plume contains a mixture of ash and insect echoes. The velocity field shows the sea breeze (motion towards the radar, blue colours) feeding into the rising column and the advection of the plume downstream (motion away from the radar, yellow/orange colours). The spectral width shows very high values in the shear region at the top of the sea breeze flow, indicating potential for the detection of turbulence that may have significance for aviation activities. An additional feature is the small clouds that are visible above the ash plume. Some of these are pure rain ($\rho_{HV}(0)$ ~ 0.98 while others have some ash (lower $\rho_{HV}(0)$), mixed hinting at their origin associated with turbulence and detrainment from the rising ash plumes.

Fig. 12 shows snapshots of the retrieved two-dimensional wind at an elevation of 1 kilometre for two times on 15 November 2022, one before the arrival of the sea breeze and the other afterwards. This illustrates the ability to monitor wind shifts in real-time in the vicinity of the fire ground as is also demonstrated in Fig. 11. The 2D wind retrievals show the wind reversal associated with the arrival of the sea breeze and local circulations around the main fire plume.

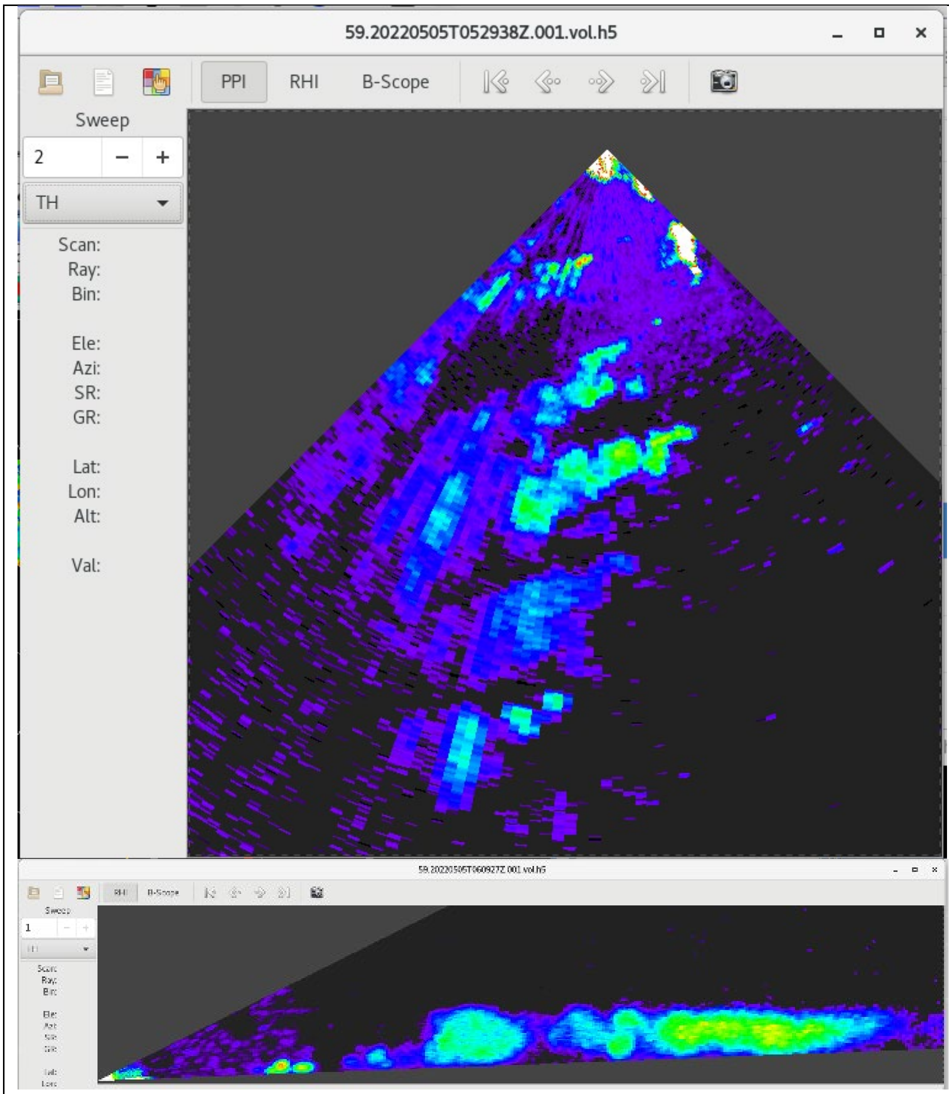

Fig. 8. Real-time radar displays showing a series of linear fire ignitions early in the day on 5 May 2022 (upper) and a vertical cross-section showing the ash plume extending more than 20 kilometre laterally.

