Radio Afterglows from Compact Binary Coalescences: Prospects for Next-Generation Telescopes

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ABSTRACT
The detection of gravitational waves from a neutron star merger, GW170817, marked the dawn of a new era in time-domain astronomy. Monitoring of the radio emission produced by the merger, including high-resolution radio imaging, enabled measurements of merger properties including the energetics and inclination angle. In this work we compare the capabilities of current and future gravitational wave facilities to the sensitivity of radio facilities to quantify the prospects for detecting the radio afterglows of gravitational wave events. We consider three observing strategies to identify future mergers – widefield follow-up, targeting galaxies withing the merger localisation and deep monitoring of known counterparts. We find that while planned radio facilities like the Square Kilometre Array will be capable of detecting mergers at gigaparsec distances, no facilities are sufficiently sensitive to detect mergers at the range of proposed third-generation gravitational wave detectors that would operate starting in the 2030s.

Key words: gravitational waves – radio continuum: transients – stars: neutron – telescopes

1 INTRODUCTION
The 2015 discovery of gravitational waves produced by a binary black hole merger by the Laser Interferometer Gravitational Wave Observatory (LIGO) kickstarted a new era of astronomy (Abbott et al. 2016a). Despite comprehensive follow-up observations carried out using telescopes across the electromagnetic spectrum, no electromagnetic counterpart was detected (Abbott et al. 2016c,d), nor were any coincident neutrinos (Adrián-Martínez et al. 2016). Almost two years later LIGO/Virgo detected gravitational waves from a neutron star merger (Abbott et al. 2017b), which was accompanied by the contemporaneous detection of a short gamma-ray burst (Abbott et al. 2017c; Goldstein et al. 2017). Approximately 10 hours later a candidate optical counterpart was discovered (Coulter et al. 2017; Soares-Santos et al. 2017; Valenti et al. 2017; Arcavi et al. 2017a; Tanvir et al. 2017; Lipunov et al. 2017), while X-ray and radio emission was detected 9 and 16 days post-merger respectively (Troja et al. 2017; Hallinan et al. 2017). The delay in detecting the X-ray and radio emission stems from different physical origins – the optical kilonova is produced by the decay of elements produced via r-process nucleosynthesis in the merger, while the X-ray and radio emission originates from the relativistic outflow launched by the merger interacting with the surrounding medium (Metzger & Berger 2012). Although none have been detected to-date, the slow moving material in the kilonova may eventually give rise to late-time radio emission (e.g. Hotokezaka et al. 2018; Katheringamaraju et al. 2019), while the synchrotron emission from the relativistic outflow was later detected at optical wavelengths (Lyman et al. 2018; Fong et al. 2019; Lamb et al. 2019a).

Continued radio monitoring of GW170817 revealed a lightcurve that gradually rose over the following months (Alexander et al. 2017b; Mooley et al. 2018a; Margutti et al. 2018), before peaking approximately 150 days post-merger (Dobie et al. 2018) and rapidly fading (Alexander et al. 2018; Troja et al. 2018; Mooley et al. 2018d). This comprehensive monitoring campaign with radio, optical and X-ray telescopes has allowed tight constraints to be placed on the spectral and temporal evolution of the non-thermal afterglow (Hajela et al. 2019; Makhathini et al. 2020; Troja et al. 2020; Hajela et al. 2020). In turn, these constraints have enabled physical properties of the merger, including the energetics, circum-merger...
density and inclination angle, to be inferred (e.g. Nakar et al. 2018). Further constraints on the outflow geometry were obtained through Very Long Baseline Interferometry (VLBI) observations (Mooley et al. 2018b; Ghirlanda et al. 2019), while the non-detection of linearly polarised radio emission constrains properties of the magnetic field of the outflow (Coris et al. 2018).

There has been extensive research into the detectability of the radio afterglow of compact object mergers (e.g. Feng et al. 2014; Hotokezaka et al. 2016; Lazzati et al. 2017; Duque et al. 2019; Gottlieb et al. 2019; Lin & Totani 2020). The joint detection of GW170817 and GRB170817A confirmed the relationship between neutron star mergers and short GRBs (Beniamini et al. 2019; Wu & MacFadyen 2019) that has been predicted for decades (Eichler et al. 1989; Narayan et al. 1992), and therefore studies into the detectability of short GRB radio afterglows are also of relevance (e.g. Ghirlanda et al. 2013, 2014; Metzger et al. 2015; Zhang et al. 2015). That being said, the intricacies of this relationship are not yet clear, as the GRB accompanying GW170817 was an outlier compared to the standard population and the gamma-ray emission likely did not originate from the core of the jet (Matsumoto et al. 2019b,a; Salafia et al. 2019).

In this work we build upon previous studies by quantifying prospects for detecting afterglows with all major current and future GHz-frequency radio facilities using observing strategies tailored to the specifications of each facility. We have expanded our study beyond current gravitational wave detectors, and therefore studies into the detectability of short GRB radio afterglows are also of relevance. In Section 4 we outline the detection and localisation capabilities of existing and planned gravitational wave detectors. Section 3 we summarise potential observing strategies for radio follow-up and the emission that may be produced by mergers. In Section 5 we summarise the other forms of radio emission that may be produced by compact binary coalescences.

We initially prepared a set of afterglow lightcurves $S_{\nu,0}$ as a function of observer time $t_0$ for observing angles from 10–90° for fixed $E_{\text{iso}}, n_0, \theta_{j,c}$ and microphysics parameters. We then calculate $S_{\nu}(t)$ for different values of $n$ by using the scaling relations

$$S_{\nu}(t) = \frac{n_0}{n} \left( \frac{t}{t_0} \right)^{1/3} S_{\nu,0}, \quad t = \left( \frac{n}{n_0} \right)^{-1/3} t_0$$

(3)

(see Granot & Sari 2002; van Eerten et al. 2012). Here we have assumed that the emission frequency lies below the synchrotron cooling frequency and above the characteristic frequency of the lowest energy electrons and self-absorption frequency (i.e. $\nu_{\text{syn}}, \nu_{\text{sa}} \ll \nu \ll \nu_{\text{ch}}$). Population modelling (e.g. Duque et al. 2019) suggests that this is a valid assumption for the GHz-frequency range, which is the focus of this work.

While we only explicitly consider fixed $E_{\text{iso}}$ and microphysics parameters in this work, for completeness we note that the lightcurves obey

$$S_{\nu}(t) \propto E_{\text{iso}}(\epsilon_B n)^{(p+1)/4} \epsilon_e^{-p-1}, \quad t = \left( \frac{n E_{\text{iso}}}{n E_{\text{iso},0}} \right)^{1/3} t_0$$

(4)

which can be used to scale the results of this work to generalised energetics and microphysics parameters. We note that this model does not consider synchrotron self-absorption, and as such, the predicted flux density is overestimated for $n > 1 \text{ cm}^{-3}$ and $\theta_{\text{obs}} < 10$ deg. We therefore do not consider parameters outside of these limits in this work.

To scale the flux density from the nominal emission frequency of our model, $\nu_0$, to a general observing frequency, $\nu$, we assume the emission obeys a simple power law with spectral index $\alpha = (1-p)/2$ (Sari et al. 1998). Since the model flux density, $S_0$, is calculated in the rest frame of the merger we also apply the standard K-correction (see e.g. Novak et al. 2017), resulting in a frequency-corrected flux density of

$$S = \frac{S_0}{(1+z)^\alpha} \left( \frac{\nu}{\nu_0} \right) \epsilon_e^\alpha$$

(5)

where we convert between redshift, $z$, and luminosity distance, $D_L$, using the cosmological parameters in Hinshaw et al. (2013) implemented in Astropy:Cosmology.WMAP9. We emphasise that this model is by no means comprehensive—it is a single, generalised, model for one of many components of the radio emission that may be produced by compact binary mergers (e.g. Hotokezaka & Piran 2015).

2.2 Other forms of emission

At early times ($t \lesssim 10$ days post-merger) the dominant source of radio emission may be the reverse shock (Sari & Piran 1995;
Resmi & Zhang 2016; Lamb & Kobayashi 2019), which propagates from the outflow towards the site of the merger. This emission is dependent on similar parameters to the forward shock, including the inclination angle. Reverse-shock emission has been detected in long GRBs (e.g. Kulkarni et al. 1999; Kobayashi 2000; Kobayashi & Sari 2000; Laskar et al. 2013; Perley et al. 2014; Alexander et al. 2017a; Laskar et al. 2019; Rhodes et al. 2020) but may be difficult to detect in short GRBs due to the required follow-up latency (Lloyd-Ronning 2018). However, observations of GRB 160821B suggest that a reverse shock component is responsible for part of the early time radio emission (Troja et al. 2019; Lamb et al. 2019b). We stress that even if reverse shock emission may be difficult to detect as a distinct component, its contribution to the overall emission may be significant enough that forward-shock jet models (including the one we use in this paper) alone may not accurately describe the early-time lightcurve evolution.

While most mergers likely launch a jet, the fate of the jet is dependent on factors including the energetics of the merger and the density of the surrounding environment. As the jet propagates into the surrounding ejecta, it may form a cocoon, which will produce a distinct signal as it expands and breaks out of the ejecta (Nagakura et al. 2014; Murguia-Berthier et al. 2014; Lazzati et al. 2017; Nakar & Piran 2017; Gottlieb et al. 2018). Beyond the initial rise and decline, this geometry may also produce a double-peak in the lightcurve (Barkov et al. 2018).

Radio emission may also be detectable from kilonovae, which produced the early-time optical and infrared emission associated with GW170817 (Pian et al. 2017; Kasen et al. 2017; Smartt et al. 2017). This emission is produced by the ejecta associated with the kilonova which expands at sub-relativistic velocity and is therefore expected to be fainter, and peak at later times, than the non-thermal synchrotron emission. The timescale of this peak ranges from months to decades and the peak luminosity is similarly uncertain (e.g., Nakar & Piran 2011; Piran et al. 2013; Hotokezaka et al. 2018; Kathirgamaraju et al. 2019; Margalit & Piran 2020). The kilonova ejecta are expected to expand quasi-isotropically, and therefore this form of radio emission may be detectable from future mergers even when the emission associated with the relativistic ejecta is not detected due to beaming.

3 RADIO TELESCOPE CAPABILITIES

In this section we outline the follow-up capabilities of radio interferometers. We exclude low-frequency (≤ 300 MHz) telescopes from this discussion as our model does not account for synchrotron self-absorption and is therefore not accurate at these frequencies. Table 1 lists the specifications of each telescope in our analysis.

3.1 Follow-up Strategies

The localisation areas of previously detected gravitational wave events span tens to thousands of square degrees (Abbott et al. 2019a, 2020a) and while the addition of more detectors to the network will lead to smaller localisation areas for events at comparable distances, improvements to detector sensitivity will also lead to the detection of more distant events with comparable localisation areas (Abbott et al. 2020b; Hall & Evans 2019). Therefore the largest impediment to detecting an electromagnetic counterpart is the ability to cover sufficient area to a sufficient depth. Below we outline possible observing strategies for detecting a long-lasting (months-years), sub-mJy radio afterglow as predicted by theoretical models (e.g. Hotokezaka et al. 2016) and observed from GW170817 (e.g. Hajela et al. 2019; Makhathini et al. 2020; Troja et al. 2020). The search for other forms of emission (e.g. an optical counterpart or a coherent radio burst) may require different strategies.

3.1.1 Targeting known galaxies

One survey strategy adopted in the follow-up of GW170817 was to target known galaxies in the localisation volume (e.g. Andreoni et al. 2017; Arcavi et al. 2017a; Coulter et al. 2017; Díaz et al. 2017; Evans et al. 2017; Valentí et al. 2017). This was also the predominant strategy used in radio follow-up, as at the time no facilities had sufficient survey speed to perform an unbiased search for a radio counterpart. Currently the best catalogues for this purpose include the Galaxy List for the Advanced Detector Era (GLADE; Dálya et al. 2018), Census of the Local Universe (CLU; Cook et al. 2019), Photometric Redshifts for the Legacy Surveys (PRLS; Zhou et al. 2021), the WISE × SuperCOSMOS Photometric Redshift Catalog (Bilicki et al. 2016), and the 2MASS photometric redshift galaxy catalogue (2MPZ; Bilicki et al. 2014). GLADE and CLU are compilations of existing surveys (and encompass observations from 2MPZ), while PRLS uses the Dark Energy Camera Legacy Survey (Dey et al. 2019) and data from the Wide-field Infrared Survey Explorer (WISE; Wright et al. 2010). Additionally, the Mass Associated for GRavitational waves ObserVations Efficiency (MAN-GROVE; Ducoin et al. 2020) combines GLADE with estimates of...
stellar mass from WISE, and Artale et al. (2020b) compute host probabilities from estimates of stellar mass and star formation rate. Numerous works explore the prospects for this search method – for example, Gehrels et al. (2016) demonstrates that simple galaxy targeting can reduce the required number of pointings by a factor of 10–100 compared to an unbiased search, while Coughlin et al. (2018) find that search efficiency can further be improved by a factor of 2. Some strategies expand on basic galaxy targeting by preferring to target galaxies that are closer (Arcavi et al. 2017b), or by using assumptions on afterglow emission (Coughlin & Stubbs 2016; Salafia et al. 2017). Telescopes with wider fields of view may be able to observe multiple galaxies in a single pointing, and this follow-up may be optimised by convolving the gravitational wave sky map with a galaxy catalogue (Evans et al. 2016).