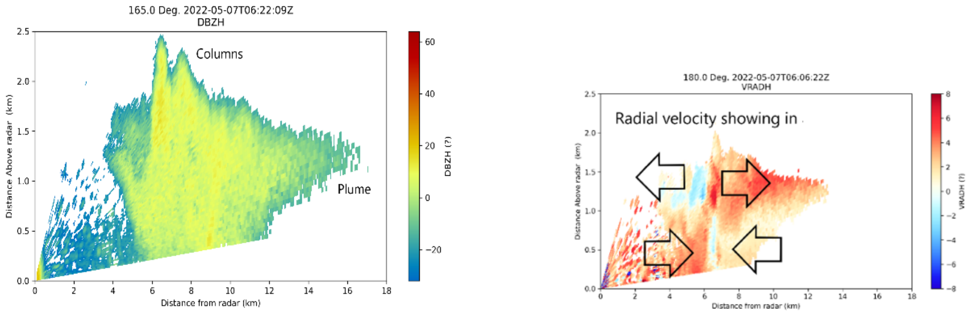

Fig. 9 Vertical cross-sections through a relatively intense ash column extending to 2.5 kilometre (left) and the corresponding radial velocity measurements (right) on 7/5/2022

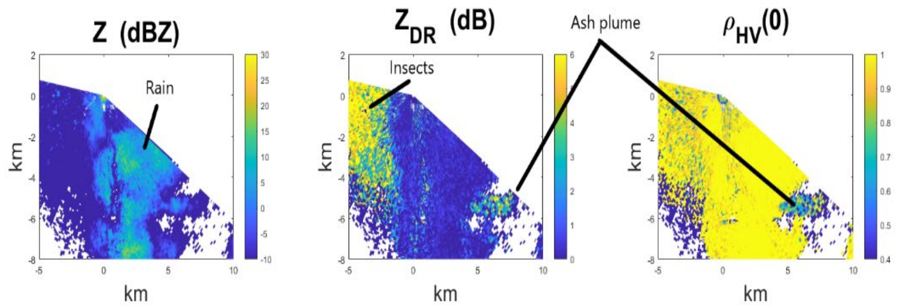

Fig. 10 Sector scans on 8/5/2022 illustrating the ability of the radar to separate out clear air (insect) echoes, moderate rain and a small ash plume from a local burn.

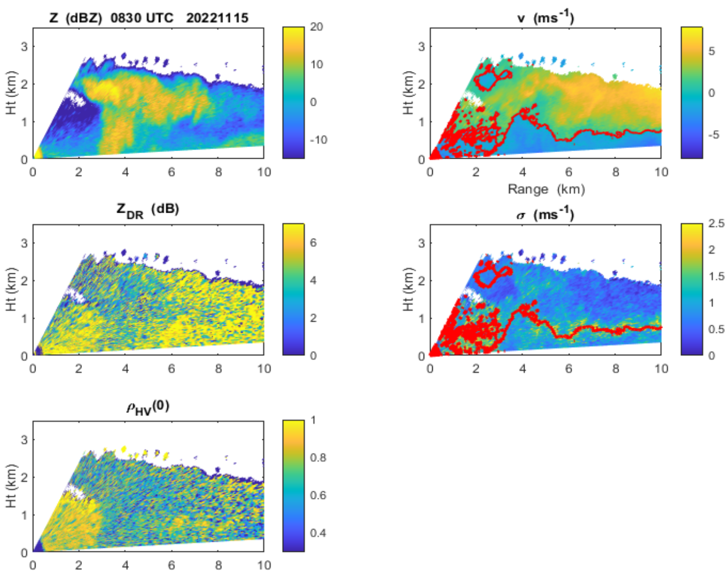

Fig. 11 Vertical cross-sections of an intense column on 15 November 2022 showing clear air echoes close to the radar, the column feeding the downwind plume and an approaching sea breeze feeding the inflow into the column. The spectral width shows enhanced turbulence at the top of the sea breeze in the region of maximum shear.