Once we have obtained a larger sample of localised mergers we will be able to use the population of known host galaxies to weight galaxy catalogues by more robust metrics than simple mass-averages. While observational constraints are currently limited by a lack of events, detailed studies of the host galaxy of GW170817 were carried out (Blanchard et al. 2017; Im et al. 2017; Levan et al. 2017; Pan et al. 2017; Ebrová et al. 2020; Contini 2018) and simulations are already revealing potential relationships between merger and host properties (e.g. Toffano et al. 2019; Artale et al. 2019, 2020a). Radio observations will have a role to play in these efforts, as they are useful in determining the presence of AGN and thereby determine whether stellar mass or star formation is the driving factor of merger formation (Zheng & Ramirez-Ruiz 2007; Corsi et al. 2017). They can also measure star formation rate in galaxies with optical obscuration (Perley & Perley 2013).

Ultimately, the limiting factor of this technique is the completeness of the survey catalogue, which for current surveys (e.g. Dálya et al. 2018; Cook et al. 2019) is lacking at distances comparable to the planned LIGO detector range of 330 Mpc (Abbott et al. 2020b). While PRLS is deeper than the other wide surveys (with a limiting magnitude of ~ 20.4 subject to other selection criteria), it only covers ~ 16% of the sky and therefore cannot be utilised for all events. We discuss the issue of galaxy catalogue completeness and its impact on follow-up in 5.1.4. For more distant events it is therefore natural to consider searches that only use the localisation obtained from the gravitational wave signal.

### 3.1.2 Unbiased searches

Telescopes with larger survey speeds are capable of performing unbiased searches for radio counterparts by observing entire localisation regions. Here we consider unbiased searches to be feasible for telescopes with a survey speed larger than 10 deg$^2$ hr$^{-1}$ for a detection threshold of 0.5 mJy. This choice reflects the requirement to cover a substantial fraction of a localisation area (typically tens–hundreds of square degrees) to a constraining sensitivity (given that afterglows are expected to peak at tens–hundreds of $\mu$Jy) in a reasonable amount of time. This technique has the obvious advantage of not being limited by the completeness of existing galaxy catalogues, while on the other hand, can result in coverage of a large amount of extraneous area and an increase in false-positives (which we discuss in Section 5.1.2). However, this can be partly mitigated by restricting candidates to those associated with known galaxies within the localisation volume.

There are multiple ways to optimise an unbiased search (e.g. Ghosh et al. 2016, 2017; Dobie et al. 2019a; Gupte & Bartos 2020) but for the purposes of this work we simply assume that a telescope can observe a given sky area without any consideration of exact observing strategies.

### 3.1.3 Monitoring known electromagnetic counterparts

The final type of follow-up involves searching for radio emission from known counterparts detected at other wavelengths, which allows for maximised sensitivity as all available telescope time can be allocated to a single pointing.

The detection of a known counterpart can also help inform the required cadence and sensitivity of radio observations. Localising the counterpart to a galaxy provides accurate distance measurements (Hjorth et al. 2017) which can also be used to infer tighter constraints on the merger inclination angle independent of any afterglow modelling (Mandel 2018). The detection of a short GRB can loosely constrain the merger energetics (Abbott et al. 2017c; Goldstein et al. 2017), and a combination of multi-wavelength detections can be used to broadly infer the overall geometry of the merger (Kasliwal et al. 2017).

Even if a radio counterpart is not detected, radio observations are still useful in placing constraints on the spectral properties of...
the synchrotron afterglow (in combination with optical and X-ray follow-up) and inferring properties of the host galaxy. Single-dish spectral line observations can also be used to constrain the average density of the host galaxy and infer the density of the environment surrounding the merger (Hallinan et al. 2017). X-ray observations can also be used as independent confirmation of these estimates (e.g. Hajela et al. 2019).

3.2 Existing Facilities

3.2.1 Australia Telescope Compact Array (ATCA)

The Australia Telescope Compact Array is an East-West array consisting of six 22-m dishes with a maximum baseline of 6 km (dependent on the array configuration). Each dish is equipped with a set of receivers that can sample frequencies from 1.1 to 105 GHz, with the System Equivalent Flux Density (SEFD) increasing towards higher frequencies (Wilson et al. 2011). In this paper we consider observations in the C/X band (4–12 GHz) which is generally the most sensitive due to the high Radio Frequency Interference (RFI) occupancy at lower frequencies.

Currently correlation is performed using the Compact Array Broadband Backend (Wilson et al. 2011), which allows observations in 2×2048 MHz windows. However, the Broadband Integrated-GPU Correlator for the Australia Telescope (BIGCAT) upgrade, which will be completed by December 2021, will double the available bandwidth to 8 GHz. As this upgrade will occur on a similar timeline to the start of the next LIGO/Virgo observing run, in this paper we assume that the upgrade is successfully commissioned and therefore the sensitivity will improve by a factor of \( \sqrt{2} \) compared to the current level.

It is not feasible to carry out unbiased follow-up with the ATCA due to its low survey speed, even using mosaicing. However, it is useful for targeted follow-up, either of galaxies within the localisation volume of the gravitational wave event, or of counterparts detected at other wavelengths. Taking into account observing overheads, it’s possible to observe \( 50 \) galaxies to a detection threshold of \( < 70 \mu \text{Jy} \) in a typical 12-hour observation (12 minutes per source), while a detection threshold of \( \sim 15 \mu \text{Jy} \) can be achieved for follow-up of a single source. We note that in many cases this can be improved by optimising pointings such that multiple galaxies are observed within the same field of view, but to simplify the estimates in this paper we assume that we can simply observe 50 galaxies with 1 per pointing.

3.2.2 Karl. G. Jansky Very Large Array (VLA)

The Karl. G. Jansky Very Large Array (VLA) consists of twenty seven 25-m antennas with maximum baselines ranging from 36.4 km (A configuration) to 1.03 km (D configuration). In this paper we consider the B configuration which has baselines spanning 0.21–11.1 km, although the A and C (which have maximum baselines of 36.4 and 3.4 km respectively) configurations would also be suitable. The telescope can observe at frequencies from 58 MHz to 50 GHz, but in this case we consider observations at S-band (3 GHz; offering the best sensitivity for the expected negative spectral index) and L-band (1.5 GHz; offering lower sensitivity but a twice-larger field of view).

Rana & Mooley (2019) propose an optimised galaxy targeting strategy for the VLA, improving the probability of detecting a radio counterpart by a factor of two compared to a simple approach. This strategy will enable observers to cover approximately 200 galaxies to a sensitivity of \( 15 \mu \text{Jy} \). The VLA can also carry out unbiased searches using on-the-fly mosaicing, where the antennas are driven at a constant rate along a strip of sky, eliminating slew overheads which are dominated by the settling time of \( \sim 7 \) seconds per pointing. This technique has already been applied to follow-up of two gravitational wave events, GW151226 (Abbott et al. 2016b) and GW190814 (Abbott et al. 2020c) covering 100 deg\(^2\)/10% (Mooley et al. 2018c) and 5 deg\(^2\)/50% (Mooley et al. 2019) of the localisation regions respectively.

3.2.3 Giant Metrewave Radio Telescope (GMRT)

The Giant Metrewave Radio Telescope (GMRT) consists of thirty 45-m antennas with a maximum baseline of 25 km. Recent upgrades to the receivers give the GMRT unparalleled sensitivity at sub-GHz frequencies, and here we consider observations in bands 3 and 4, centered on 400 and 700 MHz respectively. Observations in these lower bands are vital in understanding the spectral evolution of the afterglow, in particular, placing constraints on the evolution of the synchrotron self-absorption frequency.

Here we consider the GMRT as a dedicated follow-up instrument for localised mergers, as its combination of sensitivity and field of view is not conducive to unbiased searches. We consider 3 hour observations in both Band 3 and 4, corresponding to an image sensitivity of 15 and 20 \( \mu \text{Jy} \) respectively. This choice of exposure time is to ensure both bands can be observed in a typical GMRT session of \( \sim 6 \) hours.

3.2.4 Arcminute Microkelvin Imager Large Array (AMI-LA)

The Arcminute Microkelvin Imager Large Array (AMI-LA) consists of eight 12.8 m antennas with a maximum baseline of 110 m operating at an observing frequency of 15 GHz. The AMI-LA Rapid Response Mode (ALARRM; Staley et al. 2013) enables the telescope to respond to GRB alerts within 2 minutes of the burst, allowing for tight constraints to be placed on early-time emission (e.g. Lamb & Kobayashi 2019). However, the AMI-LA field of view limits the practicality of early-time follow-up of neutron star mergers to those with a simultaneous detection of a GRB by the Neil Gehrels Swift Observatory. While AMI-LA can also be used to monitor known counterparts, providing additional spectral coverage and achieving a sensitivity of 25 \( \mu \text{Jy} \) in a 3 hour observation, we do not consider it in our detectability analysis in Section 5.2, and omit it from Table 1, due to the superior sensitivity of the VLA at these frequencies.

3.2.5 Australian Square Kilometre Array Pathfinder (ASKAP)

The Australian Square Kilometre Array Pathfinder (ASKAP; Johnston et al. 2008; Hotan et al. 2021) is an array of thirty-six 12-m dishes with baselines ranging from 37 m to 6 km. ASKAP is designed for all-sky surveys between 700–1800 MHz (in this case we consider observations at 900 MHz to maximise the sensitivity) and uses MkII phased-array feeds (Hampson et al. 2012) consisting of 36 beams resulting in a 30 deg\(^2\) field of view. While the SEFD is higher than other comparable telescopes, the large field of view...
results in a high survey speed, making it possible to search large areas of sky for a gravitational wave counterpart. However, this does mean that ASKAP is not useful for monitoring events where an electromagnetic counterpart has already been discovered. We therefore only consider the utility of ASKAP for localising events, and not monitoring them.

Similarly, ASKAP is not particularly useful for a galaxy-targeted search strategy since tens–hundreds of candidate host galaxies can be covered with a single pointing. Some widefield telescopes select their pointing strategy by convolving the localisation skymap with galaxy catalogues (e.g., Evans et al. 2016) but in Dobie et al. (2019a) we demonstrated that this strategy does not produce any appreciable benefits for ASKAP follow-up. In this work we consider two strategies, a single deep ~ 10 hour pointing (achieving a noise of 35 \( \mu Jy \)) or a widefield strategy consisting of four ~ 3 hour pointings (achieving a noise of 110 \( \mu Jy \)) for events localised to < 100 deg\(^2\) (corresponding to ~ 60% of neutron star mergers during O4, and the majority of mergers detected with 3G detectors Abbott et al. 2020b; Hall & Evans 2019). So far ASKAP has performed follow-up of S190510g and GW190814 (Dobie et al. 2019b, Stewart et al. in prep.) and both times the latter pointing strategy was used. We note that due to the comparably low angular resolution of ASKAP, some afterglows may be contaminated by emission from the host galaxy. We discuss this problem in Section 5.1.3.

3.2.6 Apertif

The Westerbork Synthesis Radio Telescope (WSRT) is an East-West array consisting of fourteen 25-m antennas with a maximum baseline of 2.7 km. Twelve of the antennas have been fitted with L-band (operating from 1–1.75 GHz) PAFs as part of the APERture Tile In Focus (Apertif) project, improving the telescopes field of view to 9.5 deg\(^2\) (Oosterloo et al. 2010; Adams & van Leeuwen 2019). Similar to ASKAP, Apertif’s wide field of view means it is more suited to widefield searches rather than targeted follow-up, while the observing frequency and maximum baseline mean it is also subject to the same host galaxy contamination issues. The sensitivity of Apertif is comparable to ASKAP, and we consider follow-up with one deep 12 hour pointing achieving a sensitivity of 25 \( \mu Jy \) or four pointings achieving a sensitivity of 50 \( \mu Jy \).

3.2.7 MeerKAT

MeerKAT (Jonas & MeerKAT Team 2016) consists of sixty four 13.5-m diameter antennas with a maximum baseline of 8 km fitted with 1.4 GHz receivers and has a ~ 1 deg\(^2\) field of view. The highly sensitive receivers have a system equivalent flux density of ~ 430 Jy (Mauch et al. 2020), making MeerKAT a suitable facility for searching for emission from known counterparts. Here we consider two follow-up strategies – a single deep 10 hour pointing achieving a sensitivity of ~ 2 \( \mu Jy \) and ten 1 hour pointings covering 10 deg\(^2\) to a sensitivity of ~ 7 \( \mu Jy \). The former strategy applies to very well localised events (comparable to expectations for third generation detectors, see 4.2) and monitoring of known counterparts, while the latter strategy applies to unbiased follow-up of events localised to ~ 10 deg\(^2\) or targeted follow-up of less-localised events using a galaxy catalogue convolution strategy (Evans et al. 2016).

3.3 Future Facilities

3.3.1 Square Kilometre Array (SKA)

The Square Kilometre Array (SKA) will be the worlds largest radio telescope, with a mid-frequency array in South Africa and a low-frequency array in Western Australia. In this paper we focus on the mid-frequency array, which will be split into two stages.

SKA-1 mid will consist of the existing MeerKAT array and an additional one hundred and thirty three 15-m dishes, with the array expected to come online in the mid-2020s. Braun et al. (2019) outlines the anticipated array performance, and for the purposes of this paper we consider observations in Band 2, centered on 1.43 GHz as a compromise between maximising sensitivity and the expected negative spectral index of gravitational wave afterglows. We assume the same observing strategy as MeerKAT, with a 1 hour continuum sensitivity of 2 \( \mu Jy \).

We also consider observations with the SKA-2. While the design specifications for the SKA-2 are still uncertain, here we assume an order of magnitude sensitivity improvement over SKA-1 for the same observing strategies.

3.3.2 Next Generation Very Large Array (ngVLA)

The Next Generation Very Large Array (ngVLA; Murphy et al. 2018) is a planned replacement for the VLA operating between 1.2 and 116 GHz. The main array will consist of two hundred and fourteen 18-m dishes on baselines of up to 1000 km. We consider observations in the lowest frequency band, centered on 2.4 GHz due to the larger field of view and higher relative sensitivity (Selina et al. 2018). It is currently anticipated that Early Science observations will begin in 2028 with full operation from 2034 onwards\(^4\).