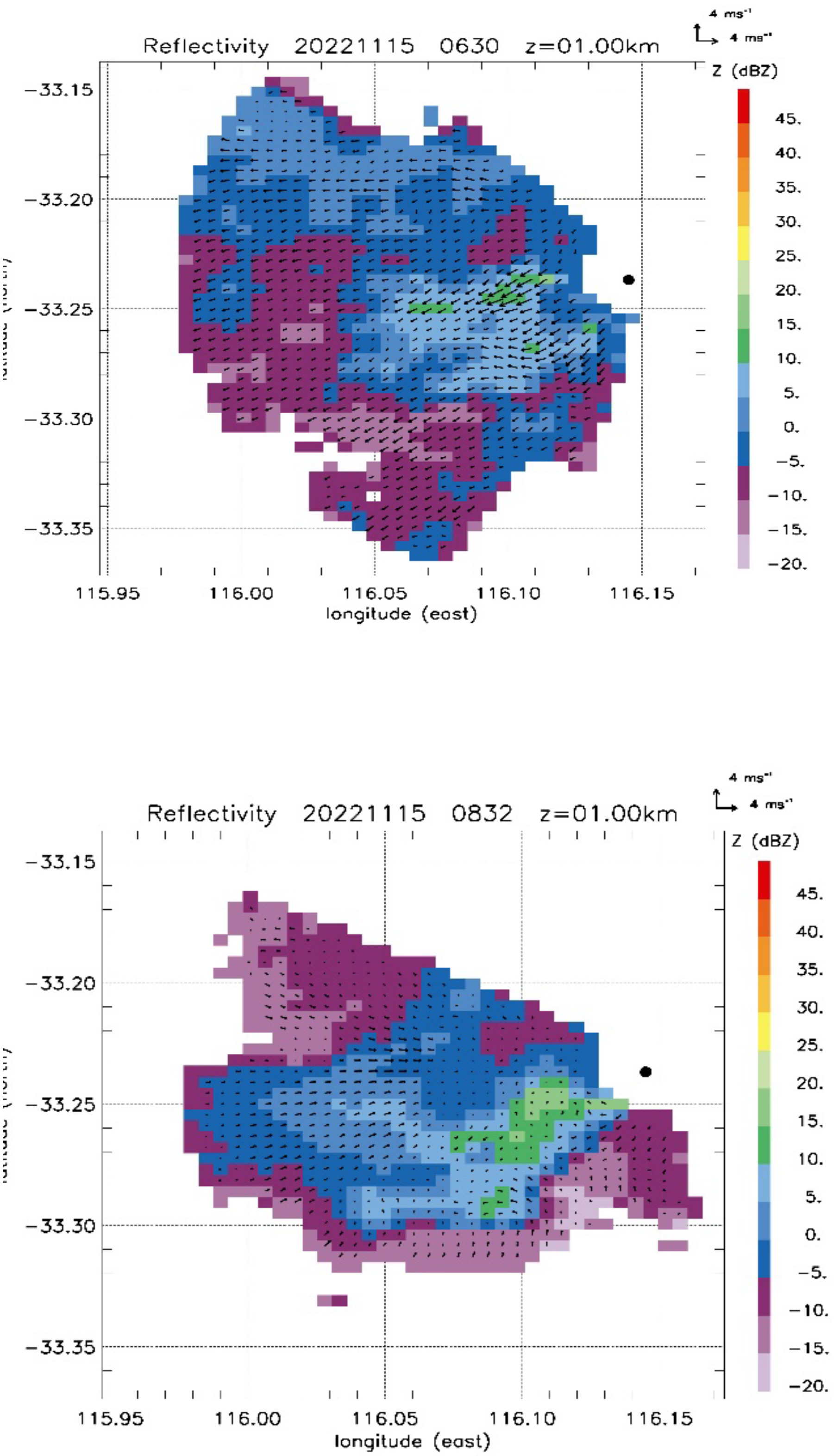

Fig. 12. Showing retrieved two-dimensional winds at an elevation of 1 kilometre for two times, before and after the arrival of the cold front, superimposed over the radar reflectivity.