The ngVLA will be capable of performing unbiased follow-up of well-localised events, observing 10 deg\(^2\) to a sensitivity of 1 \( \mu Jy \) in 10 hours (Corsi et al. 2019). The ngVLA has comparable instantaneous sensitivity to the SKA, making it the premier northern hemisphere facility for targeted follow-up of known counterparts. The ngVLA is also capable of observing at frequencies up to 93 GHz, compared to the SKA which will only observe up to 12.5 GHz (Braun et al. 2019). This will allow a better characterisation of the spectral properties of afterglows in conjunction with optical and X-ray telescopes, as was performed for GW170817 (Makhathini et al. 2020; Troja et al. 2020).

3.3.3 Deep Synoptic Array-2000 (DSA-2000)

The Deep Synoptic Array (DSA-2000) is a proposed telescope that will consist of two thousand 5-m dishes capable of simultaneously observing between 0.7-2 GHz and is scheduled to be fully operational by 2026 (Hillman et al. 2019). The telescope is optimised for survey speed, with a 10.6 deg\(^2\) instantaneous field of view and 2.5 Jy SED. Approximately 1 hour per day will be allocated to follow-up of gravitational wave events, with the focus being on well-localised events that can be covered with a single pointing. In these cases, the entire localisation region can be covered to a 5\(\sigma\) detection threshold of ~ 5 \( \mu Jy \). Similar to ASKAP, we also consider a widefield strategy of twelve ~ 5 minute pointings for follow-up of events localised to ~ 100 deg\(^2\).

While the DSA-2000 can cover a 10 deg\(^2\) localisation ten times faster than the SKA or ngVLA, it is important to note that both

\(^4\) https://ngvla.nrao.edu/page/faq#faq_16_content
telescopes can cover that area more efficiently. Gravitational wave localisations are generally irregular shapes (although this will be less true as we move to arrays with >3 detectors) and often multimodal, while telescope fields of view are either circular or rectangular. Ghosh et al. (2016) find that it is significantly more efficient to cover localisation regions with a distributed group of multiple small-FoV telescopes than a single widefield telescope due to the lower extraneous coverage. Similarly, the SKA/ngVLA will use many small-FoV pointings and will therefore achieve more efficient coverage than the DSA-2000 strategy of fewer large-FoV pointings.

3.4 Serendipitous Observations

Advances in radio telescope technology will allow for numerous widefield surveys of the radio sky to be undertaken in the coming decades. Deep all-sky surveys will provide sensitive reference images for transient follow-up, and widefield transient searches will likely provide serendipitous coverage of gravitational wave events.

3.4.1 ASKAP

The Evolutionary Map of the Universe (EMU; Norris et al. 2011) will cover the sky South of +30 deg declination to a design sensitivity ($\sigma$ noise) of $\sim 10 \mu$Jy at 1.3 GHz. This will provide the most sensitive map of the Southern radio sky to-date and be useful as a reference image for transient searches. The Rapid ASKAP Continuum Survey (RACS; McConnell et al. 2020) achieves a typical sensitivity of 250 $\mu$Jy at 900 MHz and has already been used as a reference image in follow-up of GW190814 (Dobie et al. 2019b).

The proposed Variables And Slow Transients (VAST; Murphy et al. 2013) survey is split into three main components, Wide, Deep and Galactic, and will span at least 5 years. VAST-Wide will observe an area of 10000 deg$^2$ to a detection threshold of 2.5 mJy on a daily cadence. VAST-Deep will achieve a detection threshold of 250 $\mu$Jy and will observe 10000 deg$^2$ 7 times, and a single 30 deg$^2$ field daily. VAST-Galactic will observe 750 deg$^2$ of the galactic plane 64 times to a detection threshold of 500 $\mu$Jy, which will be useful for events where optical follow-up is hindered by extinction and a high rate of unrelated transients. Here we consider the VAST-Wide and low cadence VAST-Deep surveys, as the wide areal coverage makes them more conducive to this kind of search. We also note that the ASKAP Survey Science observing strategy has not yet been finalised.

3.4.2 MeerKAT

While MeerKAT has a higher instantaneous sensitivity than ASKAP, there are currently no plans to use it for a dedicated widefield untargeted transients survey (Fender et al. 2017). Instead, transient searches will be conducted using commensal data from other surveys, which cover relatively small areas of sky (generally less than 30deg$^2$, see Holwerda et al. 2012; Serra et al. 2016; de Blok et al. 2016; Bailes et al. 2018). Therefore the proposed transients search with MeerKAT will search a smaller area of sky to a greater sensitivity compared to ASKAP. As this is less conducive to serendipitous coverage of multi-messenger events, we instead consider an idealised untargeted survey for radio transients covering 5000 deg$^2$ observed to a sensitivity of 20 $\mu$Jy with 9 observations separated by 4 months. This corresponds to a total observing time of 3750 hours.

3.4.3 Deep Synoptic Array

The Cadenced All-Sky Survey (Hallinan et al. 2019) will observe 16 epochs of the sky North of $-30$ deg on a 4-month cadence to a detection threshold of 10 $\mu$Jy, providing coverage of the majority of gravitational wave events. It will also ultimately provide a reference image with an rms noise of 500 mJy.

4 GRAVITATIONAL WAVE DETECTORS

4.1 Second Generation Detectors

4.1.1 Fourth Observing Run (O4; 2022–2023)

The Fourth Observing Run (O4) will run for one year with both LIGO detectors close to the design sensitivity of a sky and inclination angle averaged detection range of 190 Mpc (Abbott et al. 2020b). Advanced Virgo will have a binary neutron star range of 90–120 Mpc (comparable to the LIGO detector ranges during O3), while the sensitivity of KAGRA (KAGRA Collaboration et al. 2019, 2020) has a large uncertainty and estimates for its binary neutron star range is 25–130 Mpc. Assuming a KAGRA range of 80 Mpc the estimated number of detections is $10^{2.52}$ with a median 90% localisation of 33 deg$^2$. We adopt a detection range of 160 Mpc based on the minimum specifications for the LIGO detectors and reflecting the lower range of the other two detectors.

4.1.2 Fifth Observing Run (O5; 2024–2025)

The fifth observing run will begin after the A+ upgrade, which will increase the LIGO detector range to 330 Mpc (Abbott et al. 2020b). The Virgo detector will also undergo significant upgrades, and will operate with a binary neutron star range of 150–260 Mpc and KAGRA will operate with a range of at least 130 Mpc and possibly as high as 155 Mpc. For the purposes of this paper we assume a sky and inclination angle averaged detection range of 300 Mpc.

4.1.3 A Five Detector Network (2025+)

LIGO-India (Iyer et al. 2011) is expected to join operations in 2025 and will eventually reach design specifications with a range
of 330 Mpc. The geographical location of LIGO-India improves the localisation capabilities of the global network by a factor of 5–10, and in some cases may result in mergers being localised to areas as small as 1 deg².