To summarise, with only four cases of moderate-intensity prescribed burns, we were able to demonstrate the ability of a sensitive mobile radar to detect:

- high-resolution wind information, including rapid wind changes and detailed internal dynamical structure, and areas of enhanced turbulence within the fire plumes
- fire plume boundary and its horizontal and vertical evolution at better than two minute resolution
- clear separation between precipitation, clouds, clear air, and fire plume components (smoke, ash, embers).

Logistics and deployment

A key aim of the project was to demonstrate an ability to deploy the radar close to prescribed burns. Detailed surveys were undertaken for the cases discussed in the previous section (except the Walpole fire) as well as several additional potential burns. The surveys relied heavily on local knowledge and any future operational capability will require a more robust approach to find suitable sites. The Walpole example was an illustration of the value of local knowledge in finding a site on very short notice, but this approach should not be relied on. The deployments included AWS at the radar site for three of the cases and there were plans for launching radiosondes during November, but this was not undertaken. Fig. 13 shows three of the deployment sites.

Figure 13 Three examples of the operational deployment of the radar.

Regarding siting, the radar was sited very close to the target fires. The sites all had significant blockage up to elevation angles of ~ 2°. While this would be unacceptable for a fixed radar, high quality data could be obtained close to the ground because of the short ranges being sampled. Many planned burn locations were surveyed in addition to the cases where data was collected and suitable locations were found for all of them. The locations made use of clearings from harvested timber, as well as lakes and beaches. While none were used, suitable locations on private property were also found. There is further work to be done to assess optimal distances that balance competing aims for the radar data. The locations very close to the burns allow the measurement of fine detail within the fire plumes, but at the cost of limited measurements of the area surrounding the fire, which is important for monitoring wind shifts. An optimal distance to better meet the requirement for observing the winds in the area surrounding the radar as well as maintaining fine scale observations would be a little further from the fire than for the cases discussed here: in the range of 5-7 kilometre rather than the 1-3 kilometre used for the selected sites here.

There are additional practical issues associated with the radar deployment. Site access was often limited by the physical constraints of the trailer-mounted system. Operational systems will require a more physically robust solution than the Monash trailer. The radiation hazard associated with the trailer deployment also had to be carefully managed. This was done by sampling a limited azimuthal range of angles and the use of bunting to highlight an exclusion zone out to the approximate 100 metre range from the radar (visible in Fig. 9b). The radar was equipped with a kill button if people were inadvertently encroaching near the sampling angles. This again has operationalisation challenges that would be mitigated if there was a mechanism to elevate the antenna. Antenna elevation would also mitigate some of the blockage and clutter issues. For the May 2022 deployments, the computer screens used to operate the radar and view data were located on a table outside, which was often difficult to see due to glare. For November 2022 we were provided a communications truck with facilities including refreshments and large screens in the shade. This also accommodated a significant number of people who were present for other tasks, such as air quality sampling.

Transport of the trailer was with a 3 tonne or 4 tonne 4WD truck. This was excellent for towing and allowed some equipment such as tables to be brought along. However, the physical limitations of a single axle trailer meant speed was limited to 80 kilometres per hour and access to some tracks was restricted. There were long transits to sites and extended periods of observations meant that fatigue was a significant safety issue that had to be managed. Pre-deployments would mitigate some of this.

A preliminary Standard Operating Procedures (SOP) document for site selection and deployment, including the potential deployment at bushfires, was developed during the program (Jazreen, 2023. Available on request).