4.2 Third Generation Detectors

LIGO Voyager (LIGO Scientific Collaboration 2019) is a planned upgrade to the three existing LIGO facilities that will increase their range to 1.1 Gpc, and also improve the localisation of closer events. This upgrade is expected to occur by the end of the decade, and we assume an operational start date of 2030. Voyager is an intermediate step between the Advanced LIGO detectors and third generation detectors, however due to the significant improvements in the nominal detector range and the uncertainty in the design and timeline of the detector, we consider it a third generation detector for the purposes of this work.

The proposed Neutron Star Extreme Matter Observatory (NEMO; Ackley et al. 2020a) will also bridge the gap between detectors like A+ and true third-generation detectors. While the addition of this detector to the network will not significantly improve detector horizons or merger localisations, it will make the detection of post-merger gravitational waves feasible by extending the observable frequency range. This will provide insight into the nature of merger remnants (Abbott et al. 2019b), and the properties of the jet produced by the merger (e.g., Benjamini et al. 2020). Constraints on both of these will inform radio follow-up efforts.

True third generation gravitational wave detectors will be an order of magnitude more sensitive than current detectors due to reduced quantum shot noise, improved mirror coatings and the placement of the detectors deep underground to reduce Newtonian noise. Both proposed detectors will be triple Michelson interferometers (Freise et al. 2009), as opposed to the L-shaped interferometers used in second generation detectors, which enables the measurement of the gravitational wave polarisation.

The Einstein Telescope (ET; Punturo et al. 2010) will have 10 km arms, while Cosmic Explorer (CE) will have 40 km arms resulting in a higher sensitivity (Abbott et al. 2017a). While a single third generation detector will be capable of detecting compact binary coalescences, precise localisation requires multiple detectors. Hall & Evans (2019) outline various observing scenarios based on combinations of Voyager, ET and CE detectors. For the purposes of this work we consider three simplified scenarios - the proposed network of three Voyager detectors, one Voyager detector with two 3G detectors (likely both ET and CE) and three 3G detectors (likely ET and two CE). A network of one ET detector and two CE detectors will localise > 10% of neutron star coalescences at redshift $z = 0.3$ (corresponding to $\geq 50$ events per year) to $\sim 0.1$ deg² with a median localisation of 1 deg² (Hall & Evans 2019).

5 SEARCHING FOR RADIO AFTERGLOWS

5.1 Benefits and Limitations

5.1.1 Advantages over other wavelengths

The ultraviolet/optical/infrared luminosity of kilonovae is dependent on parameters including the mass and velocity of the ejecta and the fraction of lanthanides produced (e.g. see Metzger 2019, and references therein). Additionally, in higher mass mergers (including neutron star-black hole mergers), the blue component of the kilonova that was vital in localising GW170817 may not be produced and even the red component may be suppressed (Hotokezaka et al. 2013; Kasen et al. 2017). The lack of optical counterparts detected during O3 suggests that not all events will produce kilonovae comparable to GW170817 (Kasliwal et al. 2020). Radio afterglows are mostly independent of these parameters, and therefore probe an independent part of the merger parameter space to optical observations.

While the flux density of a radio afterglow is dependent on viewing angle, even significantly off-axis mergers will produce detectable emission (see Figure 1). In comparison, short gamma-ray bursts are highly anisotropic and therefore most mergers will not produce a detectable GRB counterpart. In fact, the true rate of GRBs may be as much as $10^4$ times higher than what we detect (Soderberg et al. 2006), and radio observations present a promising method of detecting afterglows from off-axis events (Levinson et al. 2002). However, the inclination angle dependence of GW detector sensitivity means that the fraction of GW events with a GRB counterpart is higher than the fraction of detectable GRBs from the general population, and the rate of joint GW-GRB detections will be a few per year for O4 and tens per year for designed LIGO specifications (Howell et al. 2019; Saleem 2020).

Extrinsic factors such as dust extinction and solar angle may also limit follow-up at other wavelengths. For example, comprehensive optical follow-up of GW170817 would not have been possible had the merger occurred a month later, and even X-ray monitoring was hindered by ~90 days of sun avoidance. Radio telescopes are not limited by either of these factors in general, although some may have worse performance pointing near the Sun.

5.1.2 False-positive rate

Radio searches are limited by the discovery of false positives in the form of variable sources manifesting as transients, as well as unrelated transients. Previous untargeted searches for radio transients over long (>1 d) timescales (Mooley et al. 2013, 2016, O’Brien et al. in prep., Stewart et al. in prep.) have been dominated by variable Active Galactic Nuclei (AGN). Some variable AGN will be straightforward to immediately classify, but there exist many that cannot be classified without comprehensive broadband observations (e.g. Sadler et al. 2006; Lovell et al. 2008; Nyland et al. 2021). Searches will also be hindered by sources exhibiting extrinsic variability caused by interstellar scintillation, which can cause variability of tens of percent at GHz frequencies (Cordes & Lazio 2002), resulting in the same compact source being unidentified in one epoch and detected in the next. This can be mitigated by comparing candidate counterparts to galaxy catalogues and ruling out any that are spatially consistent with the nucleus – neutron star mergers are likely to occur away from the galaxy nucleus. However, some telescopes may not provide sufficient astrometric accuracy to do this, necessitating follow-up observations with other facilities.

Searches consisting of multiple short-integration pointings may also discover short-duration radio transients such as Fast Radio Bursts, or flare stars (Helfand et al. 1999; Villadsen & Hallinan 2019; Pritchard et al. 2021), although these will be easily ruled out as unrelated by comparison to archival data along with subsequent follow-up observations.

As radio follow-up observations become more sensitive, we will also discover afterglows from other transients including tidal disruption events and a variety of GRBs. At a detection threshold of 10 $\mu$Jy the expected areal density of radio transients is a few per deg² at GHz frequencies (Metzger et al. 2015). Since the emission...
from most radio transients originates from a synchrotron blast wave, even broadband radio observations may not be sufficient to classify transient types, and instead long-term monitoring to determine the temporal evolution of the source, along with multi-wavelength follow-up, will be required.

While widefield optical searches discover thousands of false positives, ruling them out is made easier by having a large sample of known optical transients with more distinct spectra and underlying physics, enabling the use of machine learning techniques for immediate and automatic classification (e.g. Mahabal et al. 2008; Bloom et al. 2012; Goldstein et al. 2015; Mahabal et al. 2019; Stachie et al. 2020). Comparably few true radio transients have been detected in untargeted searches to-date (Stewart et al. 2016; Law et al. 2018) and current radio transient surveys rely on manual inspection of candidates and classification using follow-up observations and archival data. Planned widefield transients searches will allow the better characterisation of transient properties, which will ultimately enable the use of automated classification algorithms.

It is naturally preferable to confirm the association between any detected radio transient as soon as possible. It is possible (albeit, unlikely) that the radio afterglow may be detected early enough that optical emission from the kilonova is still detectable, observations of which are vital in constraining merger properties like the ejecta mass. More importantly, comprehensive broadband monitoring of the non-thermal afterglow that traces the rise, peak and decline of the lightcurve, is vital in constraining merger properties.

Overall, we strongly emphasise the importance of designing follow-up strategies that are not only sufficient to detect afterglows, but also use a cadence that enables false-positives to be ruled out in a timely manner.

5.1.3 Mergers with radio-loud hosts

Resolving the afterglow from any host galaxy emission may be a decisive factor in whether the afterglow is detectable, particularly in a widefield unbiased search. GW170817 occurred in a radio-loud host galaxy and was offset by 10.31 arcsec (Blanchard et al. 2017; Levan et al. 2017) and therefore non-standard sourcelfinding techniques may have been required to find it in an unbiased search depending on the angular resolution of the data. Host galaxy offsets for short GRBs range from 0.5–75 kpc with a median of 5 kpc (Fong et al. 2010; Fong & Berger 2013; Berger 2014). At 200(500) Mpc this corresponds to an angular offset of 10(4) arcsec, comparable to the angular resolution of at least some current radio telescopes.

For events occurring at cosmological distances, detectable with third generation detectors (see 4.2), typical offsets will be comparable to the angular resolution of the SKA. Therefore the presence of nuclear emission from the host may complicate searches, but not make them impossible. However, radio emission from star formation regions can span a much larger volume (Linden et al. 2020) and may pose more of a problem.

By comparing the expected afterglow luminosity to the typical luminosity of both AGN and star forming galaxies, Hotokezaka et al. (2016) found that most mergers will not occur in galaxies that are sufficiently radio-bright to hinder radio follow-up efforts. This is true even for telescopes with angular resolution ≥ 10 arcsec. The detectability metrics we use in this work assume that the detectability of an event is not limited by host emission.

5.1.4 Galaxy catalogue completeness

Most current radio telescopes lack the field of view and survey speed to carry out unbiased searches and are therefore restricted to the galaxy-targeted approach outlined in Section 3.1.1. The effectiveness of this strategy relies upon having a complete catalogue of galaxies within the localisation volume of each event.

There is currently no all-sky galaxy catalogue that approaches completeness at the current LIGO horizon. GLADE (Dálya et al. 2018) is complete to a distance of ~ 40 Mpc, ~ 50% complete at the nominal O4 range of 170 Mpc and < 40% complete at the design range of 330 Mpc all based on cumulative blue luminosity (which is an approximate analog for star formation, and therefore, merger rate). Additionally the galaxies in GLADE are not isotropically-distributed – the median line of sight density is ~ 10 deg⁻², compared to < 1 deg⁻² in the Galactic plane and > 10³ deg⁻² in fields covered by the HyperLEDA survey (Makarov et al. 2014).

Other existing surveys provide more complete samples along particular lines of sight. These smaller catalogues may still be useful for follow-up of specific events – e.g. the galaxy-targeted follow-up of GW190814 carried out by Gomez et al. (2019) and Ackley et al. (2020b) could have used the PRLS survey rather than GLADE. However, they do not present a general solution for follow-up of all events.

Planned all-sky surveys (e.g. LSST Science Collaboration et al. 2009; Dör et al. 2016, among others) will drastically improve upon existing catalogues and make it feasible to target galaxies for events at Gpc distances. However, these surveys will likely not be finished within the 5 years, by which time facilities like ASKAP and MeerKAT will be fully operational and the DSA-2000 and SKA may be coming online. These telescopes are not suited to galaxy targeting due to their wide fields of view (compared to most existing facilities), and therefore it’s unlikely that future galaxy catalogues will have a tangible impact on the pointing strategies used in radio follow-up. However, they will remain extremely useful for ruling out false-positive radio transient candidates and in determining whether discovered transients are associated with host galaxies within the localisation volume.

5.2 Follow-up of GW-identified mergers

To quantify prospects for detecting radio afterglows we use a simple detection metric – the flux density at the observing frequency must exceed five times the expected thermal noise, σ. This estimate does not include the noise due to source confusion, which will not be the limiting factor for the observations discussed here.

We also compare our results to the range of gravitational wave detectors which is dependent on inclination angle, scaling as

\[ R(\theta_{\text{obs}}) \approx 0.589 R \sqrt{1 + 6 \cos^2 \theta_{\text{obs}} + \cos^4 \theta_{\text{obs}}} \]

where \( R(\theta_{\text{obs}}) \) is the inclination angle dependent range and \( R \) is the gravitational wave detector range found in Table 2. The variable terms in this equation are obtained by averaging eq. 3.31 of Finn & Chernoff (1993) across the antenna pattern terms, while the

\[ \theta_{\text{obs}} \]

We note that this is a crude approximation to the true survey volume, which can be more accurately calculated via a numerical Monte Carlo integral (Mandel, private communication). We have compared both methods and find the above equation underestimates the range by ~10%. However, we have chosen to use this method as it is sufficiently accurate for our purposes and is far easier to reproduce.
normalisation constant is calculated by requiring \( \langle R(\theta_{\text{obs}}) \rangle = \overline{R} \).
Duque et al. (2019) obtain the same result by instead computing the gravitational wave detector horizon. While Finn & Chernoff (1993) only calculate antenna patterns for L-shaped interferometers, the above equation is a sufficient approximation to the 3G detector configurations for our purposes as any discrepancy is negligible compared to the current uncertainty in detector specifications and sensitivity.

5.2.1 Galaxy Targeting

Figure 2 shows the maximum distance at which an afterglow can be detected for a range of circum-merger densities spanning \( 10^{-4} \) to \( 1 \) cm\(^{-3} \), using a galaxy-targeting approach with the ATCA and the VLA as outlined in Section 3.2.

We note that while this strategy will allow most events to be detected at distances comparable to the LIGO range, the incompleteness of existing galaxy catalogues at these distances makes this strategy only feasible for the closest mergers (\( D_L \ll 100 \) Mpc). We do not consider applying this approach to any next generation radio facilities from events that have been localised by the detection of an electromagnetic counterpart. Assuming that neutron star mergers occur in comparable dense environments to short GRBs (\( n \sim 10^{-2} \) cm\(^{-3} \) Fong et al. 2015) we find that most neutron star mergers detected during O4, and a large fraction with the A+ configuration, should produce radio emission that is detectable with deep single pointing observations. However current facilities will not be sufficient for a comprehensive census of radio afterglows as we move towards the 3G era – only on-axis mergers occurring in dense environments (\( n \gtrsim 10^{-1} \) cm\(^{-3} \)) will be detectable at the Voyager horizon.

The sensitivity of future radio telescopes will partially address this problem. Figure 6 shows the detectability horizon for the ngVLA and both phases of the SKA (with the DSA-2000 horizon

5.2.2 Unbiased Searches

We therefore turn our focus to the unbiased searches described in Table 3, which we split into four broad categories.

Figure 3 shows the detectability of events in unbiased searches with current facilities. Most on-axis mergers, as well as most off-axis mergers occurring in dense environments, localised to \( \lesssim 10 \) deg\(^2\) detected with current gravitational wave facilities and the A+ upgrade will be detectable with MeerKAT and some will be detectable with the VLA and Aperif. However, we note that only a small fraction of events will be localised this well with these detectors. LIGO Voyager will have better localisation capabilities, and some events will produce afterglows that are detectable out to the detector horizon.