May 2023 project workshop

A workshop with 29 attendees from the project team, DBCA, DFES, CFA, RFS, Bureau, University of Queensland and AFAC was held over 3-4 May at the WA Bushfire Centre of Excellence facility at Nambeelup. The Bushfire Centre of Excellence generously hosted the meeting in their new facility. The review aimed to discuss the findings and lessons learnt, including from science, logistical and operational viewpoints with a range of WA and national operational practitioners. The early discussion included scene setting with a presentation from Assistant Prof Neil Lareau from the University of Nevada, Reno. Neil outlined recent U.S. work including prototype products using research and operational radars. Representatives from the University of Queensland described their Google.org-funded bushfire project results. Another key presentation described the purchase of a similar radar as the Monash system by the Bureau of Meteorology for assessment for operational applications. This was followed by summaries of the data collected with examples and operational learnings. This work has informed much of this report. The workshop also included interactive working group sessions discussing various aspects of potential use in operations, what an operational capability may look like and potential next steps for the research and development phase.

In general, there was great interest in the use of mobile radar for real-time monitoring and nowcasting of fire plume and associated environmental characteristics. The potential of mobile radars to benefit operational analysis and nowcasting were evident to all attendees. There was also an understanding that significant research is still required to build and evaluate a number of prototype radar-based operational products that could be evaluated in the context of costs and benefits, noting the significant capital expense of the radar. There was strong support for this next research component, that also recognised the need to sample more intense fires for data that better characterises capabilities to address risks and for data to test the various fire models including fire simulations coupled to numerical weather prediction.

An important conclusion was that further research should absolutely be driven by co-design with fire agencies, with the proposed strategy being to expose fire agencies and forecasters to candidate products and modify them following feedback received. From a logistical point of view, it was felt that safety aspects of radar deployment could be well handled, while acknowledging the need for a more robust platform than the current trailer for the deployment of high-power mobile radars.

The final discussions of the meeting led to the suggestion that an operational demonstration project could be developed, with researchers, forecasters and fire behavior analysts and fire management practitioners all located in the same room for a few months. This model has been successfully used to enhance co-design of operational products, accelerate transition to operations and adoption of new products, and to demonstrate value of new technology for operational use (e.g., the Sydney forecast demonstration project run by the Bureau, exposing forecasters to new radar-based rainfall products).

Figure 14: Participants at the WA mobile radar project workshop. Bushfire Centre of Excellence. Nambeelup. May 2023.

Summary

This experiment had deliberately limited objectives and was intended as a proof of concept. It was essentially to demonstrate an ability to safely deploy the radar and make useful observations that can be used in real-time for improved fire behaviour monitoring and management, and to expose fire agencies to the radar outputs. The successful deployment included a demonstration of the ability to measure structure within the fire plumes, obtain high quality dual-polarimetric radar data for analysis and sample the clear air returns to measure the wind fields in the region surrounding the fire.

We have demonstrated the capability to deploy a sophisticated, sensitive radar system in the near vicinity of a fire and then to observe fine detail of wind structure and circulations within the fire plume. Even the relatively low-intensity fires associated with environmental burns were seen to have a significant impact on the local circulations and to produce buoyant, bubble-like structures.

Research and operations opportunities

1) Operations
   a) The high temporal frequency of the radar scans enables real time monitoring of plume intensity and plume height. Rapid changes in both can reflect changes in surface fire behaviour. Rapid changes in plume intensity can indicate fire behaviour transition at the surface and can be used to assess the likelihood of extreme fire behaviour occurring. Changes in plume intensity and plume height may also be linked to transition in fuel type or fire spread speed. Plume height (growth) depends on atmospheric structure as well as fire behaviour, therefore expert interpretation is required.
   b) Doppler radar is one of the few observational and research tools that can capture the spatial and temporal extent of fire-modified winds. Fire-modified winds are poorly quantified because of limited observations, however data from Doppler radars may be used to identify local risk and potentially as intelligence to disseminate warnings to crews at fire grounds.
   c) While there is great potential for the use of the radar data, it is also clear that analysis tools integrated into the visualisation and analysis systems used by the meteorologists, FBANs and fire managers will need to be developed rather than just the supply of raw information. This will require a large degree of co-design with multiple development cycles followed by field testing, potentially in a Forecast Demonstration Program setting.

2) Science/research opportunities:

There are a number of research projects and avenues that would benefit from the comparison and validation of events captured on mobile radar. Radar presents a unique capability for capturing detailed three-dimensional (plus time) data at a fire plume (e.g. Australian Warning System information at a fire is limited by location and may not be representative of the fire environment. Numerical weather prediction data does not account for the presence of fire in the landscape). Identified research opportunities are listed below.

a. Ember transport: An ember transport model has been implemented in the Spark fire prediction model. Landing distribution of embers can be validated when observations of new (spotfire) ignitions are available, however limited data is available for validating ember transport elevated in the plume. Additionally, the drivers of the two different modes of ember transport (long distance spotting driven by lofting and transport and short distance or mass spotting driven by turbulence) are not well understood. Mobile radar data presents an opportunity to validate and improve ember transport models. Due to the critical role ember transport plays in fire spread in Australian bushfires, advances in modelling techniques and high confidence in the accuracy and uncertainty of their outputs are highly desired by fire agencies.
b. Plumes: Understanding turbulence in plumes is important for understanding and validating the entrainment of environmental air. These processes are also fundamental to the prediction of pyro-convective cloud.
c. Fire-modified winds: Recent events have highlighted that is critical to understand the hazards and risks presented by straight line damaging wind gusts and rotating features near a fire ground.
d. Low level jets: There is an unmet need to quantify the processes (or at least develop rules of thumb or probabilistic guidance) when low level jets interact with a fire plume. Understanding plume entrainment processes through the use of Doppler radar data will support this.
e. Fire Generated Vortices (FGVs): FGVs can have devastating consequences and the frequency of observations for destructive vortices at large fire events has increased in recent years. Doppler radar data located near the fires can identify small scale circulations and develop understating of the environments FGVs occur in and the ingredients for their formation, thereby leading to improved predictive skill.
f. Coupled fire-atmosphere modelling (e.g. ACCESS-Fire): There is a strong appetite from the fire agencies for research and operational capability stemming from coupled modelling as the impacts of dynamical processes at large fires are well recognised. However, CFA models have had limited objective validation (due in part to the difficulty in obtaining appropriate data. Research using mobile radar observations in combination with CFA models presents an avenue for well-validated research outcomes to understand and predict large fires. Recent evidence is the work from the U.S. using mobile radar and WRF-Fire showing that assumptions on fuel consumption and heat release may require reassessment and increase.

All the research avenues above have overlaps with current or planned research projects (many through the Centre). The research is critical to developing sufficiently accurate and robust models to predict fire behaviour at large fires and developing national and international capability for accurate predictions is imperative to mitigating impacts of fires in a changing climate.

Key milestones

May 2022: Deployment of the Monash X-band radar near environmental burns at several locations and initial data collection.

November 2022: Second deployment of the radar to sample more cases.

May 2023: User workshop held to discuss results, and potential next steps.

December 2023: Report presented to DFES, DBCA, the Bureau and the Centre.

Team members

Monash University

Peter May, Pascal Mater

Bureau of Meteorology

Mark Curtis, Alain Protat, Mika Peace, James Ashley, Adrien Guyot

WA Department of Biodiversity, Conservation and Attractions

Afie Jazreen, Nathan Ramage, Murray Mitchell

WA Department of Fire and Emergency Services

Jackson Parker, Agnes Kristina, Ana Negreiros

References

Aydell, T.B. and C.B. Clements, 2021: Mobile Ka-band polarimetric Doppler radar observations of wildfire smoke plumes, Mon. Wea. Rev., 149, 1247-1264. DOI: https://doi.org/10.1175/MWR-D-20-0198.1

Bluestein, H., 2022: Observations of tornadoes and their parent supercells using ground-based, mobile Doppler radars. Remote Sensing of water related hazards. Ed. K. Zhang, Y. Hong and A. AghhaKouchak, American Geophysical Union. ISBN:9781119159124. https://doi.org.10.1002/9781119159131.ch3

Hermes, L.G., A. Witt, S.D. Smith, D. Klingle-Wilson, D. Morris, G.J. Stumpf and M.D. Eilts, 1993: The gust front detection and wind-shift algorithms for the terminal Doppler weather radar system, J. Atmos. Oceanic. Tech., 10, 693-709. DOI: 10.1175/1520-0426(1993)0102.0.CO;2

Jones, R.F., 1950: Radar echoes from smoke. *The Meteorological Magazine* **79**, 89–90.