For events that are localised to tens of square degrees, comparable to the median localisation for 2G detectors (Abbott et al. 2020b), we consider follow-up with ASKAP and Aperif. Figure 3 also shows the maximum distance at which afterglows will be detected, and we find that it is feasible to detect the afterglow produced by most on-axis mergers with current gravitational wave detectors.

Figure 4 shows the same metrics applied to the DSA-2000, ngVLA and SKA-1 compared to the range of Voyager and 3G detectors for events localised to \( \lesssim 10 \) deg\(^2\) and \( \lesssim 100 \) deg\(^2\). We find that while the majority of events detected with Voyager will be accompanied by detectable afterglows, it will not be possible to detect afterglows in widefield follow-up of the most distant events discovered by a complete 3G network. However, we note that the median localisation achievable with a complete 3G network is \( \lesssim 1 \) deg\(^2\). Therefore widefield searches will not be necessary for most events, and the targeted single-pointing strategy outlined in Section 5.2.3 may be a more useful metric.

5.2.3 Monitoring electromagnetic counterparts

Figure 5 shows prospects for detecting radio emission with current radio facilities from events that have been localised by the detection of an electromagnetic counterpart. Assuming that neutron star mergers occur in comparable dense environments to short GRBs (\( n \sim 10^{-2} \) cm\(^{-3} \) Fong et al. 2015) we find that most neutron star mergers detected during O4, and a large fraction with the A+ configuration, should produce radio emission that is detectable with deep single pointing observations. However current facilities will not be sufficient for a comprehensive census of radio afterglows as we move towards the 3G era – only on-axis mergers occurring in dense environments (\( n \gtrsim 10^{-1} \) cm\(^{-3} \)) will be detectable at the Voyager horizon.

The sensitivity of future radio telescopes will partially address this problem. Figure 6 shows the detectability horizon for the ngVLA and both phases of the SKA (with the DSA-2000 horizon
comparable to that of the SKA-1). While most events detected with Voyager will be within range of future radio telescopes, the most distant events detected with 3G detectors will be well beyond the range of even the SKA-2. However, these detectors will detect thousands of events per year and therefore the limiting factor in obtaining a census of radio afterglows will be the amount of telescope time available rather than the current scenario which is limited by a lack of events.

### 5.3 Serendipitous detections and orphan afterglows

We also consider the detection of afterglows from known gravitational wave events and orphan afterglows (i.e. events with no previous EM/GW detection), in the transients surveys outlined in 3.4. Table 4 shows the properties of the surveys, and Figure 7 shows the application of the same detectability metrics as above.

To determine the capability of surveys to obtain a complete sample of mergers occurring within their footprint, we also apply an additional constraint of the afterglow remaining detectable for a time corresponding to the survey cadence. This ensures that the afterglow will be detected in at least one epoch of the survey, although we note that multiple detections and multi-wavelength follow-up will be undertaken.

### Table 4. Ongoing, upcoming and idealised transients surveys. The fraction of the total sky covered by the survey is in column 3, while $S_{\text{det}}$ corresponds to a 5σ detection threshold based on expected image noise. The MeerKAT survey is a theoretical idealised survey and there are no current plans to undertake it.

| Survey          | $\nu$ (GHz) | Sky coverage | Cadence (months) | $S_{\text{det}}$ (µJy) |
|-----------------|-------------|--------------|------------------|------------------------|
| VLASS           | 3           | 0.82         | 32               | 600                    |
| VAST-Wide       | 0.9         | 0.23         | daily            | 2500                   |
| VAST-Deep       | 0.9         | 0.23         | 8                | 250                    |
| MeerKAT         | 1.4         | 0.12         | 4                | 20                     |
| DSA (CASS)      | 1.35        | 0.75         | 4                | 10                     |
required to confirm the detection and classify it. The results of this change are shown in Figure 8, where we have excluded VLASS (as its slow cadence results in effectively zero range) and VAST-Wide (as its daily cadence results in no significant changes to the result above). Sensitivity remains the dominant limiting factor for off-axis events, while on-axis events occurring in denser environments are limited by survey cadence as their emission peaks at earlier times with a shorter turnover period. We note that these results cannot be scaled using equation 4, as the rise and decay of the lightcurve are also dependent on our assumptions of $E_{iso}$ and $\Gamma(\theta)$.

While planned transients searches will not provide complete samples of afterglows due to their limited sky coverage, these results demonstrate that it is worthwhile carrying out targeted searches for afterglows within those datasets. These surveys may also make it feasible to search for counterparts to poorly localised events that do not individually warrant follow-up observations. We also note that once Voyager begins operations very few orphan afterglows will be detected, as only on-axis events occurring in the most dense environments will be detectable at distances beyond the Voyager horizon, although this does not consider the duty cycle of the detector network.

6 CONCLUSIONS

In this work we have summarised the synergies between radio telescopes and gravitational wave detectors, encompassing both existing facilities and planned or proposed facilities spanning the coming decades. We demonstrate that while targeting potential host galaxies proved useful in the follow-up of GW170817, this method will be less feasible in future follow-up due to limited catalogue completeness at distances comparable to the range of gravitational wave detectors. Additionally, the larger field of view of future telescopes is more conducive to unbiased widefield searches that target the localisation region of the merger. We find that these searches with current facilities will be capable of detecting mergers at hundreds of Mpc, while future facilities will be able to detect mergers at Gpc distances. Widefield transients surveys will provide serendipitous coverage of events and may also detect afterglows of events beyond the detector horizon, and those that occur during detector downtime.

Radio observations can be used to place constraints on properties of the merger outflow and the circum-merger environment, and for events with counterparts detected at other wavelengths, we find that current radio facilities are capable of detecting some afterglows at the Voyager horizon, while future facilities will detect afterglows at distances up to tens of Gpc for the most on-axis events. However, lightcurve monitoring alone is insufficient to completely constrain the geometry of the merger, and we also discuss possible ways of breaking model degeneracies.

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Software: Astropy (Astropy Collaboration et al. 2018), Jupyter (Kluyver et al. 2016), Matplotlib (Hunter 2007), NumPy (Harris et al. 2020), SciPy (Virtanen et al. 2020)

DATA AVAILABILITY

The data underlying this article will be shared on reasonable request to the corresponding author.

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Figure 7. Detectability of radio afterglows for planned (left) and potential future (right) untargeted transients surveys. The detector range for O4, A+ and Voyager are shown in increasingly light shades of grey.

Figure 8. Detectability of a complete sample of radio afterglows (i.e. where the signal remains detectable for longer than the survey cadence) in planned and potential future untargeted transients surveys. The detector range for O4, A+ and Voyager are shown in increasingly light shades of grey. As the inclination angle of the merger decreases the detectability becomes limited by the survey cadence rather than sensitivity. This effect is more pronounced for mergers occurring in denser environments.

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