Lareau,N.P., N. J. Nauslar,and J. T. Abatzoglou, 2018: The Carr Fire Vortex: A Case of Pyrotornadogenesis?, Geophys. Res. Lett. https://doi.org/10.1029/2018GL080667 +others

Lareau, N. P., Donohoe, A., Roberts, M., & Ebrahimian, H., 2022: Tracking wildfires with weather radars. J Geophys. Rese.: Atmospheres, 127, e2021JD036158. https://doi.org/10.1029/2021JD036158

Lhermitte, R. M., 1969: Note on the observation of small-scale atmospheric turbulence by Doppler radar techniques. Radio Sci., 4, 1241–1246, https:// doi.org/10.1029/RS004i012p01241.

McCarthy, N., McGowan, H., Guyot, A., & Dowdy, A., 2018a: Mobile X-pol radar: A new tool for investigating pyroconvection and associated wildfire meteorology .Bull. Amer. Meteor. Soc. 99, 1177–1195. https://doi.org/10.1175/BAMS-D-16-0118.1

McCarthy, N., A. Guyot, A. Dowdy and H. McGowan, 2018b: Wildfire and weather radar: A review, J. Geophys. Res. 124, 266-286. https://doi.org/10.1029/2018JD029285

McCarthy, N. F., A. Guyot, A. Protat, A.J. Dowdy, and H. McGowan, H, 2020: Tracking pyrometeors with meteorological radar using unsupervised machine learning. *Geophysical Research Letters*, **47**. https://doi.org/10.1029/2019GL084305

Melnikov, V. M., D. S. Zrnic, R. M. Rabin, R. B. Pierce, P. Zhang, 2009: Radar polarimetric signatures of fire plumes (.pdf, 752 kB). *Extended Abstracts, 25th Conference on International Interactive Information and Processing Systems (IIPS)*, Phoenix, AZ, USA, AMS, 15.2.

Tory, K. and J.D. Kepert, 2020: Pyrocumulonimbus Firepower Threshold: Assessing the Atmospheric Potential for pyroCb. Wea. Forecast., **36**. 10.1175/WAF-D-20-0027.1.

Wen, G., A. Protat, P.T. May, W. Moran, and M. Dixon, 2015: A cluster-based method for hydrometeor classification using polarimetric variables. Part I: Classification, J. Atmos. Oceanic Tech **32**, 1320–1340. doi: http://dx.doi.org/10.1175/JTECH-D-13-00178.1

Wen, G., A. Protat, P.T. May, W. Moran, and M. Dixon, 2016: A cluster-based method for hydrometeor classification using polarimetric variables. Part II: Classification: J. Atmos. Oceanic Tech, **33**, 45-60.

Appendix 1: Measured radar variables, their meaning and characteristics

Radar Variables (Doppler)	What they mean	Radar Variables (Dual-pol)	What they mean
Reflectivity – Z in units of dBZ	The returned power to the radar – a measure of how much "big" stuff there is. Drizzle~ 10dBZ Light rain~ 20 dBZ Moderate rain ~ 30 dBZ Heavy rain 40 dBZ Hail storm >50 dBZ Clear air (insects) -10-10 dBZ Smoke/ash-15 – 20+ dBZ	Differential reflectivity Z_{DR} in units of dB	The difference in reflectivity between signals from the two polarisations – a measure of how elongated the material is. If it is tumbling this will reduce the value. Rain 0.5-3 dB Clear air (insects) 5-8 dB Smoke/ash 4-7 dB
Doppler velocity- v in units of ms^{-1}	The radial wind component. Can be used to detect wind shifts and retrieve circulation around a fire	Cross-correlation - $\rho_{HV}(0)$ with no units	Cross-correlation of the returned signal from the two polarisations. A measure of how much of a mixture of material there is. Rain this is ~ 0.98 Clear air (insects) ~ 0.9 Smoke plumes/ash ~0.5
Spectral width – sigma - v in units of ms^{-1}	A measure of the level of turbulence in the radar beam		